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ESTIMATION OF THE WATER STRESS INDEX OF CROPS AS A METHOD OF PREDICTING THE REQUIREMENT TO IRRIGATE

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Abstract. This article presents the application of the water stress index as a method of predicting the requirement to irrigate. The simple linear relationship between the crop canopy temperature minus the ambient air temperature ($T_c - T_a$) to the VPD is called the CWSI baseline. The data necessary to estimate the baseline and the CWSI indicator for grassland was collected at the experimental station in Sosnowica, Poland. This method of estimating the CWSI index may be helpful for identifying management decisions but the different results obtained in 1995 and 1996 and the relatively low correlation coefficients (0.54-0.73) indicate that further field research and more experimental measurements are needed.

Keywords: simulation, crop water stress, canopy temperature method, irrigation prediction.

INTRODUCTION

The use of canopy temperature to detect water stress in plants is based upon the assumption that transpired water evaporates and cools the leaves below the temperature of the surrounding air. As water becomes limited, transpiration is reduced and leaf temperature increases.

For many years, the temperature of the canopy was regarded as a parameter of water balance in the plant. In 1981 Idsoetal *et al.* [1] introduced new parameters called the 'Crop Water-Stress Index' (CWSI) as an empirical solution of the problem of the requirement to irrigate. If the water-stress of a plant can be numerically quantified [3] research can be conducted to correlate the effect of the increasing water stress of the plant on crop productivity, yield and product quality. When an optimal level of water stress has been defined, the information can be used in irrigation management decisions.

Data [3] shows that the canopy temperature method responds well to crop water-stress and may give interesting information on the behaviour of the crops given the acceptable relation with the relative evaporation/transpiration and yield [2].

DESCRIPTION OF THE METHOD

The CWSI is based on the fact that most well-watered plants on sunny days will transpire at a maximum potential rate. The water transpired from the leaf evaporates and consumes energy, thereby depressing leaf temperature. The rate of evaporation and energy consumption is dependent on the vapour pressure deficit, the greater the rate of transpiration producing a larger depression in a leaf's temperature when compared to the air temperature. As soil moisture is depleted, the transpiration rate is reduced, thereby reducing the evaporative cooling effect, which increases the temperature of the leaf. Temperature behaviour can be observed with a sensor sensitive to thermal infrared radiation. By scanning the earth's surface with such a sensor from an airplane or satellite, the temperature variation of the earth's surface can be observed. The correlation between the leaf temperature minus the air temperature and vapour pressure deficit (VPD) of the atmosphere results in the numerical value of CWSI where 0.0 indicates a non-water-stressed leaf and 1.0 indicates a completely water-stressed non-transpiring leaf. The simple linear relationship between the crop canopy temperature minus the ambient air temperature ($T_c - T_a$) to the VPD is called the CWSI baseline. The baseline allows how cool a well - watered field should be to be determined - depending on current atmospheric conditions (VPD). Baselines introduced in this paper for 1995 and 1996 were attained using empirical method and data collected during field research.

Table 1 is an example of the raw data necessary to estimate the baseline for grassland (16 July 1996).

Field measurements were collected every hour. For each data time set, a canopy minus the air temperature was calculated, the baseline is the simple linear relationship between the ΔT and VPD. As the VPD on the x-axis increases, the ΔT on the y-axis increases negatively. The upper straight line is the non-transpiring (stressed) baseline. The upper stressed baseline represents the hottest you might expect a crop canopy to be over a wide range of VPD's. This means that there is no water escaping from a non-transpiring crop canopy, there is no transpiration effect to cool the leaf.

Table 1. The example of raw data used to estimate baseline for grassland in 1996. *Tc* – crop temperature (°C), *Ta* – air temperature (°C), *Tw* – wet bulb temperature (°C)

No.	Time	*Tc*	*Ta*	*Tw*	d = VPD (kPa)	$\Delta T = Tc - Ta$ (°C)
1.	7.00	16	12.2	10.0	0.37	3.8
2.	8.00	21	13.2	10.2	0.51	7.8
3.	9.00	25	14.4	10.4	0.70	10.6
4.	10.00	22	15.0	10.8	0.74	7.0
5.	11.00	16	14.8	11.0	0.67	1.2
6.	12.00	22	14.6	11.5	0.55	7.4
7.	13.00	25	14.8	12.4	0.43	10.2
8.	14.00	20	15.0	11.8	0.57	5.0
9.	15.00	21	15.0	11.0	0.71	6.0
10.	16.00	22	15.8	11.0	0.86	6.2
11.	17.00	22	15.6	11.4	0.76	6.4
12.	18.00	18	15.2	11.4	0.68	2.8

To estimate the CWSI index, more calculations are necessary. Taking into account the baseline relationship for grassland for the 1996 season ($\Delta T = 1.89 - 5.75 \cdot \mathrm{d}$) it is possible to calculate the potential ΔT for non-stressed crops for a specific VPD value. If – for example – the VPD is 1.5 kPa ,then the potential $\Delta T = 1.89 - 5.75 \cdot 1.5$ is equal to –6.74, which means that at a VPD of 1.5 kPa this well watered, non-stressed crop has the potential to be about 6.74° C cooler than the air temperature. (Distance BC fig. 2A). If this crop was completely water stressed it would be 1.89°C hotter then the air temperature. In this case the potential range of ΔT is equal to 8.63°C.

To calculate the CWSI index, the equation can be written:

$$\mathrm{CWSI} = \text{Crop Dist. From Pot. } \Delta T\ [^{\circ}\mathrm{C}] \,/\, \text{Pot. Range of } \Delta T\ [^{\circ}\mathrm{C}] \qquad (1)$$

where: Crop Dist. from Pot. ΔT [°C] – Actual crop ΔT ($Tc - Ta$) minus the potential crop ΔT (fig. 1a and 1b) Pot. Range of ΔT [°C] – The absolute value (always positive) of the potential crop ΔT plus the upper limit (fig. 1a and 1b).

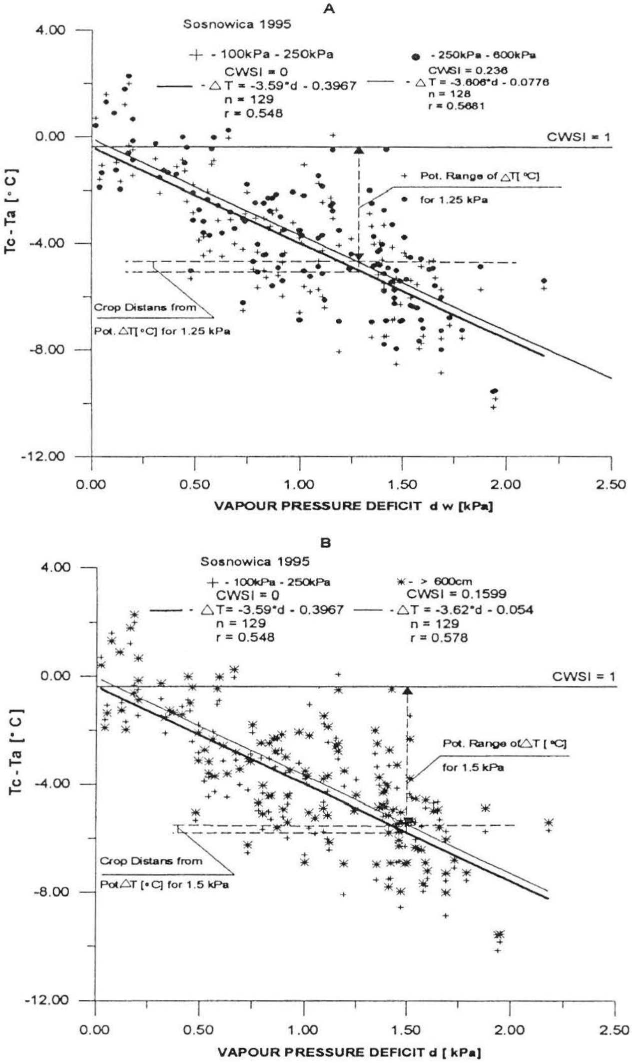

Fig. 1. The relationship of *(Tc – Ta)* to the VPD for grassland. A – the baseline for 1995 and CWSI index for soil water pressure of 250-600 kPa , B – the baseline for 1995 and CWSI – index for soil water pressure higher than 600 kPa. I, S – intercept and slope of linear regression, r – correlation coefficient, n – number of points

FIELD MEASUREMENTS

The necessary data to estimate the baseline and CWSI indicator for grassland was collected at the Sosnowica experimental station, Poland, during July and August 1995 and 1996. The field measurements included such parameters as: crop infrared temperature, air temperature, air humidity and soil water pressure for four different ground water tables (without groundwater table, 30 cm, 50 cm, 70 cm, 100 cm). The crop surface temperature was measured with a radiometer PRR 200 (Made in Poland) at 1m height. This data was then verified using measurements obtained with an 'Infrared AG Multimeter' Model 15/0B (Made in the USA) using simple linear relationship:

$$Tc = 0.288 \cdot Tc_S + 9.49 \tag{2}$$

where: T_c – verified crop temperature [°C],

Tc_s – crop temperature measured at the lysimeter station [°C].

Air temperature and wet bulb temperature were measured at 2 m height.

RESULTS AND DISCUSSION

Measurements of infrared leaf temperature and other meteorological conditions were conducted for two years during July and August 1995, 1996 from 7.00 am to 6 p.m every hour. Table 2 shows the fluctuation range of radiation temperature, air temperature and the relative humidity during the observation term.

Table 2. The range of fluctuation for measured meteorological condition in 1995 and 1996

Year	Radiation temperature (°C)	Air temperature (°C)	Relative humidity (%)
1995	15 - 39	13.4 - 28.0	39 - 99
1996	10 - 37	9.8 - 28.8	32 - 95

Figure 1 shows the baseline and CWSI index for two different lysimeters with different soil water potential for 1995 – figure 1A for soil water pressure 250-600 kPa, and figure 1B for soil water pressure higher than 600 kPa. The baseline (CWSI = 0, $\Delta T = T_c - T_a = -3.59 \cdot d - 0.3967$) was calculated for the range of soil water pressure from 100 kPa to 250 kPa which was regarded as the optimal water conditions for grass.

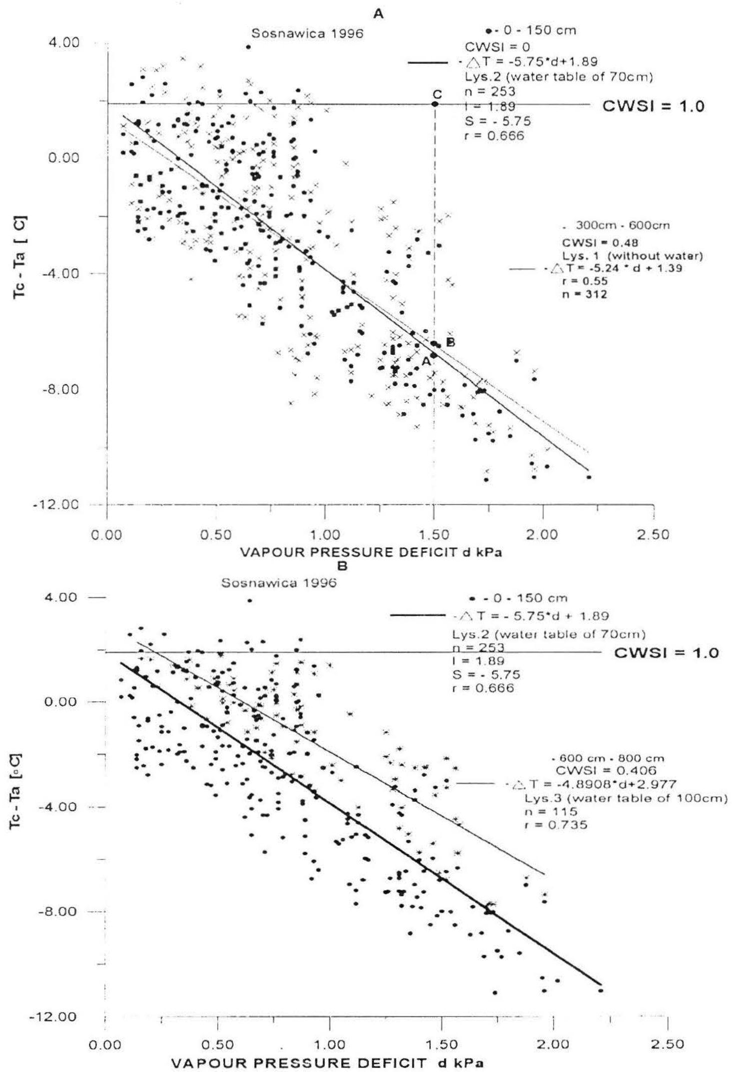

Fig. 2. The relationship of $(Tc - Ta)$ to the VPD for grassland. A – the baseline for 1996 and CWSI index for soil water pressure of 300-600 kPa, B – the baseline and CWSI index for soil water pressure 600-800 kPa. For explanation see fig. 1

The baseline intercept indicates that the non-transpiring crop canopy is 0.396°C cooler than the air temperature, which is a contradictory result with a theoretical foundation. The CWSI = 0.236 (for soil water pressure 250-600 kPa) and CWSI = 0.159 (for soil water pressure more than 600 kPa) relationships show the same situation.

Moreover, the CWSI index calculated over a range of soil water pressures between 250 kPa and 600 kPa is 50% higher than the CWSI parameter calculated for soil moisture pressure more than 600 kPa. Both of these results and the relatively low correlation coefficients (lower than 0.6) for linear relationships may be caused by the inaccuracy of both the radiometer and tension meters. The PRR200 radiometer was working without the necessary filter on the 8-14 μm length of the infrared beam radiation and over an unknown experimental field of view. Another source of error may be the method for verifying the infrared temperature of the crops. The linear relationship between measurements obtained using radiometer PRR200 and the 'Infrared AG Multimeter' Model 15/OB characterises a very low correlation coefficient ($r = 0.303$)

Figure 2 shows the baseline and CWSI indices for grassland for 1996. They seem to be more reliable and confirm the theoretical bases of the method discussed. Although the CWSI index calculated for lysimeter 1 (CWSI = 0.48, soil water pressure 250-600 kPa) is higher than CWSI index for lysimeter 3 (CWSI = 0.406, soil water pressure 600-800 kPa) these two lysimeters were under different ground water level:

- lysimeter 1 – without groundwater table,
- lysimeter 2 – ground water table of 100 cm depth.

Measurements results obtained during years 1995 and 1996 indicate that soil water pressure over a range 250-800 kPa doesn't influence crop water stress in any substantial way. The great dispersion of points and the low regression coefficients confirm that the CWSI index is mainly a function of meteorological conditions.

SUMMARY AND CONCLUSION

The field research conducted at the Institute of Land Reclamation and Grassland Farming experimental station in Sosnowica confirmed that crop water stress is a function of leaf radiation temperature. This method for estimating the CWSI index may be helpful in identifying management decisions. Different results obtained in 1995 and 1996 years show that the CWSI parameter is mainly connected with meteorological conditions (summer 1995 sunny and dry, summer 1996 much cooler and wet). The relatively low correlation coefficients (0.54-0.73) indicate that further field research needs more experimental measurements (radiometer filter, estimation of field of view). Nevertheless, these measurements may be helpful in order to identify better the parameters and meteorological variables influencing the CWSI index.

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ZASTOSOWANIE WSKAŹNIKA CWSI W PROCESIE IRYGACJI UŻYTKÓW ZIELONYCH

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Streszczenie. Artykuł prezentuje jedną z użytecznych i praktycznych metod opracowywania harmonogramów nawodnień opartą o obliczanie parametru CWSI (Crop Water Stress Index). Linia bazowa indeksu CWSI określana jest jako prosta liniowa zależność pomiędzy różnicą temperatur łanu i powietrza oraz ciśnieniem ssącym gleby. W pracy pokazano przykład zastosowania metody CWSI w oparciu o badania przeprowadzone na eksperymentalnej stacji badawczej zlokalizowanej w Sosnowicy, w Polsce. Prezentowany model może być pomocnym narzędziem wspomagającym procesy decyzyjne, ale zróżnicowane wyniki uzyskane na podstawie danych eksperymentalnych oraz stosunkowo niskie współczynniki korelacji, wskazują że metoda wymaga dalszych prac badawczych oraz pomiarów prowadzonych na rzeczywistych obiektach.

Słowa kluczowe: symulacje, stres wodny, temperatura radiacyjna roślin, prognozy nawodnień