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EVALUATING CROP WATER STRESS USING INFRARED THERMOMETRY

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A b s t r a c t. The Crop Water Stress Index (CWSI) has been used as a remotely sensed indicator of plant water stress. Crop water stress index is estimated using canopy temperature measured with the infrared thermometer (IRT) and is based on the difference between the crop canopy temperature and the ambient air temperature (*Tc-Ta*). The purpose of this study was to demonstrate a dependence of the (*Tc-Ta*) on atmospheric water vapour pressure deficit (*d*) under conditions of non-limiting soil water content (the CWSI baseline) and to evaluate the maximum admissible value of (*Tc-Ta*) for grassland, alfalfa and winter wheat.

K e y w o r d s: infrared thermometry, crop water stress index

INTRODUCTION

Measurements of crop canopy temperature have long been recognised as a way of assessing plant water status. Monteith and Szeicz [7] showed that infrared thermometry (IRT) could be used to measure canopy temperature. Idso *et al.* [5] showed that the difference between canopy and air temperature (*Tc-Ta*) could be used as a measure of crop water stress. Idso *et al.* [4] introduced a new parameter - the Crop Water Stress Index (CWSI), being an empirical approach to this problem. Afterward many developments and applications of the method were done [1,3,6,9,10].

The primary goal of this research is to estimate CWSI of some crops cultivated in the Noteć river catchment area as well as to determine the CWSI baselines and the maximum allowed value of (*Tc-Ta*) for these crops.

PHYSICAL BACKGROUND

The concept of CWSI is based on the fact that well-watered plants in full sunlight will transpire (lose water from the leaves) at a maximum potential rate. The water transpired from the leaves evaporates and consumes energy, thereby depressing the leaf temperature. The rate of evaporation and energy consumption is dependent on the vapour pressure deficit (*d*) of the atmosphere in which the plants are growing. The greater the vapour pressure deficit, the greater the rate of evaporation producing a larger depression in leaf temperature when compared to air temperature. As soil moisture is depleted, the transpiration rate is reduced, thereby reducing the evaporative cooling effect, which increases the temperature of the leaves.

The IRT remotely measures the leaf or crop canopy temperature (*Tc*). It has been observed that the difference between the crop surface temperature (*Tc*) and the air temperature (*Ta*) depends on the vapour pressure deficit (*d*) of the atmosphere except for the severely stressed conditions. Correlating (*Tc-Ta*) to *d* one can predict how cool a crop surface should be at the specific *d* when soil water is not limiting. This relationship is assumed to be a linear function and is usually referred as the baseline. This regression line is obtained from measurements in a well-watered crop transpiring at potential rate. The CWSI value on the baseline is equal zero and indicates no water stress. The CWSI equal to 1.0 indicates a completely water-stressed non-transpirating crop. Through research at different CWSI levels under field conditions, a CWSI and (*Tc-Ta*) critical values where growth is inhibited and reduced due to soil moisture stress can be defined.

The concept of the canopy surface temperature-based CWSI is shown in Fig.1. Every observed pair of (*Tc-Ta*) and *d* values will fall between the two lines. It is therefore possible to define the CWSI from the ratio between the distance of the observed (*Tc-Ta*) value to the non-stressed line (ΔTa) and the distance between the two lines (ΔTp) for the observed *d*. The equation to calculate the CWSI has the form:

$$\mathrm{CWSI} = \frac{\Delta Ta}{\Delta Tp} = \frac{(Tc - Ta)\,obs - (Tc - Ta)min}{(Tc - Ta)max - (Tc - Ta)min} \qquad (1)$$

where *Tc* - canopy infrared temperature (°C), *Ta* - air temperature (°C), (*Tc-Ta*)*obs* - actual observed temperature difference between the canopy and the air, (*Tc-Ta*)*max* - temperature difference for fully water-stressed crop,

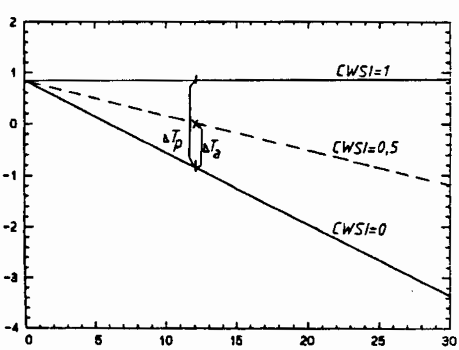

Fig. 1. The concept of the crop water stress index CWSI; *Tc* - canopy infrared temperature, *Ta* - air temperature, *d* - vapour pressure deficit.

(*Tc-Ta*)*min* - temperature difference for well-watered crop.

The relationship (*Tc-Ta*)*min* versus *d* can be approximated by the linear regression, called the CWSI baseline, in the form:

$$(Tc-Ta)min = I + Sd \quad (^{o}C) \qquad (2)$$

where: *I*, *S* - intercept and slope of the linear regression, respectively *d* - water vapour pressure deficit in the air (hPa).

The upper straight line is the non-transpiring (stressed) line. Since there is no water escaping from a non-transpiring crop canopy, there is no evaporative effect to cool the leaves. Therefore, the energy from the sun absorbed by the leaves results in accummulated heat. The upper stressed line represents the hottest one might expect a crop canopy to be over a wide range of *d*. Idso *et al.* [4] suggested that (*Tc-Ta*)*max* could be estimated by extrapolation of the baseline to a value of (*Tc-Ta*) at which the vapour pressure gradient between the canopy and the air, and therefore transpiration, is zero. So it can be assumed that:

$$(Tc-Ta)max = I \quad (^{o}C) \qquad (3)$$

MATERIALS AND METHODS

The investigations were carried out in irrigated fields of grasslands (meadows and pastures), alfalfa and winter wheat during the 1993 and 1994 growing seasons. The fields are located in the Noteć river catchment area on the peat-muck soils (grasslands) and the degraded chernozems (alfalfa and winter wheat).

The canopy temperature was measured manually with a hand-held Infrared AG Multimeter Model 510B (Everest Interscience, Fullerton, USA). The infrared thermometer (IRT) has a 15-degree field of view and a 8-14 μm bandpass filter. A constant emissivity setting of 0.98 was used for all measurements and no corrections were made for reflected radiation and actual canopy emissivity. The accuracy of the infrared temperature measurements is ± 0.5 °C. The IRT was held at an angle of 25-30° from the horizontal, 1.5 m above the ground surface (i.e., about 1.1-1.3 m above the grass and alfalfa canopy and 0.4-0.6 m above the wheat canopy). Using this technique, the area viewed by the IRT is approximated by an ellipse with semi-axes of 4.5 and 1.4 m and an area of 4.9 m^2 on the grass and alfalfa canopy surfaces and by an ellipse with semi-axes of 1.8 and 0.6 m and an area of 0.9 m^2 on the winter wheat canopy surface. The measurements were made at the cloudless sky in the full-growth crop stage, when the crop completely covered the soil surface. The infrared temperature was determined by taking, from one point, four measurements to the north, south, east and west, and averaging. Other measurements, made with the same apparatus, were air temperature, relative humidity and solar radiation with the accuracies ± 0.2 °C, ± 4 % and ±100 W m^{-2}, respectively. Vapour pressure deficit was determined using the psychrometric Tables [8]. Volumetric soil water contents using a neutron probe and soil water pressure potentials, using tensiometers, were measured during infrared temperature measurements.

A linear regression of (*Tc-Ta*) as a function of vapour pressure deficit *d* was derived as the baseline. The relationships were estimated from the measurements taken when soil water content was higher than the minimum allowed, that is when the soil water pressure potential was higher than -50 kPa at a depth of 45-50 cm under wheat and alfalfa and at a depth of 15-20 cm under grass.

RESULTS AND DISCUSSION

The period of measurements spanned two growth cycles and provided an opportunity to observe large ranges of air and canopy temperature, solar radiation and vapour pressure deficit. When the grassland canopy temperature measurements were taken, air temperature ranged from 13.9 to 31.5 °C, solar radiation ranged from 103 to 802 W m^{-2} and vapour pressure deficit ranged from 4.1 to 32.4 hPa. When the alfalfa canopy temperature measurements were taken, air temperature ranged from 15.8 to 26.4 °C, solar radiation ranged from 124 to 565 W m^{-2} and vapour pressure deficit ranged from 4.8 to 19.3 hPa. When the winter wheat canopy temperature measurements were taken, air temperature ranged from 19.1 to 26.9 °C, solar radiation ranged from 129 to 666 W m^{-2} and vapour pressure deficit ranged from 10.5 to 21.9 hPa.

The experimental data and the linear relationships of (*Tc-Ta*) to vapour pressure deficit *d* are shown in Fig. 2 for grassland (a), alfalfa (b) and winter wheat (c). fully reliable results are obtained for grassland, while the results for alfalfa

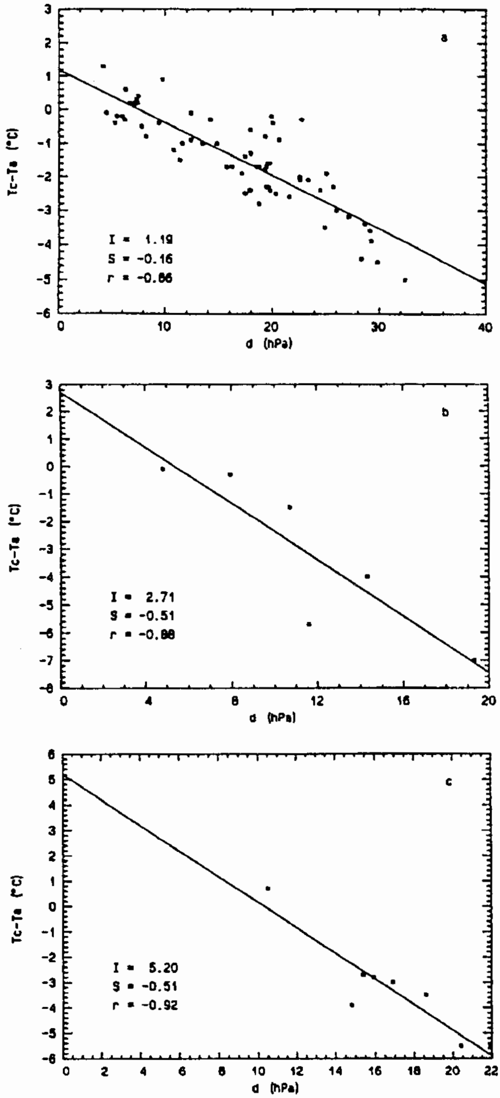

Fig. 2. The CWSI baselines for grassland (a), alfalfa (b) and winter wheat (c); *Tc* - canopy infrared temperature, *Ta* - air temperature, *d* - vapour pressure deficit, *I*, *S* - intercept and slope of the linear regresion, r - correlation coefficient.

and winter wheat are of less reliability due to the small number of measurements.

The linear regression lines are the non-water-stressed baselines on which CWSI=0. As it is seen, as vapour pressure deficit *d* increases, the rate of evaporation increases (which consumes more energy), thereby lowering the temperature of the canopy and the actual difference (*Tc-Ta*).

The intercepts of the regressions are equal to (*Tc-Ta)max* and form the non-transpiring (fully stressed) lines on which CWSI=1. They represents the hottest conditions in which a crop canopy can be under a wide range of *d*. They are equal to: 1.2 °C for grassland, 2.7 °C for alfalfa and 5.2 °C for winter wheat. It means that these crops when completely water stressed would be respectively 1.2, 2.7 and 5.2 °C hotter than the air.

The non-water-stressed baseline coefficients are of good agreement with those reported by Idso [3] and Clawson *et al.* [1]. The high correlation coefficients indicate the strong dependence of (*Tc-Ta*) on vapour pressure deficit *d*.

Considering grasslands in details, depending on the degree of crop water stress, one can expect, at the vapour pressure deficit *d* of 20 hPa, the change in the crop canopy temperature between -2.0 °C below the air temperature (no water stress) and +1.2 °C above the air temperature (full water stress).

The maximum value of the difference (*Tc-Ta*) represents the conditions under which crop transpiration is completely stopped. Such situation must not be allowed. That is why the maximum admissible value of (*Tc-Ta*) must be determined at which the small or allowed reduction of the evapotranspiration rate and the crop growth is encountered. The results reported by Halim *et al.* [2] and Wiegand *et al.* [9] suggest the CWSI=0.5 as the maximum allowed or critical value. Substituting Eqs. (2) and (3) into Eq. (1) it can be calculated that:

$$(Tc - Ta)cr = I + Sd\,(1 - \mathrm{CWSI})\ (^{o}\mathrm{C}) \quad (4)$$

where (*Tc-Ta*)*cr* - maximum allowed (critical) difference between crop canopy and air temperature (°C), *I*, *S* - the linear regression coefficients of (*Tc-Ta*) to *d*, *d* - vapour pressure deficit (hPa), CWSI - crop water stress index.

The critical values of the difference between the canopy temperature and the air temperature (*Tc-Ta*) for the CWSI =0.5 are given in Table 1. As it can be seen, under cool and wet meteorological conditions, the grassland canopy surface temperature is admitted to be 0.4-0.8 °C higher than the air temperature, the alfalfa canopy temperature is admitted to be 0.2-1.4 °C higher than the air temperature, and the wheat canopy temperature is admitted to be 2.6-4.9 °C higher than the air temperature. But, when weather is hot and dry, the canopy surface temperature must be lower than the air temperature by 0.8-1.2, 3.6-4.9, 1.2-2.5 °C for grassland, alfalfa and winter wheat, respectively.

Table 1. Maximum admissible difference between the canopy and air temperature (*Tc-Ta*)*cr* for various vapour pressure deficits *d*

d (hPa)	(*Tc-Ta*)*cr* (°C)		
	grassland	alfalfa	winter wheat
5	0.8	1.4	4.9
10	0.4	0.2	2.6
15	0.0	-1.1	1.4
20	-0.4	-2.4	0.1
25	-0.8	-3.6	-1.2
30	-1.2	-4.9	-2.5

CONCLUSIONS

The canopy surface temperature measured with the infrared thermometer can provide many valuable information on the energy balance and water transport in the soil-plant-atmosphere continuum. The canopy temperature seems to respond well to crop water stress. The main conclusion to be drawn from this study is that the canopy temperature can be useful in infrared temperature-based crop water stress index determination. The CWSI baselines for grassland, alfalfa and winter wheat, derived in the study, enabled us to estimate the maximum allowed (critical) temperature difference between the crop canopy and the air. These indices can be suitable for early detection of soil water shortage, and useful in real-time irrigation scheduling.

REFERENCES

1. **Clawson K.L, Jackson R.D., Pinter P.J.**: Evaluating plant water stress with canopy temperature differences. Agron. J., 81(6), 858-863, 1989.
2. **Halim R.A., Buxton D.R., Hattendorf M.J., Carlson R.E.**: Water-deficit effects on alfalfa at various growth stages. Agron. J., 81(5), 765-770, 1989.
3. **Idso S.B.**: Non-water-stressed baselines: a key to measuring and interpreting plant water stress. Agric. Meteorol., 27, 59-70, 1982.
4. **Idso S.B., Jackson R.D., Pinter P.J., Reginato R.J., Hatfield J.L**: Normalizing the stress degree day for environmental variability. Agric. Meteorol., 24, 45-55, 1981.
5. **Idso S.B., Jackson R.D., Reginato R.J.**: Remote sensing of crop yields. Science, 196, 19-25, 1977.
6. **Jackson R.D., Idso S.B., Reginato R.J., Pinter P.J.**: Canopy temperature as a crop water stress indicator. Water Resour. Res., 17, 1133-1138, 1981.
7. **Monteith J.L., Szeicz G.**: Radiative temperature in the heat balance of natural surfaces. Q.J.R. Meteorol. Soc., 88, 496-507, 1962
8. **Rojecki A.**: Psychrometric Tables. PIHM, Warszawa, 1959.
9. **Stockle C.O., Dugas W.A.**: Evaluating canopy temperature-based indices for irrigation scheduling. Irrig. Sci., 13, 31-37, 1992.
10. **Wiegand C.L., Nixon P.R., Jackson R.D.**: Drought detection and quantification by reflectance and thermal responses. Agric. Water. Management, 7, 1-3, 1983.

OCENA STRESU WODNEGO ROŚLIN PRZY UŻYCIU TERMOMETRII W PODCZERWIENI

Wskaźnik stresu wodnego upraw rolniczych (CWSI) używany jest jako zdalnie (bezdotykowo) mierzony wskaźnik stresu wodnego roślin. Wskaźnik stresu wodnego roślin obliczany jest przy użyciu temperatury łanu roślin mierzonej termometrem w podczerwieni i jest oparty na różnicy pomiędzy temperaturą łanu roślin i temperaturą otaczającego powietrza (*Tc-Ta*). Celem tych badań bylo przedstawienie zależności (*Tc-Ta*) od niedosytu wilgotności powietrza w warunkach nielimitującej zawartości wody w glebie (linia bazowa CWSI) oraz oszacowanie maksymalnej dopuszczalnej wartości (*Tc-Ta*) dla użytków zielonych, lucerny i pszenicy ozimej.

S ł o w a k l u c z o w e: termometria w podczerwieni, wskaźnik stresu wodnego roślin.