Proceedings of the 31st Annual Central Plains Irrigation Conference, Kearney, Nebraska, Feb. 26-27, 2019
Available from CPIA, 760 N. Thompson, Colby, Kansas

IRRIGATION SCHEDULING WITH TEMPERATURE APPROACHES

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INTRODUCTION

Plants that are experiencing limitations on water availability, in the soil root zone, show how hard it is the water extraction process by increasing the temperature of their leaves. When there is little or no water availability limitations plants are cool. However, the larger the soil water deficit (below volumetric water content at field capacity) the higher the leaves or canopy temperature increase. In particular, measuring crop canopy temperature, using infra-red (IR) sensors, has been found to be useful in determining the degree of crop water stress. Canopy temperature can be used in the crop water stress index method (CWSI) to detect the level of stress (e.g., how difficult is for the plant to extract water from the soil) and use that information to decide when to irrigate. The common CWSI procedure is to measure canopy temperature, air temperature and relative humidity and use those data in a temperature scaling formulae. However, this method presents a constraint. In some environments (or conditions), CWSI does not perform well because the lower and upper canopy minus air temperature boundaries may not be well defined. This situation typically arises under conditions of strong winds and/or when wind speeds are fluctuating largely throughout the day. An alternative is to use an approach that incorporates the wind factor as well as canopy biophysical characteristics such as crop height (hc, m), leaf area index (LAI, $m^2\ m^{-2}$), and surface roughness for momentum transfer (Zom, m). Thus, this article presents a method to calculate sensible heat flux, based on temperature crop biophysical characteristics and wind speed, as a mean to determine CWSI to manage irrigation.

THE TEMPERATURE-BASED SENSIBLE HEAT FLUX

Sensible Heat Flux Calculation

The sensible heat flux (H, W m^{-2}) can be calculated using the surface bulk aerodynamic resistance model; as shown in Equation 1 below.

$$H = \rho_a Cp_a (T_o - T_a)/r_{ah} \tag{1}$$

where ρ_a is humid air density (kg m^{-3}); Cp_a is specific heat of dry air (1005 J $kg^{-1}\ K^{-1}$); T_a is average air temperature (K) measured one and a half to two meters above the crop canopy; rah (s m^{-1}) is the surface aerodynamic resistance (to heat transfer from the surface to the atmosphere); T_o is aerodynamic temperature (K). The aerodynamic temperature is air temperature mixed (due to the interaction of the wind with the vegetated surface) with crop temperature and it occurs at about two thirds of the height of the crop for a healthy crop depicting a large vegetation surface cover (fc > 70 %). However, when the crop is under stress and the surface is not fully covered (fc ≤ 70 %) then the aerodynamic temperature occurs at a lower height than at the 2/3 of the crop height. Details on the characterization of T_o can be found in (Chávez et al., 2005). In general, T_o can be characterized through an empirical approach as a function of infra-red readings of surface temperature (Tr, canopy plus some soil background), air temperature (Ta), biophysical crop characteristics (e.g., LAI, hc, fc), horizontal wind speed (U, m s^{-1}) measured above the vegetation of interest (or translated from an agricultural weather station considering surface roughness differences), friction velocity (U*, m s^{-1}), and relative humidity (RH), for instance.

The form of the multiple linear regression equation used to model the aerodynamic temperature is depicted in Equation (2) below. A number of permutations among explanatory variables were performed for different crops (i.e., corn, soybean, cotton, alfalfa, vineyard, and potato) using data from different locations (in Iowa, Colorado, and Chile). Table 1 summarizes selected parameterization coefficients for T_o models.

$$T_o = \Omega_1 T_r + \Omega_2 T_a + \Omega_3 LAI + \Omega_4 \ u + \ldots \qquad (2)$$

where omega (Ω) is a fitted coefficient found after regressing the explanatory variables versus the response variable “aerodynamic temperature” derived from measurements of sensible heat flux (through the inversion of Eq. 1). Measurements of H are typical done with eddy covariance energy balance systems (towers). Other forms of measuring H include: Bowen ratio, large aperture scintillometers (LAS), aerodynamic profile towers, surface renewal, and by using lysimetric data and the land surface energy balance approach, to name some of the methods.

Table 1. Calibration coefficients to estimate aerodynamic temperature.

	Multiple linear regression coeffficients for To modeling for given variables									
Vegetation	Tr	Ta	LAI	U	hc	RH	rah	U*	intercept	R^2
Corn, soybean	0.524	0.26	0.02	-0.3	-0.5	0.05			4.2	0.8
Cotton, dryland	0.5	-0.5					0.15		-1.4	0.76
Alfalfa, stressed	1.5	-0.53					0.05		0.36	0.97
Vineyard, irrigated	0.12	0.8	23.8	-0.98					-20.4	0.96
Potato, irrigated	0.022	0.8	0.12				-0.2	-18.2	23.34	0.87

It is worth noting in Table 1 that the calibration coefficients vary depending on the crop type. Since biomass is being included in the multiple linear regression (in most calibrated T_o models), something else was causing the change in the coefficients; mainly for Tr and Ta. Thus, the plant row space was considered in the interpretation of coefficients variability. Results, in general, indicate that the wider the row spacing the smaller the coefficient of Tr and the larger the coefficient of Ta, for instance. Therefore, the amount of heat flux from the inter-row greatly affects the magnitude of temperature contribution from the soil toward the aerodynamic temperature. Conversely, the more vegetated and uniformly covered is a surface the smaller the coefficient of Ta and the more Tr explains T_o.

Figure 1 below graphs the variability of coefficients as a function of row spacing.

Surface Aerodynamic Resistance (r_{ah}, s m^{-1}) Calculation

The aerodynamic resistance to heat transfer from the vegetated surface to the atmosphere where the air temperature is measured is a function of crop height and wind speed for homogeneous surfaces depicting a large vegetation surface cover (fc >70 %). Equation 3 is the r_{ah} model for neutral atmospheric conditions.

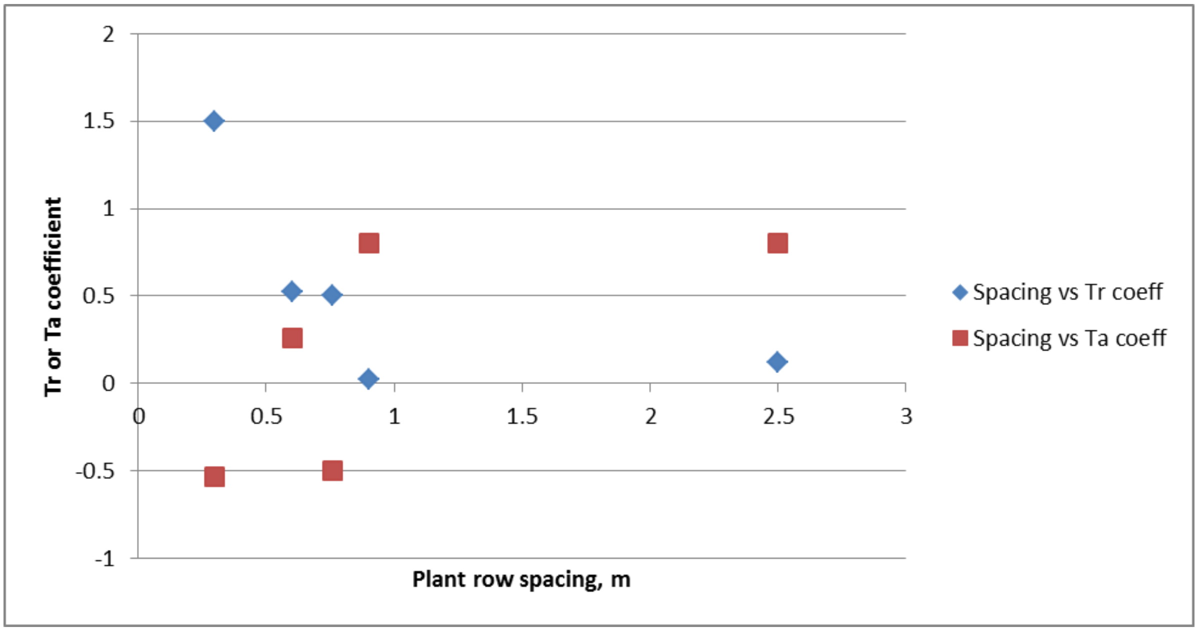

Figure 1. Aerodynamic temperature equation fitting coefficients (for Tr and Ta) variation pattern as a function of plant row spacing.

$$r_{ah} = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right)}{u_* \times k} \quad (3)$$

where, Zm is the height (m) of the wind speed measuring device (anemometer); d is the zero-plane displacement height (m), which is equal to 0.67 hc for fully vegetated surfaces; Zom is the roughness length (m) for momentum transfer (= 0.123 hc) for fully vegetated surfaces; and K is the von Karman constant (0.41). Equation 3 works for neutral atmospheric conditions that developed when the surface is well watered, the crop is free of stress and there is an equilibrium of temperature between the surface and the air above. This condition is not common, generally atmospheric stability corrections are needed (as explained in Chávez et al., 2005).

One way to adjust Zom and d when surface conditions depart from homogeneous and fc < 70% is to incorporate LAI and fc as done by Lu et al. (2009) and Colaizzi et al. (2004); Equations 4 and 5.

$$Zom = 0.123\ hc + 0.04\ hc + 0.25\ fc^{0.5} \quad (4)$$

$$d = hc\ [1 - (2 / LAI) * (1 - e^{-0.5\ LAI})] \quad (5)$$

CALCULATING CWSI WITH ESTIMATED H

The calculation of CWSI based on scaled temperature differences alone was described in Chávez (2015). Below follows the description of CWSI calculation using the sensible heat flux (H) as estimated using the aerodynamic temperature approach.

CWSI can be defined as the difference of the evaporative fraction (EF) from unity as shown in equation 6 below.

CWSI = 1 – ETa / ETc (6)

where, ETa is actual crop evapotranspiration and ETc is "potential" crop evapotranspiration (no stress). The fraction ETa / ETc is the evaporative fraction; or the fraction of ETc that actually was evapo-transpired. Therefore, 1 – EF yields the crop water stress index and can be represented as in Equation 7 after H units are converted from energy (W m^{-2}) to equivalent water depth (m).

CWSI = H / ETc (7)

Equation 7 above is possible because ETa can be obtained from measurements or estimates of latent heat flux (LE, W m^{-2}). Also, since the land surface energy balance states that Rn = LE + H + G, where Rn is net radiation and G the soil heat flux (both with same units as LE and H), then LE can be solved as a residual of the energy balance equation (as LE = Rn – G – H). Also, ETc can be approached as Rn – G (the available energy). Thus, substituting ETa by Rn – G – H, and ETc by Rn – G, in equation 6 and after simplifications, one obtains Equation 7 above.

ETc can be calculated using the two-step approach. This is, using a crop coefficient and a reference evapotranspiration (ETref) as shown in Equation 8 below.

ETc = Kc * ETref (8)

where, Kc is reported in the literature for different vegetation types and growth stages (Hoffman et al., 2007). In the same publication by Hoffman, Chapter 8 describes the computation of ETref for a grass or an alfalfa surface. Weather data from an agricultural weather station are needed to calculate ETref.

IRRIGATION SCHEDULING WITH THE TEMPERATURE APPROACH

Once CWSI has been determined, the irrigation manager can monitor CWSI of a given crop and decide when to trigger an irrigation event once the CWSI is approaching a threshold value. In the literature, values of CWSI for different crops can be found. For instance O'Shaughnessy et al. (2012) use a CWSI of 0.45 for sorghum in the Texas Panhandle. In a study, for drip irrigated corn in CO the CWSI threshold was found to be close to 0.20. This is, irrigation should be triggered at that CWSI level to avoid starting suffering yield loss. Corn will suffer yield loss at a lower CWSI than sorghum. In a study in the Texas Panhandle, Yazar et al. (1999) found a CWSI threshold for corn of 0.33 or less for minimal or no yield loss. In this study, corn was irrigated via a LEPA system.

The amount of water to apply (irrigation amount) to the crop (field), once the CWSI threshold is approaching, should be calculated knowing the soil water holding capacity and the crop management (or maximum) allowed depletion (MAD).

CONCLUSIONS

In this study, an alternative to the estimation of CWSI just using scaled temperature is presented. The sensible heat flux estimation using the aerodynamic temperature approach is used instead of scaled temperatures, in the determination of CWSI. Using T_o and H seems a more robust approach because it incorporates wind speed and plant biophysical characteristics that the original approach of the CWSI method did not use.

ACKNOWLEDGEMENTS

The author is grateful to the following institution and individuals for the support received: Financial support (Project # COL00688) received from Colorado Agricultural Experiment Station and the USDA National Institute for Food and Agriculture (NIFA) is greatly appreciated; field support from USDA ARS Bushland, CSU AVRC, USU, and collaboration with Dr. Marcos Carrasco (Chile).

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