REMOTELY SENSED CROP CANOPY TEMPERATURE, AMBIENT RELATIVE HUMIDITY AND AIR TEMPERATURE: THEORETICAL ANALYSIS AND EXPERIMENTAL VERIFICATION

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ABSTRACT

Recent advancement in infrared thermometry has permitted the measurement of leaf or vegetation canopy temperature without contact. The aim of this paper is to demonstrate from theoretical background the relationship between canopy temperature, relative humidity and air temperature. Field experimental data are presented to verify the theoretical relationships.

INTRODUCTION

Clawson et al. (1989) and Jackson et al (1981) detailed briefly the historical facts leading to continuing interest in the leaf and canopy temperatures. Various researchers have related temperature of the leaf to plant water status (Ehrler, 1973; Idso, 1982; Jackson, 1982; Jackson et al., 1981; Idso et al., 1981). Earlier studies on this subject involved measurement of individual leaf temperature by the use of thermocouple (Tanner, 1963; Jackson et al., 1977). .However recent advancement in Infrared thermometry has made possible the measurement of canopy temperature by remote sensing (i.e. without contact). This development presents enormous advantage in field measurements since whole field can be measured at a time and does not present sampling problem.

The physiological and control mechanisms of plant behavior are influenced by microclimate (Campbell 1986). There is therefore close interaction between plants and their immediate environmental factors such as relative humidity and air temperature.

The aim of this paper is to demonstrate from theoretical point of view the relationship between canopy temperature and ambient relative humidity and air temperature.

THEORY

The energy balance of crop can be written as

$$Rn = LE + H + G \qquad (1)$$

where Rn is net radiation, LE and H are latent and sensible heat fluxes, respectively, and G is the soil heat flux (all terms expressed as Wm^{-2}). Following the electrical resistance analog of Monteith (1963) as modified by verma and

Barfield (1979), LE and H within a fully developed boundary layer can be expressed as

$$LE = \frac{\rho Cp}{\gamma} \frac{\left(e_c^* - e_a\right)}{\left(r_c + r_{av}\right)} \tag{2}$$

and,

$$H = \rho Cp \frac{\left(Tc - Ta\right)}{r_{as}} \tag{3}$$

Assuming the soil heat flux, G is negligible, (i.e., G = 0), $r_a = r_{av} = r_{as}$ and substituting for H, and LE in equation 1
we obtain

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

where ρ is the density of air, (Kgm^{-3}), Cp is the specific heat of air at constant pressure ($Jkg°C^{-1}$), γ is the psychrometric constant ($Pa°C^{-1}$), e_c^* is the saturated vapour pressure (Pa) evaluated at canopy temperature (Tc, °C), e_a is the actual vapour pressure of the air (Pa) evaluated at air temperature (Ta, °C), r_c is the canopy resistance to the flux of water vapour (sm^{-1}), and r_{av} and r_{as} are the aerodynamic resistances to the fluxes of water vapour and heat (sm^{-1}).
Substituting,

$$\gamma^* = \gamma\left(1 + r_c/r_a\right) \tag{5}$$

in equation (4) Tc can be expressed as:

$$Tc = Ta + \frac{Rn.r_a}{\rho Cp} \times \frac{\gamma^*}{\Delta + \gamma^*} - \frac{\left(e_a^* - e_a\right)}{\Delta + \gamma^*} \tag{6}$$

Vapour pressure deficit (VPD), determined at the same time that canopy temperature was calculated as follows:

$$VPD = e^* - e \tag{7}$$

where e is the saturated vapour pressure at air temperature and e, the ambient vapour pressure in air equals the following (Rosenberg, 1974):

$$\mathrm{RH} = \frac{e}{e^*} \times 100 \qquad (8)$$

The value of e* is a function of temperature, closely approximated by the following relationship (Murray, 1967):

$$e^* = 6.1078 \exp[17.269\mathrm{T}/(237.3 + \mathrm{T})] \qquad (9)$$

where T is in °C.

The slope of the saturated vapour pressure curve $\Delta\Delta = \frac{de^*}{dt}$ which relates saturated vapour pressure of the air against air temperature is given by an empirical relationship as follows (Jackson et al 1988):

$$\Delta = 45.03 + 3.014\mathrm{T} + 0.05345\mathrm{T}^2 + 0.00224\mathrm{T}^3 \qquad (10)$$

where T is the average of the canopy and the air temperatures :

$$\mathrm{T} = (\mathrm{Tc} + \mathrm{Ta})/2 \qquad (11)$$

It is possible from equation 6 to obtain theoretically the maximum or upper limit of Tc (Tcu) corresponding to canopy temperature of a fully stressed crop when rc approaches infinity. Equation (6) becomes (see appendix 1)

$$\mathrm{Tcu} = \mathrm{Ta} + \frac{\mathrm{Rn}.\mathrm{r_a}}{\rho \mathrm{Cp}} \qquad (12)$$

To obtain the lower limit of temperatures, rc is set as zero i.e. the plant presents no resistance to vapour transport. Equation (6) becomes (see appendix 2)

$$\mathrm{T_{cl}} = \mathrm{Ta} + \frac{\mathrm{Rn}.\mathrm{r_a}}{\rho \mathrm{Cp}} \times \frac{\gamma}{\Delta + \gamma} - \frac{\left(e_a^* - e_a\right)}{\Delta + \gamma} \qquad (13)$$

EXPERIMENTAL WORK

Field experiments were conducted on sorghum subject to wet watered condition. The details of the experimental procedure are presented in Olufayo et al.(1996). Measurements on the well watered plots include air temperature, relative humidity and canopy temperature. The canopy temperature was measured using TASCO THI 300 (Osaka, Japan) hand held infrared thermometer. The spectra band-pass of the instrument was 6-12 m with a resolution of 0.1 0C and field of view of 100. The air temperature and relative humidity were measured within crop canopy using thermohygrometer (TESTOTERM, Forbach, France).

RESULTS

To obtain an accurate solution of equation 13, a computer program was used to obtain iteration by evaluating Δ at $(T_{cl} + Ta)/2$. The theoretical derived canopy temperature (Tc) showing the upper (Tcu) and lower limits (Tcl) from equation 6 are presented in Fig. 1a and 1 b assuming values of net radiation Rn of 400 and 700 W m^{-2} and aerodynamic resistance ra of 10 sm^{-1}, $\rho Cp = 1200\ Jm^{-3}\ °C^{-1}$). (From available meteorological data an average value of net radiation between 400 and 700 W m^{-2} is considered reasonable for our tropical condition). The figures demonstrate a straight line relationship between canopy temperature (Tc) and air temperature (Ta). This relationship will be slightly non-linear if ρ and Cp are allowed to vary according to air temperature and humidity. This result show that under a given condition, the higher the ambient temperature the higher the leaf/canopy temperature. Obviously leaves are warmer under sunny condition than cloudy condition or at night.

On the lower limit of canopy temperature, we stated that the crop resistance is zero. In other words the crop is acting like a free water surface (see equation above). The curvilinear relationship of the lower limit of canopy temperature T_{cl} as function of Ta is shown in Fig 1 with relative humidity ranging from 0 to 100%. At 100% relative humidity, T_{cl} approaches Tcu, but 2 °C to 4°C lower. This must occur as Tc exceeds Ta because e_c^* exceeds e_a^*. Therefore, a vapour pressure gradient remains between the crop and the air. Transpiration continues as a result of this gradient (even in saturated air) to cool the crop below Tcu but necessarily below Ta.

The Upper limit (Tcu) is independent of VPD while the lower limit is a relationship. Data from experimental work are presented in Figure 2. The data points were identified based on different ranges of wind speed. A linear curve was obtained between the temperature difference (i.e. Tc -Ta) and VPD which confirms the theoretical relationship. The scatter points are due to instrumental, measurement errors and unstable field microclimatic conditions. The empirical equation obtained which relates the temperature difference and VPD is

$$(Tc - Ta) = -2.5VPD + 3.76 \qquad r^2 = 0.75 \quad n = 27 \qquad (14)$$

CONCLUSION

Leaf/canopy temperature are influenced by the ambient temperature and relative humidity. Under constant values of net radiation, aerodynamic resistance, the canopy temperature was demonstrated theoretical to be linearly related to air temperature. When expresses as a function of vapour pressure deficit of the air, canopy minus air temperature was shown to vary between a fixed upper limit independent of VPD and a lower limit that linearly related to VPD.

Experimental results was shown to confirm the theoretical relationship. A high correlation value of $r^2 = 0.75$ was found between the temperature difference and the VPD.

APPENDIX 1

Recall that equations 4 in the text is given as:

$$T_c - T_a = \frac{r_a R_n}{\rho C_p} . \frac{\gamma(1+r_c/r_a)}{\Delta+\gamma(1+r_c/r_a)} - \frac{(e_a^* - e_a)}{\Delta+\gamma(1+r_c/r_a)} \qquad (4)$$

For a fully stressed crop the crop resistance, rc approaches infinity, the second term of equation ‘4) will tend to zero
Hence,

$$T_c - T_a = \frac{r_a R_n}{\rho C_p} \times \left[\frac{\gamma(1+r_c/r_a)}{\Delta+\gamma(1+r_c/r_a)} \right] \qquad (A1)$$

Similarly both the numerator and denomenator of the components in bracket tends to infinity and hence leads to equation (12) in the text:

$$Tc = Ta + \frac{Rn.r_a}{\rho Cp} \qquad (12)$$

APPENDIX 2

From equation 4 in the text

$$T_c - T_a = \frac{r_a R_n}{\rho C_p} . \frac{\gamma(1+r_c/r_a)}{\Delta+\gamma(1+r_c/r_a)} - \frac{(e_a^* - e_a)}{\Delta+\gamma(1+r_c/r_a)} \qquad (4)$$

Assume a well watered plant with a canopy acting as a free water surface the plant presents no resistance to vapour transport and the rc is set as zero therefore $r_c/r_a = 0$
Hence,

$$T_{cl} = Ta + \frac{Rn.r_a}{\rho Cp} \times \frac{\gamma}{\Delta+\gamma} - \frac{(e_a^* - e_a)}{\Delta+\gamma} \qquad (13)$$

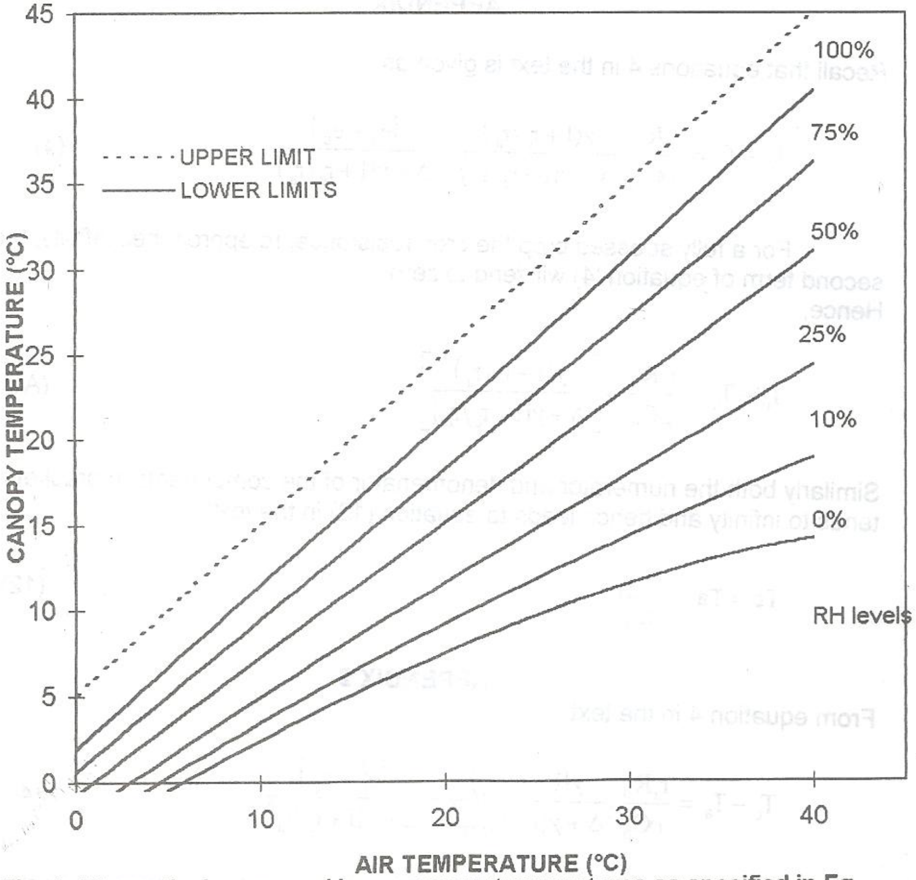

Fig. 1a Theoretical upper and lower canopy temperatures as specified in Eq. (12) and (13), where Rn = 400 W m^{-2} and r_a = 10 sm^{-1}. the solid lines represent various levels of relative humidity (RH)

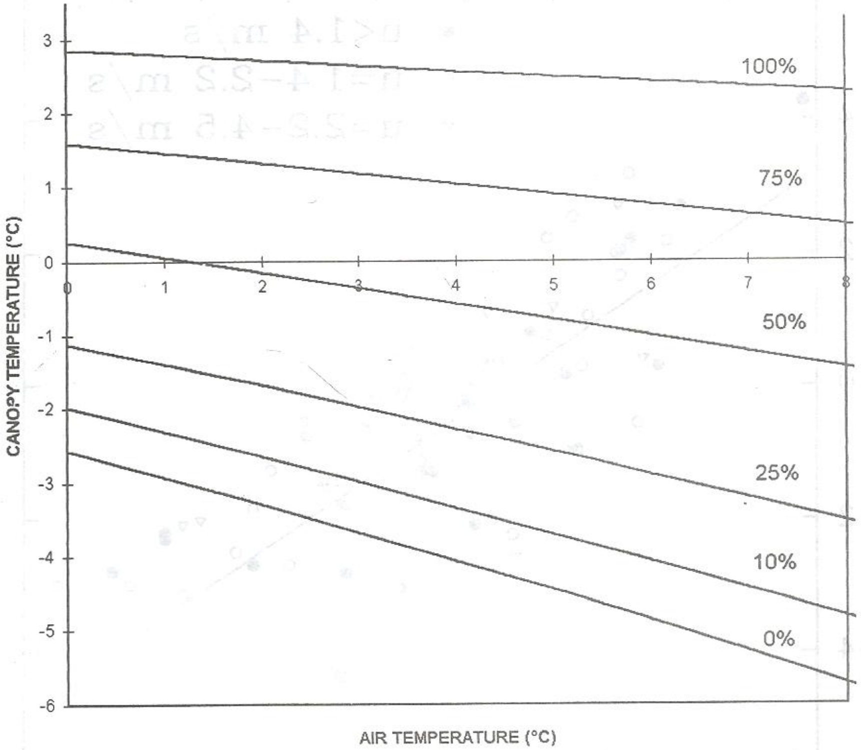

Fig. 1b Theoretical lower limits of canopy temperature (Rn = 700 W m^{-2} and ra = 10 sm^{-1}) at various levels of relative humidity (RH)

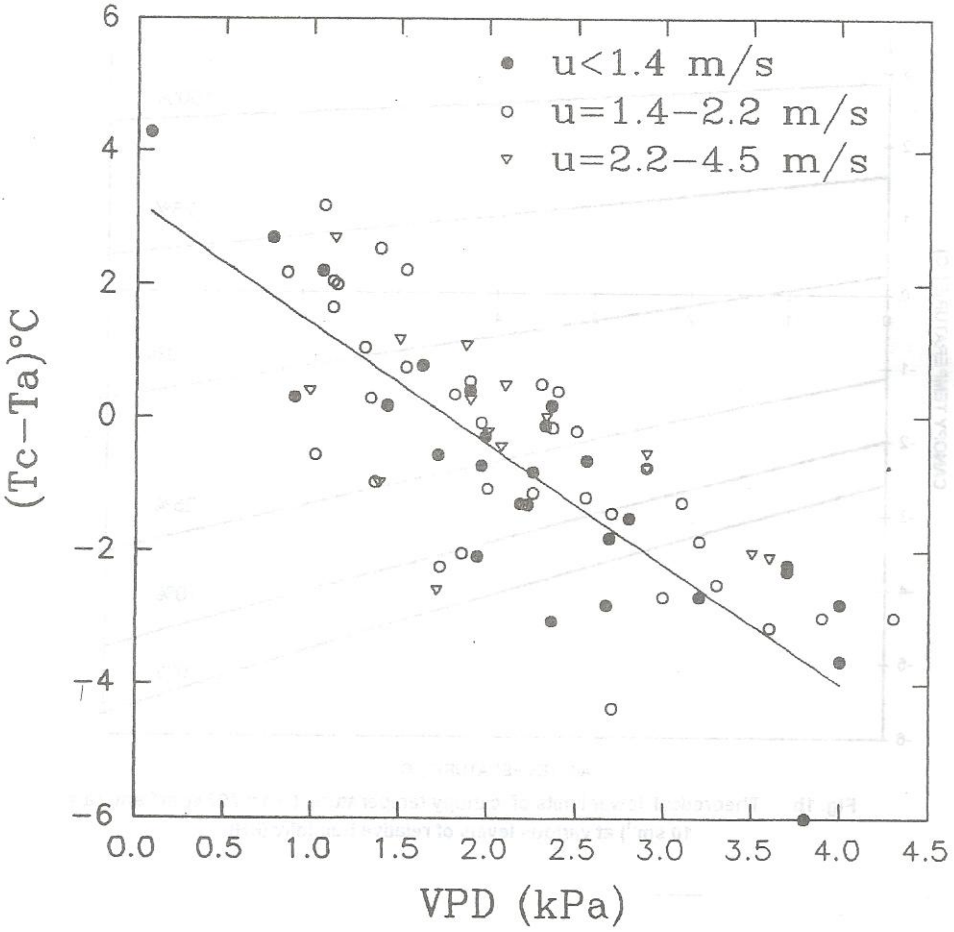

Fig. 2 Experimental lower limits of Tc-Ta against vapour pressure at different ranges of wind speed (u)

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