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# SIMULATING SUNFLOWER CANOPY TEMPERATURES TO INFER ROOT-ZONE SOIL WATER POTENTIAL

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**SIMULATING SUNFLOWER CANOPY TEMPERATURES TO  
INFER ROOT-ZONE SOIL WATER POTENTIAL**

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## SIMULATING SUNFLOWER CANOPY TEMPERATURES TO INFER ROOT-ZONE SOIL WATER POTENTIAL

### ABSTRACT

A soil-plant-atmosphere model for sunflower (*Helianthus annuus* L.), together with clear sky weather data for several days, is used to study the relationship between canopy temperature and root-zone soil water potential. Considering the empirical dependence of stomatal resistance on insolation, air temperature and leaf water potential, a continuity equation for water flux in the soil-plant-atmosphere system is solved for the leaf water potential. The transpirational flux is calculated using Monteith's combination equation, while the canopy temperature is calculated from the energy balance equation. The simulation shows that, at high soil water potentials, canopy temperature is determined primarily by air and dew point temperatures. These results agree with an empirically derived linear regression equation relating canopy-air temperature differential to air vapor pressure deficit. The model predictions of leaf water potential are also in agreement with observations, indicating that measurements of canopy temperature together with a knowledge of air and dew point temperatures can provide a reliable estimate of the root-zone soil water potential.

## INTRODUCTION

Direct observation of some plant parameter should provide the best approach for irrigation scheduling (Jackson, 1982). Plant factors that have been studied for assessing stress are leaf water potential, stomatal resistance, leaf temperature, and canopy temperature. Since leaf-based measurements are time consuming when fields of one hectare or larger are to be sampled, the most promising approach, from a practical point of view, would be to measure canopy temperature using infrared radiometers. Indeed, the technology is already available to do this from land-based vehicles, aircraft and satellites.

The possibility of inferring root-zone soil water from leaf temperature measurements was first suggested by Tanner (1963). Its technical feasibility was demonstrated by Idso and Ehler (1976), who developed a technique for estimating water contents in the root zones of cotton and sorghum from mid-day leaf-air temperature differentials. Millard et al. (1978) then showed that the technique could be applied from aircraft, obtaining a significant correlation of mid-day airborne thermal scanner observations with pre-sunrise plant water tension, a parameter related to crop growth and development.

In this paper, a soil-plant-atmosphere model for sunflower (*Helianthus annuus* L.) is developed and used to study the relationship between leaf- and canopy-based measurements. Using an empirical relation between the stomatal resistance and leaf water potential, the model solves for the leaf water potential which satisfies Monteith's (1965) equation for transpiration and van den Honert's (1948) equation for root water uptake. The canopy temperature is then obtained from the energy balance equation. This approach to modeling transpiration parallels Soer (1980) and Choudhury (1983), and assumes that the water balance of the plant does not change during the transpiration process i.e., that the loss of plant tissue water during transpiration is negligible. Simulation results are obtained using clear sky weather data from Phoenix, Arizona and Baltimore, Maryland.

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## DESCRIPTION OF THE MODEL

Monteith's (1965) equation for transpiration contains a variable resistance term (the canopy stomatal resistance) for describing vegetative control of water loss to the atmosphere. The basic idea of soil-plant-atmosphere models is to account for this vegetative control by developing an equation of continuity for water flux in the soil-plant-atmosphere system. The transpirational flux  $E_T$  ( $\text{m s}^{-1}$ ) is calculated using Monteith's (1981) modification of his 1965 equation. This modification accounts for the dependence of net radiation on the canopy temperature by defining an effective boundary-layer resistance,  $r_{\text{eff}}$  ( $\text{s m}^{-1}$ ), as follows:

$$E_T = \frac{\Delta R_n + c_p \rho_a (e_a^* - e_a) / r_{\text{eff}}}{L_v [\Delta + \gamma((r_a + r_c) / r_{\text{eff}})]} \quad (1)$$

where  $R_n$  is the net radiation ( $\text{W m}^{-2}$ ) that would be absorbed by the canopy if the canopy were at air temperature,  $e_a^*$  and  $e_a$  are, respectively, the saturated vapor pressures (kPa) at air and dew point temperatures,  $\Delta$  is the slope of the saturated vapor pressure curve ( $\text{kPa K}^{-1}$ ) at air temperature,  $c_p$  and  $\rho_a$  are, respectively, the specific heat ( $\text{J kg}^{-1} \text{K}^{-1}$ ) and density ( $\text{kg m}^{-3}$ ) of air,  $\gamma$  is the psychrometric constant ( $\text{kPa K}^{-1}$ ),  $L_v$  is the latent heat of vaporization ( $\text{J m}^{-3}$ ),  $r_c$  is the canopy stomatal resistance ( $\text{s m}^{-1}$ ), and  $r_{\text{eff}}$  is the effective boundary-layer resistance ( $\text{s m}^{-1}$ ) for heat and long-wave radiative transfers, given by

$$\frac{1}{r_{\text{eff}}} = \frac{1}{r_a} + \frac{1}{\left( \frac{c_p \rho_a}{4 \epsilon_c \sigma T_a^3} \right)} \quad (2)$$

where  $\epsilon_c$  is the canopy emissivity, assumed to be 0.97 as per Idso et al. (1969),  $\sigma$  is the Stefan-Boltzman constant,  $T_a$  is the air temperature (K) and  $r_a$  is the usual boundary-layer resistance ( $\text{s m}^{-1}$ ), calculated according to Grace (1977) as

$$r_a = \frac{113}{\text{LAI } U^{1/2}} \quad (3)$$

where  $U$  is the wind speed ( $\text{m s}^{-1}$ ) and LAI is the leaf area index (assumed in the following calculations to be 3.5).

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The net radiation at the top of the canopy is calculated from global insolation ( $S$ , following Choudhury, 1982), albedo ( $\alpha = 0.2$ ), longwave emissivities of the canopy ( $\epsilon_c$ ) and air ( $\epsilon_a$ , following Idso, 1981) and air temperature ( $T_a$ ) as

$$R_{no} = (1 - \alpha) S + (\epsilon_a - \epsilon_c) \sigma T_a^4 \quad (4)$$

Then, from the observed extinction coefficient of net radiation in a sunflower canopy (Impens, 1973), we calculate the absorbed net radiation as

$$R_n = R_{no} [1 - \exp(0.074 LAI^2 - 0.822 LAI)] \quad (5)$$

The mechanics of stomatal control are not yet fully understood. According to Kramer (1969), the stomatal resistance depends most strongly upon insolation ( $S$ ) and leaf water potential ( $\psi$ ). Air temperature and humidity are also found to affect the stomatal resistance (Jarvis, 1976; Sharpe, 1973). Observations of Saugier (1976) and Sionit and Kramer (1976) for sunflower indicate that the conductance (which is the inverse of resistance) depends linearly upon  $\psi$ , and such a dependence has been observed for other crops also (c.f., McCree, 1974; Briscoe et al., 1976), although there are exceptions (Denmead and Millar, 1976; Turner and Begg, 1973). The dependence of stomatal resistance on insolation appears to be curvilinear (Saugier, 1976, Ehrlir and van Bavel, 1968), while the dependence on air temperature is parabolic, with a minimum of about 33°C (Sharpe, 1973). Considering the data presented by Saugier (1976) and our observations, the following stomatal resistance equation is used:

$$r_c = \frac{1.8 \times 10^3}{LAI (\psi - \psi_c)} \left[ 1 + \left( \frac{500}{S + 75} \right)^2 \right] [1 + 0.01 (t_a - 33)^2] \quad (6)$$

where  $t_a$  is air temperature (°C) and  $\psi_c$  is the critical potential for stomatal closure, assumed to be -160 m (1 m = 98 kPa).

The rate of soil water extraction  $E_R$  ( $m s^{-1}$ ) by plant roots is calculated according to van den Honert (1948) as

$$E_R = \frac{\psi_s - \psi}{R_s + R_p} \quad (7)$$

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where  $\psi_s$  is the soil water potential (m),  $R_s$  is the resistance for water flow to the root surface (s), and  $R_p$  is the resistance for water flow from the root surface to the leaf stomata (s). The resistance for water flow to the root surface is calculated from a parametric form of the Gardner-Cowan equation derived by Feddes and Rijtema (1972) from simulations with variable crop rooting densities within the soil:

$$R_s = \frac{0.0013}{Z_{\text{eff}} K(\psi_s)} \quad (8)$$

where  $Z_{\text{eff}}$  is the effective rooting depth (assumed to be 0.6 m) and  $K(\psi_s)$  is the soil hydraulic conductivity (m/s), calculated according to Clapp and Hornberger (1978) for a silt loam soil as

$$K(\psi_s) = 7 \times 10^{-6} \left[ \frac{\psi_{\text{sat}}}{\psi} \right]^{2.57} \quad (9)$$

where  $\psi_{\text{sat}}$  is the saturation tension, assumed to be -0.8 m. Also, the plant resistance is assumed to be  $3 \times 10^8$  s, after Boyer (1971).

The continuity equation for water flux is obtained by equating the rate of water uptake by plant roots (eqn. 7) to the rate of water loss to the atmosphere (eqn. 1), i.e.

$$E_T = E_R \quad (10)$$

By prescribing appropriate weather data ( $S$ ,  $e_a$ ,  $T_a$  and  $U$ ) and the soil water potential ( $\psi_s$ ), eqn. (10) is solved for the leaf water potential ( $\psi$ ). The canopy resistance is then calculated from eqn. (6), and the rate of transpiration from eqn. (1). The canopy temperature  $T_c$  is then obtained from the energy balance equation as

$$T_c - T_a = [R_n - L_v E_T] (r_{\text{eff}}/c_p \rho_a) \quad (11)$$



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## RESULTS AND DISCUSSION

In attempting to infer soil water status from infrared radiometric observations of canopy temperature, Jackson et al. (1981), Idso et al. (1981a) and Idso (1982) addressed the need for a "non-water-stressed baseline", which would essentially account for the weather-dependent variability of canopy temperatures. They showed from field observations that, during a significant portion of the daylight period, canopy temperature can be predicted from prevailing air and dew point temperatures; that is, they showed that there exist significant crop-specific linear relationships between canopy-air temperature differential and air vapor pressure deficit.

At the prescribed soil water potential of  $-3\text{ m}$ , the simulated canopy-air temperature differential as a function of air vapor pressure deficits is shown in Fig. 1. The input weather data are for seven clear sky days from 0900 to 1500 LST during May in Phoenix and during June and July in Baltimore. The wind speed varied from  $1.5$  to  $6.0\text{ m s}^{-1}$ , air temperature from  $22$  to  $35^\circ\text{C}$ , and the above-canopy net radiation from  $475$  to  $720\text{ W m}^{-2}$ . The simulation results are in agreement with the empirically derived linear regression equation of Idso (1982) for sunflower, and, considering the range of weather data used in the simulation, this result supports the contention of Idso et al. (1981a) that air and dew point temperatures are indeed the important weather variables determining canopy temperature. We are not aware of any published model calculation for sunflower showing that the canopy temperatures are determined primarily by air and dew point temperatures.

As root-zone soil water is depleted, canopy temperature increases in order to balance the reduced transpiration with the sensible heat flux. To quantify the effect of depleting soil water on the canopy temperature, Jackson et al. (1981) defined a crop-water-stress-index (CWSI) as

$$\text{CWSI} = 1 - \frac{\Delta + \gamma((r_a + r_c^0)/r_{\text{eff}})}{\Delta + \gamma((r_a + r_c)/r_{\text{eff}})} \quad (12)$$

where  $r_c^0$  is the stomatal resistance of an unstressed crop (which we assume to be at the soil water potential of  $-3\text{ m}$ ) and  $r_c$  is the stomatal resistance of a water-stressed crop (which we consider

to be at a soil water potential lower than  $-3$  m). The CWSI is zero for unstressed crops, and it approaches unity when  $r_c$  becomes large due to depletion of soil water.

The simulated range of CWSIs at various soil water potentials are shown in Fig. 2. The dependence of CWSI on the water potential is curvilinear, although a linear approximation could be used.

By a simple manipulation of eqns. (1) and (11), one can relate the canopy-air temperature differentials of unstressed and stressed canopies,  $\delta T^0$  and  $\delta T$ , respectively, under identical weather conditions as

$$\delta T = \left( \frac{R_n r_{eff}}{c_p \rho_a} \right) \text{CWSI} + (1 - \text{CWSI}) \delta T^0 \quad (13)$$

from which it can be seen that as the CWSI approaches 1,  $\delta T$  approaches the maximum value  $(R_n r_{eff}/c_p \rho_a)$  (which is about 10K assuming  $R_n \approx 600 \text{ W m}^{-2}$  and  $r_{eff} \approx 20 \text{ s m}^{-1}$ .) Thus, infrared radiometers can be used to calculate the CWSI (Jackson et al., 1981), and from Fig. 2 an estimate of the soil water potential can be obtained.

By comparing observed leaf water potential, stomatal resistance, and leaf-air temperature differential of well-watered and water-stressed peas, Clark and Hiler (1973) concluded that leaf water potential was the parameter most sensitive to changes in soil water status. However, leaf water potential, like canopy temperature, is strongly affected by atmospheric variables (Choudhury and Federer, 1983); and this variability can be shown quite easily, since from eqns. (10) and (11) it follows that the canopy-air temperature differential ( $\delta T$ ) is related to the leaf water potential ( $\psi$ ) as

$$\delta T = \left[ R_n - \frac{L_v(\psi_s - \psi)}{R_s + R_p} \right] (r_{eff}/c_p \rho_a) \quad (14)$$

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From eqn. (8) one can verify that at high soil water potentials  $R_p \gg R_s$ , and, therefore, for no-stress conditions the relationship is

$$\delta T^o = \left[ R_n + \frac{L_v \psi^o}{R_p} \right] (r_{eff}/c_p \rho_a) \quad (15)$$

where  $\psi^o$  is the leaf water potential of the unstressed canopy. Since the vapor pressure deficit is the significant variable for  $\delta T^o$  (Fig. 1), it follows from (15) that this deficit will also be the significant variable for  $\psi^o$ . Observations of Idso et al. (1981b) support this conclusion. In fact, the observed dependence of  $\psi^o$  on the vapor pressure deficit is almost linear, as would be expected from eqn. (15). This atmospheric induced variability of  $\psi$  has to be accounted for before the soil water potential can be estimated (cf., Idso et al., 1981b and Choudhury and Federer, 1983).

Now the question arises, would  $\psi$  be more responsive to soil water status than  $\delta T$ , according to the present model? One can verify that up to a soil water potential of  $-70$  m (which is far exceeding the depletion level of 70% of available water, often considered appropriate for irrigation scheduling)  $R_p > R_s$  and, therefore, a good approximation for the  $\delta T$  vs.  $\psi$  relationship would be

$$\delta T = \left[ R_n - \frac{L_v (\psi_s - \psi)}{R_p} \right] \left( \frac{r_{eff}}{c_p \rho_a} \right) \quad (16)$$

By differentiating (16) with respect to the soil water potential ( $\psi_s$ ) one gets

$$\frac{d(\delta T)}{d\psi_s} = - \left( \frac{L_v r_{eff}}{R_p c_p \rho_a} \right) \left[ 1 - \frac{d\psi}{d\psi_s} \right] \quad (17)$$

The value of the coefficient  $(L_v r_{eff}/R_p c_p \rho_a)$ , which relates the slopes of  $\delta T$  and  $\psi$  with respect to the soil water potential, is about 0.15. The present model thus supports Clark and Hiler (1973) in showing that leaf water potential should be more responsive to changes in soil water potential than is canopy-air temperature differential. Remote sensing technology cannot be applied directly to sample leaf water potential. However, an indirect approach to inferring leaf water potential via remote sensing is possible through the CWSI. From eqns. (13) and (16), for example one can obtain

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$$\psi = \psi_s - (1 - \text{CWSI}) (\delta T^\circ - \frac{R_n r_{\text{eff}}}{c_p \rho_a}) / (\frac{L_v r_{\text{eff}}}{R_p c_p \rho_a}) \quad (18)$$

Radiometric observations can give CWSI and hence from Fig. 2 one can estimate  $\psi_s$ ;  $\delta T^\circ$  can be calculated knowing air and dew point temperatures using the regression equation in Fig. 1; and reasonable values of other terms in (18) are discussed following eqns. (13 and (17).

Although the present simulation lends support to the empirical regression equation between  $\delta T^\circ$  and VPD in Fig. 1, one can also obtain an explicit analytic expression for  $\delta T^\circ$  in terms of weather variables and plant parameters. By combining eqns. (1), (6), (11) and (15) one obtains a quadratic equation for  $\delta T^\circ$ , which has the solution

$$\delta T^\circ = [R_n - \frac{B + (B^2 - 4AC)^{1/2}}{2A}] (r_{\text{eff}} / c_p \rho_a) \quad (19)$$

where

$$A = R_p / L_v$$

$$B = \Gamma - \psi_c - (R_p E_o / L_v)$$

$$C = \psi_c E_o$$

$$\Gamma = \frac{\gamma 1.8 \times 10^3}{\text{LAI } r_{\text{eff}} [\Delta + \frac{\gamma r_a}{r_{\text{eff}}}] } [1 + (\frac{500}{S + 75})^2] [1 + 0.01 (t_a - 33)^2]$$

$$E_o = \frac{\Delta R_n + c_p \rho_a (e_a^* - e_a) / r_{\text{eff}}}{\Delta + (\gamma r_a / r_{\text{eff}})}$$

By comparing eqns. (11) and (19), one obtains an equation for unstressed transpiration ( $E_{\text{TU}}$ ) as

$$E_{\text{TU}} = \frac{B + (B^2 - 4AC)^{1/2}}{2L_v A} \quad (20)$$

## CONCLUSION AND OUTLOOK

The soil-plant-atmosphere model for sunflower developed in this paper provides an understanding of the observed dependence of leaf water potential and canopy temperature on weather variables and root-zone soil water potential. A knowledge of air and dew point temperatures is needed for accounting for the effects of weather variables. Infrared remote sensing can be used efficiently to infer the root-zone soil water potential of large areas, although the leaf water potential would be more responsive to changes in soil water status. With regard to infrared remote sensing, a stringent requirement is that of nonheterogeneity within the field-of-view, since canopies of various crops, bare soil, etc. would have differing responses to soil water conditions. Although the numerical results presented in this paper are specific to sunflower due to the crop-specific nature of the stomatal resistance function (Eqn. 6), the model and general conclusions regarding the remote sensing possibility of root-zone soil water potential may well be valid for other crops.

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### **CAPTION TO THE FIGURES**

**Figure 1. Comparison of simulated dependence of canopy-air temperature difference on air vapor pressure deficit with the empirically derived linear regression equation by Idso (1982).**

**Figure 2. Simulated range of crop water stress index at various root-zone soil water potentials. A straight line is drawn to illustrate the trend and a possible approximation.**

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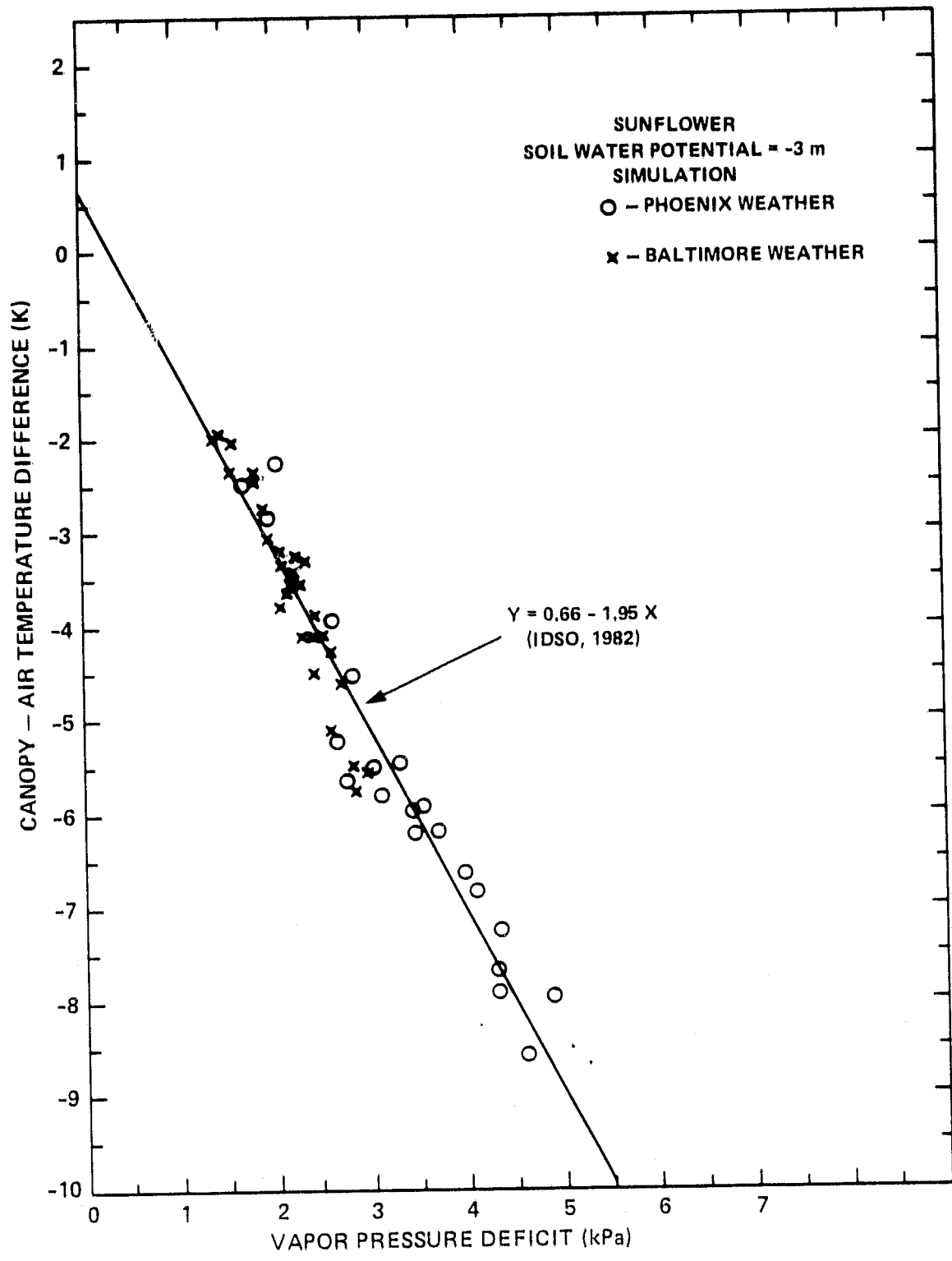


Figure 1

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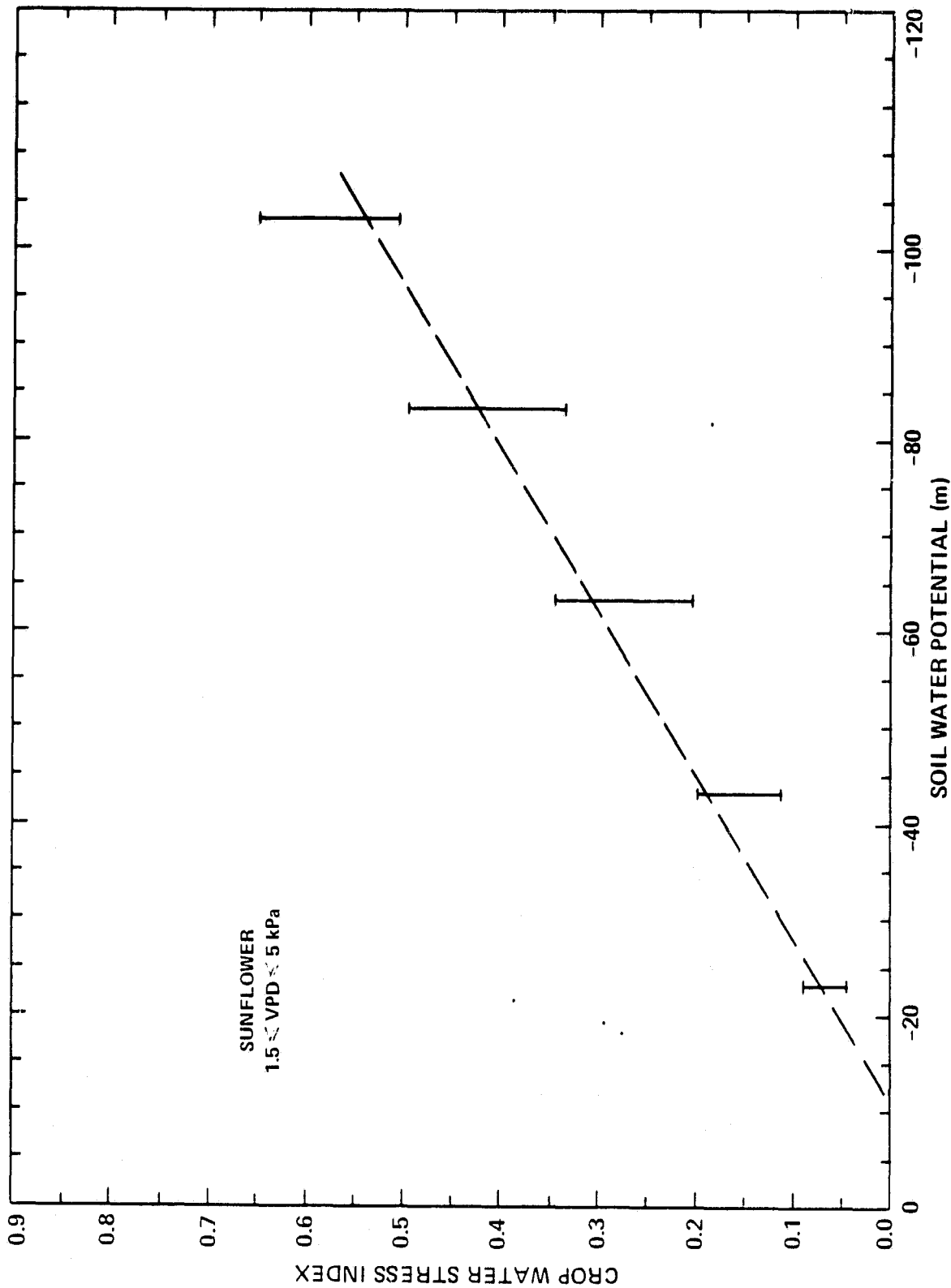


Figure 2