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Simulating Soybean Canopy Temperature
as Affected by Weather Variables
and Soil Water Potential

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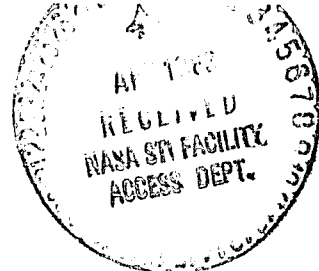
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SIMULATING SOYBEAN CANOPY TEMPERATURE AS AFFECTED
BY WEATHER VARIABLES AND SOIL WATER
POTENTIAL

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ABSTRACT

The soil water loss during the drying period of any irrigation cycle leads to progressive leaf dehydration and consequent rise in canopy temperature. Irrigation scheduling through crop temperature measurements is a technique well suited for infrared radiometric remote sensing. A soil-plant-atmosphere model together with observed hourly weather data are used to simulate soybean (*Glycine max* L.) leaf water potential, stomatal resistance and canopy temperature at various soil water potentials. Using an empirical relation between the stomatal resistance and leaf water potential, the model solves for the leaf water potential which satisfies Monteith's and van den Honert's equations for transpiration. The canopy temperature is then obtained from the energy balance equation. The hourly weather data are for several clear sky days during summer at Phoenix and Baltimore, and covered a wide range of variables. For soil water potentials near field capacity the simulation gives a base line relationship between the canopy-air temperature difference (δT) and air vapor pressure deficit (VPD) which agrees well with a linear regression equation developed from observations. At high soil water potentials the effect of weather variables on the canopy temperature can largely be accounted for in terms of air and dew point temperatures. The δT values at lower soil water potentials are found to be uniquely related to the base line δT values. The simulation indicates that the root zone soil water potential may be inferred from observed δT and the base line δT calculated from air and dew point temperatures. At high soil water potentials the simulated stomatal resistances show scatter, the range of which agrees well with a set of observations. The simulated increase of stomatal resistance with decreasing soil water potential is also in agreement with a set of observations. The simulation somewhat overestimates the leaf water potentials which is suggested to be due to some characteristic differences among soybean varieties.

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SIMULATING SOYBEAN CANOPY TEMPERATURE AS AFFECTED
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INTRODUCTION

Effective use of irrigation water is rapidly becoming a subject of considerable interest, and a method for irrigation scheduling based upon crop temperature measurements has been suggested (Aston and van Bavel, 1972; Jackson, 1982). This technique for irrigation scheduling is well suited for infrared radiometric remote sensing. It has long been recognized (Tanner, 1963) that crop temperature can be used as an indicator for soil water stress; as plant available soil water decreases the canopy temperature increases. To identify crop water stress more-or-less unambiguously by crop temperature measurements, it is necessary to quantify the effects of weather variables on the canopy temperature.

Carlson et al. (1972) observed that air temperature and vapor pressure deficit (VPD) are the significant weather variables affecting soybean canopy temperature. For a small range of VPD, Ehrler (1973) found a significant linear relationship between the canopy-air temperature difference (δT) and VPD for cotton. Using data from different geographic locations, Idso et al. (1981) showed that during a significant portion of daylight periods unique linear relationships exist between δT and VPD for non-stressed alfalfa, soybean and squash.

The objective of this paper is to develop a soil-plant-atmosphere model for soybeans and study the sensitivity of canopy temperature to weather variables, soil water potential, and crop rooting density. The model is tested against the observations of Idso et al. (1981) for canopy temperatures, Brady et al. (1974) for leaf water potentials, and Brady et al. (1975) and Sivakumar and Shaw (1978) for stomatal resistances.

MODEL DESCRIPTION

The Monteith's (1965) equation for transpiration contains a variable resistance term for representing vegetative control of vapor loss. The basic idea of the soil-plant-atmosphere models (Federer, 1979; Soer, 1980 and Luxmoore et. al., 1981) is to account for this vegetative control of vapor loss by setting up an equation of continuity for the plant water status. If in the transpiration process the canopy neither gains nor loses any water then the continuity equation can be written as

$$\frac{\Delta R_n + C_p \rho_a (e_a^* - e_a) / r_a}{L_V [\Delta + \gamma (1 + \frac{r_c}{r_a})]} = \frac{\psi_s - \psi_l}{R_s + R_p} \quad (1)$$

where the left hand side is the Monteith's equation for transpiration and the right hand side is the van den Honert's (1948) equation for water uptake by plant roots.

The left hand side contains the atmospheric parameters which determine the atmospheric evaporative demand and the stomatal control of transpiration. The saturated vapor pressures (kPa) at air and dew point temperatures are, respectively, e_a^* and e_a , and their difference is the vapor pressure deficit (VPD). The slope of saturated vapor pressure evaluated at approximately the air temperature is Δ (see Jackson et al., 1981). The density (kg m^{-3}) and the heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$) of air, are, respectively, ρ_a and C_p , γ is the psychrometric constant (kPa K^{-1}) and L_V is the latent heat of vaporization per unit volume (J m^{-3}). The aerodynamic resistance r_a (s/m) is calculated from wind speed U (m/s) at height Z according to Thom and Oliver (1977) as

$$r_a = \frac{4.72 \left[\ln \left(\frac{Z-d}{Z_0} \right) \right]^2}{1 + 0.54 U} \quad (2)$$

where the roughness height Z_0 and the zero-plane displacement d can be calculated from the crop height CH as (see Bailey and Davies, 1981a)

$$\log d = 0.9793 \log CH - 0.1536 \quad (3a)$$

$$Z_o = 0.164 CH - 0.021 \quad (3b)$$

The net radiation absorbed by the canopy R_n ($W m^{-2}$) is calculated according to Rosenthal et. al. (1977) using empirical relations for canopy absorption (Kanemasu et. al., 1976) and the net radiation above the canopy (Uchijima, 1976) as

$$R_n = (0.82 S - 90) (1 - \exp(-0.398 LAI)) \quad (4)$$

where S is the global insolation ($W m^{-2}$) and LAI is the leaf area index. Since in using this empirical equation for net radiation I am not calculating the long-wave radiation balance explicitly, the dependence of net radiation on the canopy temperature is neglected.

The right hand side of Equation (1) is the resistance analogue for transpiration (van den Honert, 1948; Gardner, 1964); the numerator is potential difference between leaf (or xylem) and soil water, and the denominator is the total resistance for water flow through soil and plant. When the atmospheric evaporative demand (i.e., the left hand side of Equation (1)) is zero (which would occur generally at night), the leaf water potential ψ_l (m) will tend to equilibrate with the soil water potential ψ_s (m) (cf., Biscoe et al., 1976). Boyer (1968), however, notes that because of plant growth the leaf water potential before sunrise could be 10 to 20 m lower than the soil water potential. As the evaporative demand increases the plant increases the suction for soil water by decreasing the leaf water potential.

The resistance for water flow through soil R_s is calculated according to Soer (1980) for silt loam soil parameters (Clapp and Hornberger, 1978) as

$$R_s = 550 (\psi_s / \psi_{sat})^{2.57} \quad (5)$$

where the 'saturation' suction ψ_{sat} is -0.8 m.

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canopy resistance follows from Equation (7), and the left side of Equation (1) gives the rate of transpiration (E). Then from energy balance (cf., Jackson et. al., 1981) the canopy-air temperature difference δT is obtained as

$$\delta T = (R_n - L_V E) \frac{r_a}{C_p \rho_a} \quad (8)$$

Note that the dependence of net radiation on the canopy temperature is not accounted for explicitly due to my use of an empirical equation (4).

INPUT DATA

Significant linear relationships between δT and VPD observed by Idso et. al. (1981) included data from different geographic locations and covered a wide range of weather variables. Since weather variables are not totally uncorrelated, the present simulation is done using observed (U.S. Department of Commerce) hourly weather data for clear skies during summer at Phoenix (Az.) and at Baltimore (Md.). A total of sixteen days data consisting of four days for Baltimore during June and July and twelve days for Phoenix during May and June. The weather variables during 1000 to 1400 LST (local standard time) covered a wide range; VPD from 1.6 to 8.3 kPa, wind speed from 1.5 to 6.5 m/s and air temperature from 23 to 43° C.

Current weather data do not include global insolation. A model developed by Choudhury (1982) was shown to be accurate to 98% or better when compared with careful pyranometer observations for clear skies. Considering that the errors in using the empirical equations, such as Equation (4), are generally 10 to 15%, the present simulation are done using the insolation values calculated from the model.

The crop height is assumed 0.9 m and the leaf area index 4 as representative for a mature soybean crop (Luxmoore et. al., 1971; Sivakumar et. al., 1977; Bailey and Davies, 1981a). The rooting density is somewhat dependent upon the soil texture and crop variety. In sandy soils

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the root length per unit area (L_T) is about $9 \times 10^3 \text{ m}^{-1}$ (Robertson et. al., 1980; Jones et. al., 1982), and in the surface 0.8 m profile consisting of loam, silt loam and sandy loam (overlying several meters of coarse sand and gravel) Arya et. al. (1975) found an L_T value of about $1.3 \times 10^4 \text{ m}^{-1}$. According to Mayaki et. al. (1976) about 90% of the root dry matter of mature soybeans in silt loam soils is in the surface 0.9 m layer. Raper and Barber (1970) found the root length per plant, also in the surface 0.8 m layer, differed among the varieties ranging from 600 to 800 m. Since the root length per plant of 680 m observed by Arya et. al. (1975) is within the range observed by Raper and Barber (1970), an L_T value of $1.4 \times 10^4 \text{ m}^{-1}$ is assumed to be representative for mature soybean crops in silt loam soils. Recognizing the uncertainty in and the dynamic nature of root distribution some results will also be given for L_T values of $(1.4 \pm 0.2) \times 10^4 \text{ m}^{-1}$. The chosen uncertainty in the L_T value reflects the variation in the root length observed by Raper and Barber (1970) when compared with Arya et. al. (1975). Note that for unirrigated plants L_T would be smaller since Sivakumar et. al. (1977) observed that the root length at any depth in silt loam soil decreased when the soil water potential decreased below -20 m.

SIMULATION RESULTS

At the soil water potential of -1 m the simulated dependence of δT on VPD is shown in Figure 1 together with the regression line calculated by Idso et. al. (1981) using observations on non-stress soybeans at Kansas, Nebraska and North Dakota. In the observations VPD did not exceed 6 kPa, and for this range of VPD the simulation generally agrees with the prediction based on the regression line to within 0.5 K. The data plotted in Idso et. al. indicates a standard error of about 1 K with respect to the regression line. Whereas the observed data are scattered evenly with respect to the regression line, the simulated results are seen to be somewhat biased (lower δT values), particularly in the VPD range of 2.5 to 4.5 kPa. In fact, a closer look at the simulated results indicates a quasi-linear relationship between δT and VPD, similar to the

locus for lower bound of δT calculated by Jackson et al. (1981) for constant stomatal resistance. Considering the range of weather variables used in this simulation, the scatter in Figure 1 supports Idso et al. (1981) in showing that air and dew point temperatures are the significant weather variables affecting the canopy temperature during most of clear sky day period. Note that air and dew point temperatures also appeared as the significant weather variables affecting evapotranspiration from forests (Luxmoore et al., 1981).

Canopy temperature reflects the integrated response of plant to the existing weather and soil water conditions. If the effect of weather variables can be accounted for in terms of air and dew point temperatures, e.g. by Figure 1, it may be possible to infer the soil water conditions from the canopy temperature measurements. Figure 2 shows the relationship between the δT values at the soil water potential of -1 m (as shown in Figure 1) and the δT values at the potentials of -41, -61 and -81 m. Significant relationships between these sets of δT s seen in this figure appear potentially useful in remote sensing of root zone soil water conditions. Referring to Figure 1, let us assume that the observed value of δT is δT_0 . If the soil water potential were -1 m (which is close to the field capacity) the observed value would have been δT_e (one may calculate this knowing air and dew point temperatures using the regression equation of Idso et al.). This δT_e value can now be used as the X-coordinate and δT_0 value as the Y-coordinate in Figure 2 to bracket the soil water potential. In the example shown the observed δT corresponds to the soil water potential of about -40 m.

The highly correlative nature of δT s at two different soil water potentials (as seen in Fig. 2) can be expressed mathematically. If, following Jackson et al. (1981), we define a crop water stress index (CWSI) as

$$CWSI = 1 - \frac{\Delta + \gamma (1 + r_c^0/r_a)}{\Delta + \gamma (1 + r_c/r_a)} \quad (9)$$

(where r_c° and r_c are, respectively, the canopy resistances at the soil water potentials of -1 m and ψ_s) then by a simple manipulation of eqns. (1) and (8) one can write

$$\delta T = \left(\frac{R_n r_a}{C_p \rho_a} \right) \text{CWSI} + (1 - \text{CWSI}) \delta T^\circ \quad (10)$$

where δT° and δT are, respectively, the δT values at the soil water potentials of -1 m and ψ_s . Changes in soil water potential affects δT through the CWSI. At any soil water potential a linear regression analysis between δT and δT° (for the same VPD) should give a high correlation coefficient, and the scatter in this relationship would be due to variable wind conditions. For the silt loam soil studied here, a soil water potential of -40 m would correspond to a depletion of the plant available soil water by about 75%. From the slope of δT vs. δT° curve at $\psi_s = -41$ m shown in Figure 2 we calculate the $\text{CWSI} = 0.2$. Thus, for irrigation scheduling, based on 70 to 80% depletion it would be undesirable for the CWSI to exceed much beyond 0.2.

Kramer (1969) suggested that measurements of stomatal resistance would be a direct approach to inferring the root zone soil water potential. Brady et. al. (1975) found a second-order polynomial relationship between the stomatal resistance (sampling period 1300 to 1500 CDT) of soybean and soil water potential (silt loam soil), and Sivakumar and Shaw (1978) found that the daily average value of the leaf conductance is directly proportional to the soil water potential.

The simulated leaf stomatal resistances from Equation (7) at the soil water potential of -1 m are shown in Figure 3 as a function of VPD. In agreement with the observations of Tan and Black (1976) the resistance increases as VPD increases. A linear relationship with the VPD would be a good approximation except for cases of high evaporative demand (wind speed exceeding 4 m/s with VPD greater than about 5 kPa). The soybean canopy temperature data of Kansas shown in Idso et al. (1981) indicate that VPD generally does not exceed 6 kPa, and Figure 3 shows that for VPD up to 6 kPa the range of stomatal resistance is 136 to 215 s/m. This range for simulated

resistances is in good agreement with the observed range, from 140 to 190 $s\ m^{-1}$, by Brady et al. (1975).

The range of stomatal resistances from 2.2 to 6 kPa at various soil water potentials is shown in Figure 4. The increase in stomatal resistance with decreasing soil water potential is consistent with observations of Sionit and Kramer (1976). The regression equations calculated by Brady et al. (1975) and Sivakumar and Shaw (1978) for soybean crops are also plotted to show agreement with the simulation. Note that the range of resistance increases as the soil water potential decreases, as was observed by Brady et al. (1975) for soybean and Tan and Black (1976) for forests. Furthermore, it is seen that the upper bound of the resistance (VPD about 6 kPa) increases more rapidly compared to the lower bound (VPD about 2.2 kPa) as the soil water potential decreases. Indeed, Tan and Black (1976) observed this dependence of stomatal resistance on the VPD as the soil water potential decreased, which led them to conclude that if the measurements of stomatal resistance are to be used for inferring soil water conditions, the range of VPD should be constrained to small ranges and be prescribed. Clearly, stomatal resistances at high VPDs (say VPD greater than 4 kPa) will be more sensitive to the changes in soil water potential, but the simulation shows that such resistances are also more sensitive to changes in the wind speed. Therefore, if VPD is to be the only weather variable that is prescribed in the stomatal resistance-soil water potential relationship then it may be useful to constraint this variable to some moderate value of say 4 kPa.

The dependence of leaf water potential on VPD during 1300 to 1500 LST is shown in Figure 3 at the soil water potential of $-1\ m$, and the range of the potential corresponding to stomatal resistances Figure 4 is shown in Figure 5. The regression equation for soybean calculated by Brady et al. (1974) is plotted in Figure 5 to show that the observed data as expressed through the regression equation and its standard error or estimate (8.7 m) is fairly well represented in the simulation. Note that in contrast to the stomatal resistances shown in Figure 5, the range of leaf water potential decreases as the soil water potential decreases. From leaf- and soil-water potential measurements

Brady et al. (1974) had concluded that in response to the daily evaporative demand the leaf water potential of soybean decreases on the average of 90 to 100 m. In the simulation this decrease is essentially given by the difference of leaf and soil water potentials, and Figure 5 shows the magnitude of this decrease to be 70 to 115 m at the soil water potential close to field capacity, and 60 to 90 m at the soil water potential of -80 m. In this regard the present simulation agrees marginally with Brady et al. (1974). In assessing these comparisons it is pertinent to consider the measurement uncertainties. The leaf and soil water potentials measured by Brady et al. (1974) before sunrise did not follow a 1:1 relationship which, as such, disagrees with the assumption of plant- and soil-water equilibrium. The pressure chamber method used for leaf water potential measurements did not include xylem osmotic potential, which Brady et al. estimate could be as much as -10 m when the pressure potential is -80 m. If the leaf water potentials calculated from the regression equation of Brady et al. (1974) are to be uniformly decreased by 10 m, the prediction based on the regression equation would still pass through the simulated range, however, the standard error of estimate for the regression equation would go beyond the lower bound of the range for most soil water potentials. Thus, if the apparent contradiction of data with soil- and plant-water equilibria is to be reconciled by decreasing the measured leaf water potentials by 10 m or more, then the simulation will be less satisfactory with respect to these potentials. Carlson et al. (1979) observed that the leaf water potentials of two soybean cultivars giving the *same* stomatal resistance sometimes differed by more than 20 m. Observations of Sionit and Kramer (1976) show that the stomatal resistance at different growth stages of soybeans sometimes differing by a factor of two or more at the same leaf water potential. Therefore, disagreements with respect to the leaf water potential (or the stomatal resistance) would indicate the need for a better relationship between the stomatal resistance and leaf water potential (Equation 7). The seasonal average predawn and midday values of irrigated soybean leaf water potential (planted in silt loam soil) observed by Jung and Scott (1980) were, respectively, -42 and -116 m. If under the assumption of soil- and plant-water equilibrium, the predawn value of leaf water potential is assumed to represent the soil water potential then the observed midday value of the leaf water potential (-116 m) would not be inconsistent with the present simulation. However, the corresponding observed seasonal average midday stomatal resistance of 60 s/m

is about a factor of three smaller than that predicted by the simulation. Thus, although the present simulation provides some qualitative understanding of a few independent sets of observations, it also shows the need for a better quantification of the stomatal resistance – leaf water potential relationship for different soybean cultivars. It is also pertinent to quantify the mechanics of osmotic regulation and the role of leaf turgor in stomatal control (cr., Turner et al., 1978; Zur and Jones, 1981).

The above simulation results are obtained for root length per unit area (L_T) value of $1.4 \times 10^4 \text{ m}^{-1}$. This plant characteristic vary with time, and Figure 6 illustrates the δT vs. VPD relationship for L_T values of 1.2×10^4 and $1.6 \times 10^4 \text{ m}^{-1}$. It is seen that the δT values decrease as the L_T value increases, i.e., as the rooting density of a plant increases the canopy temperature decreases. The dependence of δT on L_T are not the same at all VPDs; for example, at the VPD of 2 kPa the change in δT s is about 0.3 K, and at the VPD of 7 kPa the change in δT s is about 1.0 K. The simulation suggests that some scatter in the observations of Idso et al. (1981) may also have arisen from differing rooting densities. Also, since the observed rooting density in sandy soils (Robertson et al., 1980; Jones et al., 1981) appears to be lower than in loam soils (Arya et al., 1975; Raper and Barber, 1970), the simulation would suggest that the canopy temperature of soybeans planted in sandy soil to be somewhat higher compared to the crop planted in loam soils.

SUMMARY

A soil-plant-atmosphere model for soybean was described and simulation results using observed hourly weather data were compared with observed canopy temperatures, stomatal resistances, and leaf water potentials. The air and dew point temperatures are found to be the significant weather variables affecting the canopy temperatures. Under identical weather conditions, the model gives a lower canopy temperature for a soybean crop with a higher rooting density. A knowledge of crop rooting density, in addition to air and dew point temperatures, is needed in interpreting infrared radiometric observations for soil water status. The observed dependence of stomatal resistance on VPD and soil water potential is fairly well reproduced. Analysis of the simulated leaf water potentials indicated overestimation, possibly due to differences in the cultivars.

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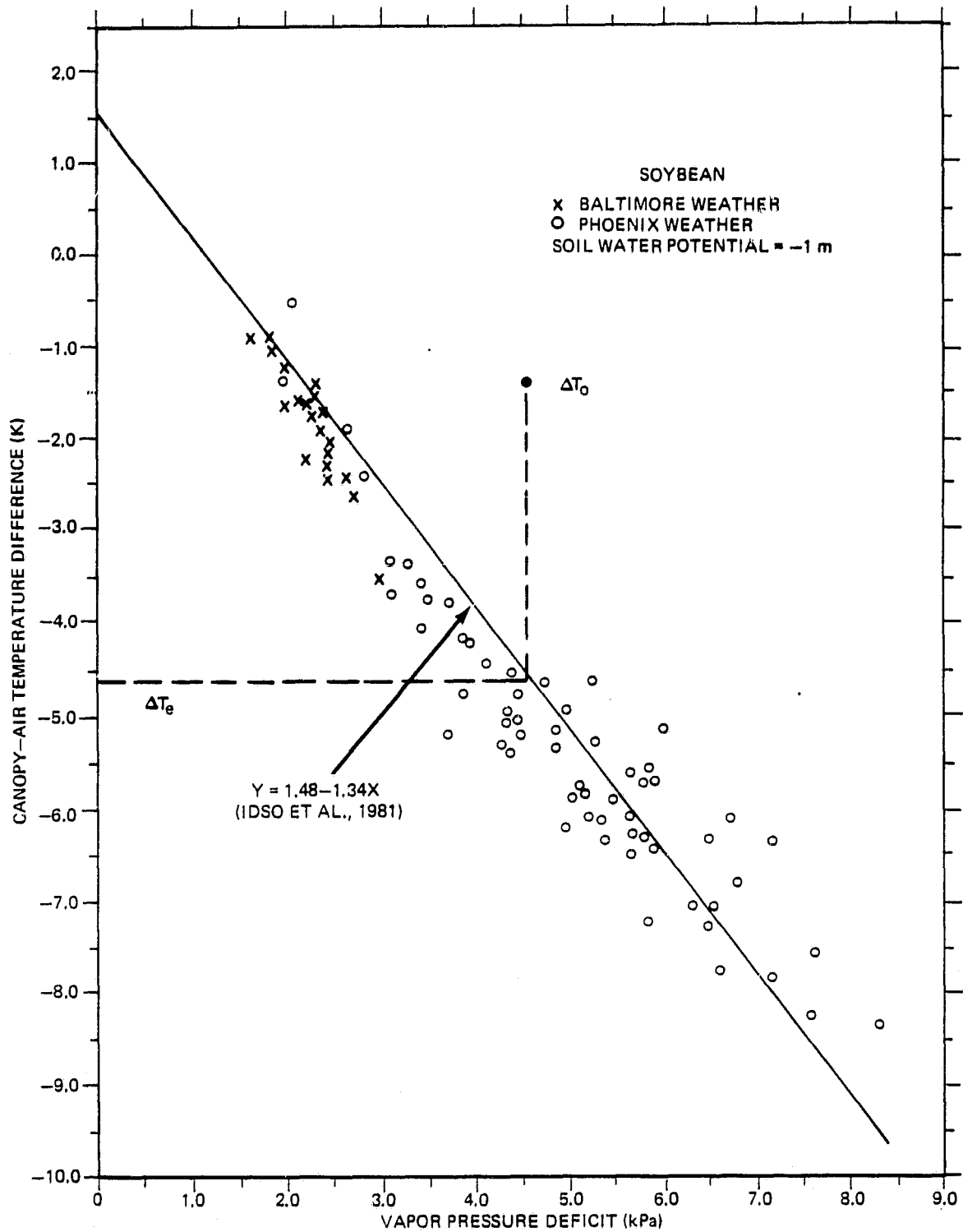


Figure 1. Simulated variation of soybean canopy-air temperature difference with air vapor pressure deficit. The regression equation calculated by Idso et. al. (1981) from observations on unstress canopies is plotted. The soil water potential is -1 m.

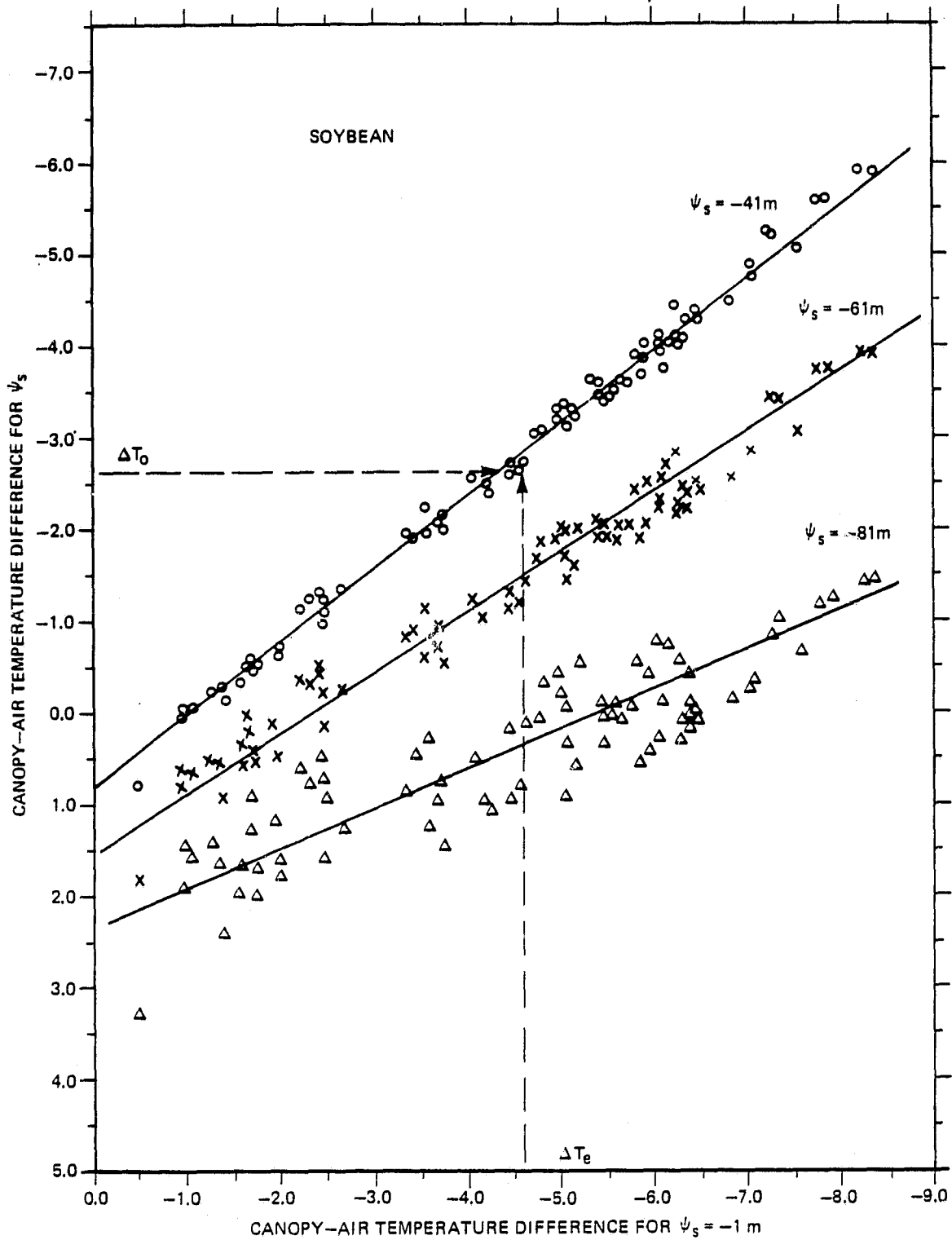


Figure 2. Relationship of the canopy-air temperature differences at the soil water potentials of -41, -61, and -81 m with respect to the soil water potential of -1 m. With decreasing soil water potential the scatter increases due to differing wind speeds.

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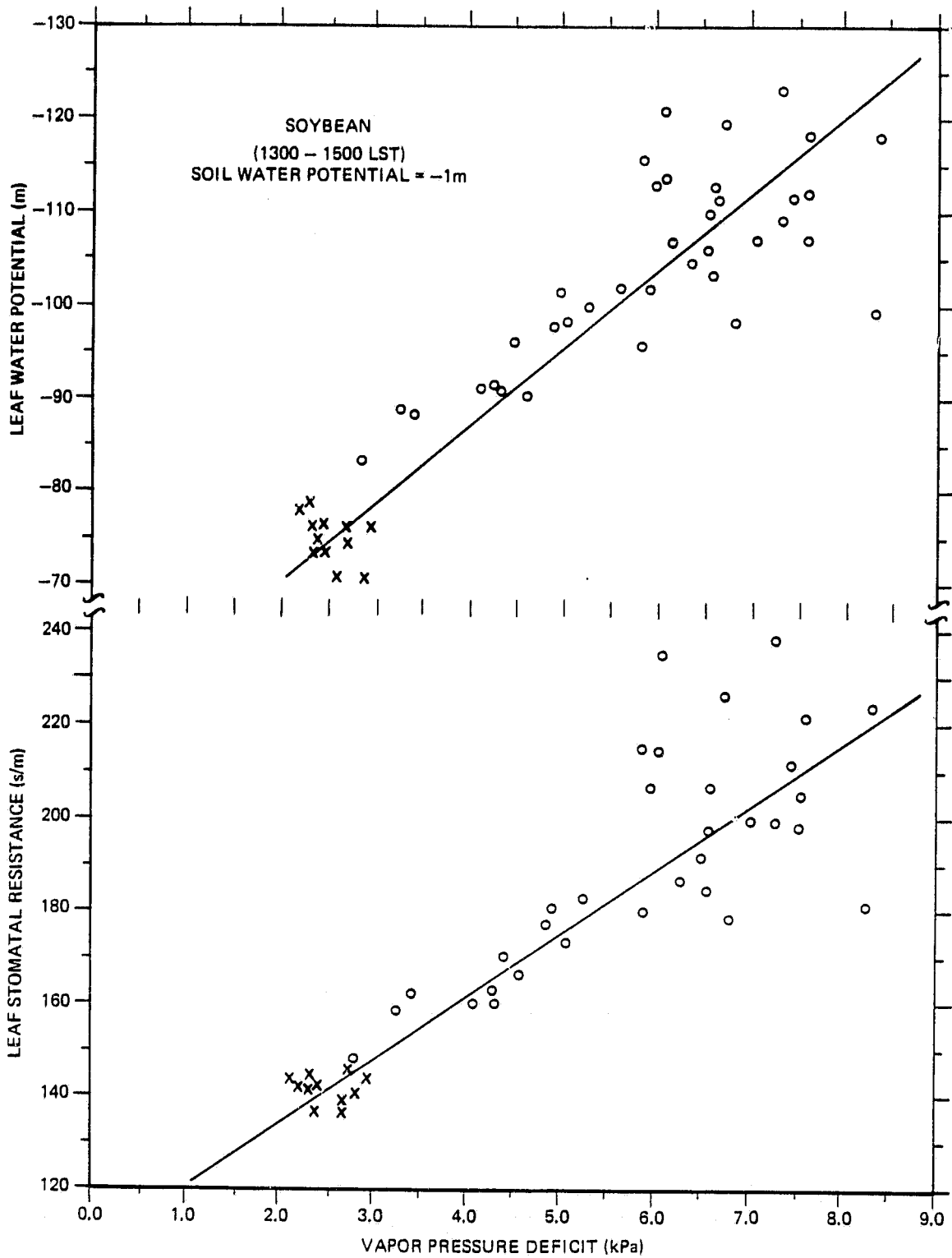


Figure 3. Simulated dependence of leaf stomatal resistance and leaf water potential on the air vapor pressure deficit. The soil water potential is -1 m. Straight lines are drawn to show the trend.

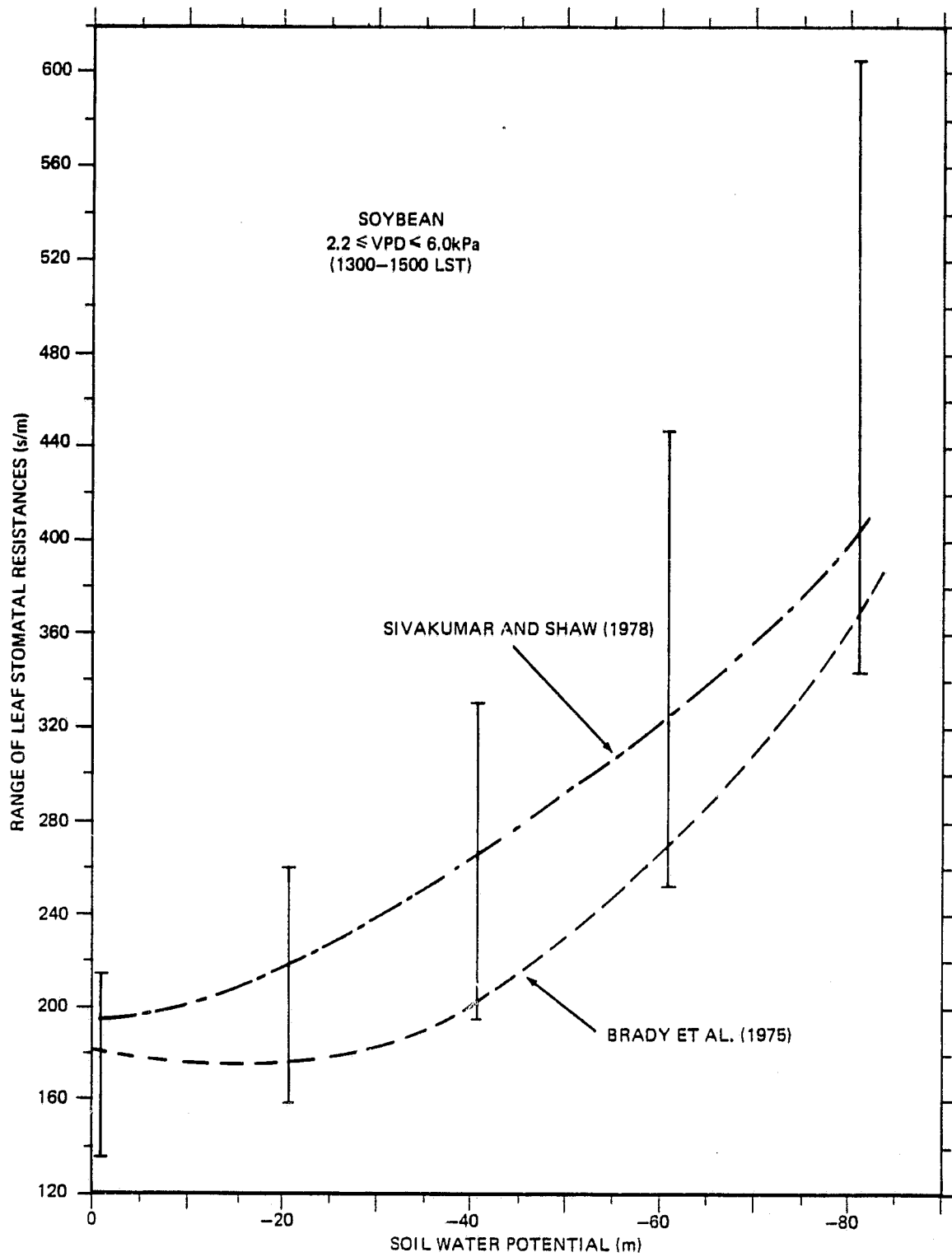


Figure 4. The simulated range of leaf stomatal resistances at various soil water potentials. The dependencies inferred from observations by Brady et al. (1975) and Sivakumar and Shaw (1978) are also plotted.

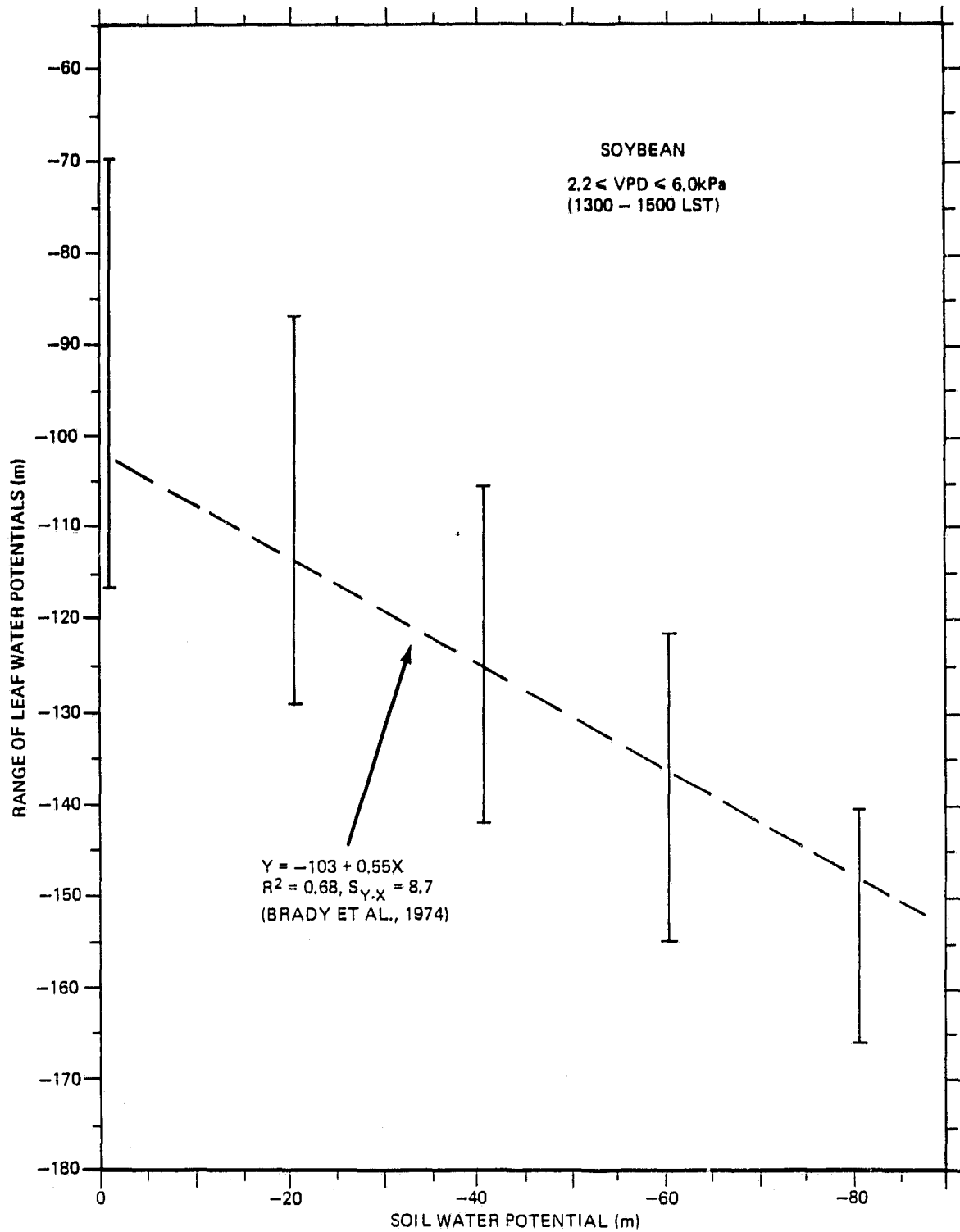


Figure 5. The range of leaf water potentials at various soil water potentials. The regression equation calculated by Brady et. al. (1974) is shown.

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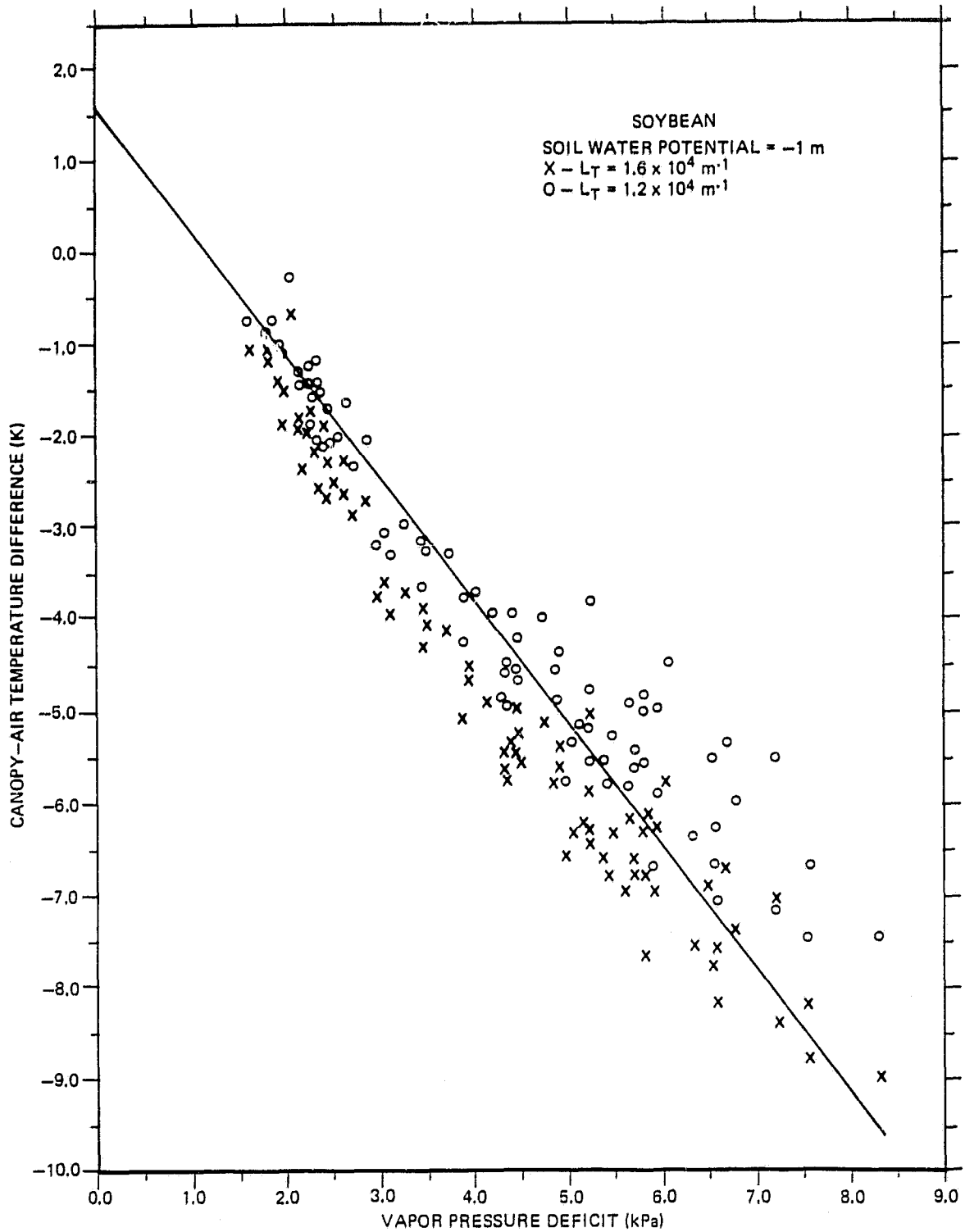


Figure 6. The effect of differing rooting densities on the canopy-air temperature difference at the soil water potential of -1 m. The canopy temperature decreases as the root length per unit area (L_T) increases. The rooting density affects the canopy temperatures more at higher vapor pressure deficits.

FIGURE CAPTIONS

- Figure 1. Simulated variation of soybean canopy-air temperature difference with air vapor pressure deficit. The regression equation calculated by Idso et. al. (1981) from observations on unstress canopies is plotted. The soil water potential is - 1 m.
- Figure 2. Relationship of the canopy-air temperature differences at the soil water potentials of - 41, - 61, and - 81 m with respect to the soil water potential of - 1 m. With decreasing soil water potential the scatter increases due to differing wind speeds.
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- Figure 4. The simulated range of leaf stomatal resistances at various soil water potentials. The dependencies inferred from observations by Brady et. al. (1975) and Sivakumar and Shaw (1978) are also plotted.
- Figure 5. The range of leaf water potentials at various soil water potentials. The regression equation calculated by Brady et. al. (1974) is shown.
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