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ABSTRACT

Spatial variability of canopy temperature has been shown to provide an useful criteria for irrigation scheduling, and a knowledge of this variability is needed for comparing infrared radiometric observations of differing spatial resolutions. A soil-plant-atmosphere model for corn (*Zea mays* L.) together with the scaling theory for soil hydraulic heterogeniety are used to study the sensitivity of spatial variation of canopy temperature to field-averaged soil texture and crop rooting characteristics. The soil-plant-atmosphere model explicitly solves a continuity equation for water flux resulting from root water uptake, changes in plant water storage and transpirational flux. Dynamical equations for root-zone soil water potential and the plant water storage models the progressive drying of soil, and day-time dehydration and night-time hydration of the crop. The statistic of scaling parameter which describes the spatial variation of soil hydraulic conductivity and matric potential is assumed to be independent of soil texture class. The field-averaged soil hydraulic characteristic are chosen to be representative of loamy sand and clay loam soils. Two rooting characteristics are chosen, one shallow and the other deep rooted. The simulation shows that the range of canopy temperatures in the clayey soil is less than 1K, but for the sandy soil the range is about 2.5 and 5.0K, respectively, for the shallow and deep rooted crops. Irrigation scheduling based on a fixed canopy temperature variability would lead to variable depletion of available water, depending upon soil texture and crop rooting characteristics. Because of a smaller variability in clayey soils, one may use the ground-based radiometric observations to 'calibrate' coarse resolution observations (as would be available from a air-borne sensor), provided that a soil hydraulic heterogeniety is the only important heterogeniety within the resolution area.

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INTRODUCTION

Production of agricultural crops in arid and semi-arid regions of the world is highly dependent upon irrigation. In humid regions irrigation is also being used to increase yield. While water used for irrigation is increasing, the water available for irrigation is decreasing (aquifer recharge being less than depletion). There is an increasing emphasis to maximize the benefit from each unit of irrigation water. The key question posed in irrigation scheduling is when and how much water is to be applied to offset the yield-reducing stress conditions of a crop.

Recently Jackson (1982) has reviewed the irrigation scheduling techniques based on soil, meteorologic, and plant factors. He argues that while soil and meteorologic factors used in irrigation scheduling stride to indicate crop stress and needed irrigation water, direct observation of some plant parameter should be a superior approach. The plant parameters which have been studied as indicators of plant stress are leaf water potential, stomatal resistance, and leaf or canopy temperatures. The leaf based measurements (potential, resistance and temperature) are time consuming when fields of the size of hectare or larger are to be sampled to obtain a representative value. Therefore, according to Jackson (1982) the most promising approach to irrigation scheduling would be the measurements of canopy temperature using infrared radiometers. A further highly appealing nature of irrigation scheduling or identifying crop stress using infrared radiometers is that the technique could be applied to large areas using airborne and spaceborne infrared sensors.

At high soil water potentials the canopy temperatures are independent of soil texture and the actual soil water potential; the canopy temperatures being determined by atmospheric evaporative demand and plant characteristics. Since with decreasing soil water potential the canopy temperature increases, Tanner (1963) argued that it may be possible to infer soil water status from the

canopy temperatures. In order to eleviate the effects of diurnal and day-to-day variations in weather conditions on the canopy temperature, Aston and van Bavel (1972) addressed the need of a reference canopy temperature. The reference temperature could be of a nearby well-watered plot. Alternately, they suggested that a cropped field can be its own internal reference, because, all fields being heterogeneous, a differential soil drying would introduce a spatial crop temperature variability. The magnitude of this variability may signal the onset of crop water deficits.

The problem of accounting the effect of variable weather conditions on a crop canopy temperature has been addressed further by Idso *et al.* (1981a) and Idso (1982), among others. Idso *et al.* (1981a) observed that during a significant portion of clear sky daylight period the canopy temperatures of well watered crops are determined largely by air and dew point temperatures. Idso (1982) gives empirically derived linear regression equations for calculating unstress canopy temperature of 26 crops in terms of air and dew point temperatures. These equations could be used to infer the crop water status from infrared radiometric observations knowing concurrent air and dew point temperatures (Choudhury, 1982 and 1983). In remote sensing applications, however, it may be difficult to acquire the ancillary weather data of concurrent air and dew point temperatures.

The alternate approach to irrigation scheduling suggested by Aston and van Bavel (1972) which would not require any weather data, namely the use of spatial variability of canopy temperatures, was recently field tested by Clawson and Blad (1982). In sprinkler irrigated corn plots of Valentine fine sand underlying clay horizons of dimensions 18.3 × 36.6 m, Clawson and Blad (1982) found that irrigation with CTV = 0.8 K (where CTV = maximum minus minimum observed canopy temperatures) reduced the amount of irrigation water by about 54% with only 5% reduction in yield as compared to a well-watered plot. This saving of irrigation water is certainly worth noting, and while a plot-averaged canopy temperature would indicate the average soil water status of the field, the field variability of the canopy temperature indicates the differential root water uptake. The distribution of root-zone soil water within a field would lead of a differential stress

conditions and hence a spatial variation of crop yield (Bresler *et al.*, 1981). Irrigation using canopy temperature variability should be able to minimize the spatial variation of crop stress, and it follows from Mitscherlich's equation for plant growth (Ware *et al.*, 1982) that the total yield of a field could be increased.

Apart from irrigation scheduling application, a knowledge of spatial variability of temperature is also needed in comparing radiometer observations of differing spatial resolutions (for example, ground-based and satellite-borne sensors), as has been pointed out by Vauclin *et al.* (1982).

The degree of heterogeniety in agricultural fields is highly variable. The heterogeniety could be both deterministic (topographic) and stochastic, and at present there are no general framework for describing the variability of soil hydraulic properties. However, by sacrificing some generality, the scaling theory of Philip (1967) has provided a simple physically based model to describe a stochastic heterogeniety (Warrick *et al.*, 1977; Russo and Bresler, 1980). In this theory, the spatial variability of unsaturated hydraulic conductivity and matric potential is described by a frequency distribution and autocorrelation functions of a single stochastic variable, called the scaling parameter. The frequency distribution of the scaling parameter has been found to be normal (Russo and Bresler, 1980) and log-normal (Warrick *et al.*, 1977), and the auto-correlation length varied from a few tens of meters (Vieira *et al.*, 1981) to less than a meter (Sisson and Wierenga, 1981). Spatial variability of infiltration rates in a Yolo loam agricultural field studied by Vieira *et al.* (1981) is quite significant in showing that there were *no* correlation of the rates when the soil samples were separated by 50 m or more, although the field was considered to be *"exceptionally uniform"* for agricultural purposes. Peck *et al.* (1977), Sharma and Luxmoore (1979) and Lascano and van Bavel (1982), among others, have discussed the application of scaling theory to soil water flow problems.

Assuming a scale heterogeneous medium with uncorrelated log-normal distribution of scaling parameter. Choudhury and Federer (1983) studied the effect of soil heterogeniety on a corn canopy temperature. The simulation model of Choudhury and Federer solves the continuity equation of

water flux in the soil-plant-atmosphere system by relating the canopy resistance and the rate of change of plant tissue water with the leaf water potential. The dynamical equations of soil- and plant tissue-water were integrated to simulate the effects of progressive soil drying and plant dehydration on the canopy temperature. For a field averaged soil hydraulic properties representive of a sandy loam soil and a fixed rooting density, the simulation showed that during the first several days of soil drying the field averaged canopy temperature increases fairly slowly but the canopy temperature variability shows a distinct onset with an almost exponential rise to a maximum value, after which it decreases. These simulated trends were found to be in qualitative agreement with the observation of Gardner *et al.* (1981) and Clawson and Blad (1982).

The present simulation is of the nature of a sensitivity study of spatial variation of a corn canopy temperature. The factors considered in this study are field-averaged soil texture and crop rooting characteristics. The spatial heterogeniety of the fields, as described by the statistic of scaling parameter, is assumed to be identical for all soil textures. The present simulation addresses the question – For fields which are statistically identical with regard to spatial heterogeniety but differ in mean hydraulic and crop rooting characteristics what would be the range of canopy temperatures?

Clearly, the range of canopy temperatures would be directly relavent in comparing radiometric observations of differing spatial resolutions. Differences in the canopy temperature which may result from radiometer look angle (cf., Jackson, 1982) is not addressed in this paper.

From field experiments Clawson and Blad (1982) had found an efficient irrigation scheduling scheme for corn with a canopy temperature variability (CTV) of 0.8 K, but they questioned whether this value would be applicable to other field conditions. The question of prescribing an efficient irrigation scheduling scheme based on the results of present simulation is not addressed because there are no unique mathematical criteria currently available to provide such a prescription. However, the field-averaged values of the depletion level for available water, the stomatal resistance

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and the leaf-water potential, all of which have been used for irrigation scheduling (see Jackson, 1982), will be discussed.

SIMULATION METHODS AND PARAMETER SELECTION

Soil-Plant-Atmosphere Model

The dynamics of soil-plant-atmosphere system is simulated using Choudhury and Federer's (1983) model. The model is schematically illustrated in Figure 1, and a brief description follows.

The continuity equation of water flux in the soil-plant-atmosphere system, namely

$$\frac{\Delta R_n + C_p \rho_a (e_a^* - e_a)/r_a}{L_v [\Delta + \gamma (r_a' + r_c)/r_a]} = \frac{\psi_s - \psi}{R_s + R_p} + \frac{\psi_q - \psi}{R_q} \tag{1}$$

(where R_n is net radiation, e_a^* and e_a are, respectively, the saturated vapor pressures at air and dew point temperatures, Δ is the slope of saturated vapor pressure with respect to the air temperature, γ is psychrometric constant, L_v is the latent heat vaporization, r_a' and r_a are, respectively, the boundary-layer resistances for vapor and heat transfers and the other symbols are defined in Figure 1) is made to be a self-consistent equation for determining the plant water potential (ψ) by expressing the canopy resistance (r_c) in terms of ψ via the following empirical equation

$$r_c = \frac{1.4 \times 10^4}{LAI\,(\psi - \psi_c)} \left[1 + \frac{175}{S + 10}\right] \tag{2}$$

where LAI is the canopy leaf area index, S is the global insolation and ψ_c is the critical plant water potential for stomatal closure. The eqn. (2) is derived from the observations of Uchijima (1976) and Reicosky and Lambert (1978), and following the suggestion of Kramer (1969) that the leaf water potential and global insolation are the most important factors determining the stomatal resistance.

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The day-time plant dehydration and night-time recharge is modeled through an empirical relationship between the water stored in the plant (Q) (which is the volume of plant water above permanent wilting per unit surface area) and the corresponding potential ψ_q as

$$\psi_q = -450 \times f - (131\,X + 84)(1 - f) \tag{3}$$

where

$$X = 1 - \frac{Q}{Q_o}$$

$$f = \frac{1}{1 + \left(\frac{X}{0.175}\right)^5}$$

and Q_o is the amount of water stored at maximum potential (i.e., $\psi = 0$).

The soil resistance (R_s) calculated from root depth and soil hydraulic conductivity according to Feddes and Rijtema (1972), and the plant resistance (R_p) is calculated from root length per unit area according to Cowan (1965) taking into account the plant stress induced nonlinearities (Boyer, 1971; Nulsen and Thurtell, 1978). Monteith's (1981) equation is used to calculate the boundary-layer resistance for heat transfer (r_a) from wind speed and air temperature.

The dynamics of soil water potential (ψ_s) and the water stored in the plant (Q) are governed by the equations

$$Z_{eff}\, C(\psi_s) \frac{d\psi_s}{dt} = -\frac{\psi_s - \psi}{R_s + R_p} - K(\psi_s) \tag{4}$$

$$\frac{dQ}{dt} = -\left[\frac{\psi_q - \psi}{R_q}\right] \tag{5}$$

where Z_{eff} is root depth, $K(\psi_s)$ is the soil hydraulic conductivity and $C(\psi_s)$ is the soil capacitance.

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The above soil-plant-atmosphere model applies to a vegetation-covered soil for which soil evaporation is negligible. The input hourly meteorological parameters are global insolation, wind speed and air and dew point temperatures; the plant parameters are the root depth, the leaf area index and the root length per unit area; the soil parameters are hydraulic conductivity and capacitance, which will be elaborated in the next section.

With the above input parameters, Equation (1) is solved for the plant water potential ψ by initializing ψ_s and Q. After ψ is calculated, the dynamics of ψ_s and Q follow from Equations (4) and (5). The model thus generates successive steady states of plant water potential. The left hand side of eqn. (1) gives the transpirational flux, and the canopy temperature follows from the energy balance equation. Further details of the model together with model validation by comparison with observed plant water potentials and stomatal resistances can be found in Choudhury and Federer (1983). A representative set of validation results are shown in Figure 2. The weather data of Figure (2b) taken from Reicosky and Lambert (1978) are used in the present simulation.

Soil Heterogeniety

In the present simulation, the hydraulic conductivity K (ψ_s) and soil capacitance C (ψ_s) are expressed in terms of soil water potential ψ_s using the parametric equations of Clapp and Hornberger (1978) as:

$$K(\psi_s) = K_{sat} \left[\frac{\psi_{sat}}{\psi_s}\right]^{2+3/b} \tag{6}$$

$$C(\psi_s) = -\frac{\theta_{sat}}{\psi_{sat} b} \left[\frac{\psi_{sat}}{\psi_s}\right]^{1+1/b} \tag{7}$$

where b is an empirical constant and θ_{sat}, ψ_{sat} and K_{sat} are the saturation values of, respectively, volumetric moisture, potential and conductivity.

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According to Dagan and Bresler (1979) although all parameters of Equations (6) and (7) (namely, b, θ_{sat}, ψ_{sat} and K_{sat}) are stochastic for a heterogeneous soil, the randomness could be confined to only K_{sat} and ψ_{sat} using the scaling theory as:

$$K_{sat} = \alpha^2 \bar{K}_{sat} \tag{8}$$

$$\psi_{sat} = \bar{\psi}_{sat}/\alpha \tag{9}$$

where the scaling parameter α is a stochastic variable and $\bar{K}_{sat}$ and $\bar{\psi}_{sat}$ are the field-averaged values.

The field-averaged soil hydraulic parameters chosen for the present simulation correspond to loamy-sand and clay-loam soils (Clapp and Hornberger, 1978); for loamy sand: b = 4.38, θ_{sat} = 0.41, $\bar{\psi}_{sat}$ = −0.1 m and $\bar{K}_{sat}$ = 1.5 × 10^{-4} m/s, and for clay loam: b = 8.5, θ_{sat} = 0.476, $\bar{\psi}_{sat}$ = −0.63 m and $\bar{K}_{sat}$ = 2 × 10^{-6} m/s.

Based on the observations of Warrick *et al.* (1977) for soil series Panoche and Pima it is assumed that with 95% probability the spatial variation of the conductivity and the potential can be described by taking the scaling parameter α between 0.2 and 2.5, with α=1 for the mean soil hydraulic characteristics. The simulation results are, therefore, obtained with α=0.2, 1.0 and 2.5. (Clearly, if the spatial heterogeniety of the fields are not identical then for the same 95% probability the bounds of α, namely 0.2 and 2.5, would have to be modified.) This approach to studying the effects of spatial variability on soil water problems is along the line of Bresler *et al.* (1979) and Lascano and van Bavel (1982). A slightly different approach was followed by Choudhury and Federer (1983) who did the dynamic simulation by stochastically generating a sequence of α values by prescribing a frequency distribution (the crude Monte-Carlo approach). The present approach is computationally much less time consuming.

Corn Rooting Characteristics

The rooting characteristics (depth and density) of all crops are highly variable, and the significant factors affecting these characteristics are growth stage, soil temperature, texture and

strength, irrigation management and planting density (see, for example, Kramer, 1969; Milthorpe and Moorby, 1974).

At the silking time for corn grown in sandy soils Robertson *et al.* (1980) observed the root length per unit area (L_A) of 5.7×10^3 m^{-1} with no irrigation and 1.9×10^4 m^{-1} with light infrequent irrigation. In a silt loam soil (which had a consolidated layer below 0.75 m) Mengel and Barber (1974) observed L_A values of 9×10^3 and 1.25×10^4 m^{-1}, respectively, after 60 and 95 days of planting. Barber (1971) observed significant variation in corn root morphology with cultivation practice. From the observed variation of rooting density at different soil depths, Grimes *et al.* (1975) concluded that 75% of these variations could be accounted for in terms of soil strength. Reicosky and Lambert (1978) found that 85 to 90% of the roots of a mature corn crop were in the 0.31 m thick Varina sandy loam A1 horizon which was overlying a consolidated layer. However, the data of Grimes *et al.* (1975) show that for mature crops in permeable (low strength) soils 85 to 90% of the roots are in the surface meter of soil. For isolated corn plants grown in loamy fine sand Taylor and Klepper (1973) observed root lengths greater than 16 km. If one neglects the root-to-root growth limiting interactions operative under field conditions then a root length of 16 km would give an L_A value of about 1×10^5 m^{-1} for a planting density of 7 plants/m^2.

The intention of the above discussion was to provide some quantitative results regarding the observed variation in corn rooting characteristics. To simulate the effect of differing rooting characteristics on the canopy temperature the combination of effective rooting depth Z_{eff} (m) and root length per unit area L_A (m^{-1}) (i.e., (Z_{eff}, L_A)) are chosen to be (0.3, 5×10^3) and (1.2, 1.5×10^4). The chosen range is fairly large, but one should recognize that a larger variation could occur.

SIMULATION RESULTS

According to Kramer (1969) the single most important plant stress indicator is the leaf-water potential. The importance of the potential as an indicator of stress stems from the fact that cell division and growth, which are central to the ultimate crop yield, are related directly to the potential (Hsio, 1973). Clark and Hiler (1973) tested several plant measurements (the potential, stomatal resistance and infrared temperature) in order to select the most effective crop stress indicator; the selected indicator was the leaf-water potential. Ehling *et al.* (1968) and Brady *et al.* (1974), among others, observed that leaf- and soil-water potentials are related linearly to each other. Idso *et al.* (1981b) found the leaf water potential to depend upon the atmospheric vapor pressure deficit.

The simulated field averaged mid-day leaf and soil water potentials are shown in Figure 3. The relationship between the two potentials is fairly linear, although the linearity is more for the clay loam soil as compared to the loamy sand soil. Both both soils a marked deviation from linearity is seen to occur at low soil water potentials. In Equation (1) the soil water potential appears linearly in the numerator and non-linearly in the denominator through the dependence of R_s on the hydraulic conductivity. At high soil water potentials the plant resistance (R_p) is several orders of magnitude larger than the soil resistance (R_s), and, therefore, the dependence of soil water potential in Equation (1) is essentially linear at high potentials. As the soil dries, the soil resistance increases and begins to compete with the plant resistance. Thus, with decreasing soil water potential, the Equation (1) becomes a non-linear function of the potential.

Since the plant resistance is the controlling factor for root water uptake when the soil water potential is high, differences in crop rooting characteristics would be expected to affect the leaf water potential, as is seen in Fig. 3. Under a high evaporative demand, a crop with a higher rooting density would be able to transpire more efficiently and, therefore, would have a higher leaf water potential. A factor of two difference in the potentials of a deeply rooted and a shallow rooted

crop is seen in Figure 3. Thus, although leaf and soil water potentials are related lineraly, one will not be able to infer the soil water potential directly by measuring the mid-day leaf water potential.

In order to account for the effect of atmospheric variability on the leaf water potential, Choudhury and Federer (1983) had defined an index, called the plant water stress index, as

$$\text{PWSI} = \frac{\psi - \psi^{\circ}}{\psi_c - \psi^{\circ}} \tag{10}$$

where ψ° is the leaf water potential in the absence of any soil water deficit (the value assumed is for the day 1 of simulation) and ψ_c is the critical potential for stomatal closure. The PWSIs calculated from ψ values in Fig. 3 are shown in Fig. 4, which indicates that this index is also relatively insensitive to the crop rooting densities. If the long-held wisdom of irrigation scheduling based on 60 to 70% depletion of available water is to be maintained then PWSI should not be allowed to exceed a value of about 0.35. Thus, instead of using the ψ values directly to infer the soil water potential, one can use the index PWSI to infer the potential with less ambiguity.

The relationship between pre-sunrise leaf and soil water potentials are shown in Figure 5. While a 1:1 relationship exists for a deep root crop, the leaf water potential of a shallow rooted crop is seen to be generally lower than the soil water potential. This inequality in the potentials results from day-time plant dehydration which get gradually restored during the night. Under a high evaporative demand a shallow rooted crop gets dehydrated more because their roots are less capable of extracting soil water so as to meet the evaporative demand. Since the restoration of lost plant water continues throughout the night, the leaf water potential reaches the highest value just prior to sunrise. Boyer (1968) had noted that the leaf water potential before sunrise could be 10 to 20 m lower than the soil water potential (see also Brady *et al.*, 1974). The leaf water potential during the night needs to be several meters lower than the soil water potential if water is to be 'pulled' to the leaf for cell growth and division and other metabolic use.

The simulated field-averaged stomatal resistances and soil water potentials at 1300 hour are shown in Figure 6. At high soil water potentials the stomatal resistances depend upon rooting characteristics and atmospheric evaporative demand. As the evaporative demand increases or the rooting density decreases, the stomatal resistance increases (cf., Fig. 6). During the drying period of an irrigation cycle, the stomatal resistance increases initially at a slow rate but then fairly rapidly. In a shallow rooted crop, the rapid increase in the stomatal resistance occurs earlier than for a deep rooted crop because of the relatively quicker depletion of root-zone soil water in a shallow rooted crop. The dependence of stomatal resistance on soil water potential, as could be derived from this figure, agrees well with the observations of Brady *et al.* (1975).

Since *in situ* observations of the root-zone soil water potential are subject to errors in measuring the root distribution, a measurement of stomatal resistance has been suggested to be an indirect way of inferring this potential (cf., Brady *et al.*, 1975). The present simulation although shows that the stomatal resistances are affected by the soil water potential, it questions any unambiguous determination of the potential by measuring the resistance only. Figure 6 clearly shows such an ambiguity at high soil water potentials, since both resistances 120 s/m and 340 s/m correspond to a soil water potential of about −3 m. A measurement of pre-sunrise leaf water potential appears to be the most direct approach to measuring the soil water potential (c.f., Figure 5.) For irrigated corn crops Sumayao *et al.* (1980) observed the stomatal resistances to be lower than 500 s/m. The present simulation would suggest that this value of the stomatal resistance for irrigated corn may not be applicable to other locations having a different evaporative demand or having a different rooting characteristics. Thus, in irrigation scheduling using stomatal resistance measurements, one would need additional information about an average evaporative demand and the crop rooting characteristics.

The simulated field-averaged canopy-air temperature differences (δT) and soil water potentials at 1300 hour are shown in Fig. 7. Similar to the above results for the leaf water potentials and stomatal resistances, the canopy temperatures are seen to be affected by the crop rooting density, in

addition to the soil water potential. The relationship of δT with the soil water potential is approximately linear. The canopy temperatures of a deeply rooted crop are lower compared to a shallow rooted crop.

The above simulation results pertained to field-averaged leaf water potentials and stomatal resistances. While both of these plant-based measurements have been used to characterize soil water conditions of agricultural fields, they are more time consuming than the canopy temperature measurements using infrared radiometers. Based on the suggestion of Aston and van Bavel (1972), Clawson and Blad (1982) found that the spatial variability of canopy temperatures would be a good indicator of crop water deficiencies.

The simulated range of 1300 hour canopy temperatures (i.e., maximum minus minimum temperature) are shown in Figures 8a and 8b, respectively, for clay loam and loamy sand soils. Each figure contains results for two rooting characteristics, and the depletion of 70 percent of available soil water is annotated. The depletion of 70 percent of available water has been used as a criterion for irrigation scheduling.

The canopy temperature variability is clearly a function of soil texture and rooting characteristics. In coarse textured sandy soils the effect of differential soil drying is reflected more strongly on the canopy temperature through differing soil resistances (which is directly related to the hydraulic conductivity). Under progressive soil drying a deep rooted crop undergoes a more severe stress, although later in cronology, as compared to a shallow rooted crop. The irrigation scheduling criteria of 70 percent depletion level of available water means different canopy temperature variability for soils with differing texture and crops with differing rooting characteristics. While for sandy soils a marked canopy temperature variability may be seen at the 70 percent depletion level, very little variability occurs for clayey soils. Alternately, if irrigation scheduling is done based on a prescribed canopy temperature variability then the depletion level of the available

water would be different for soils with differing texture and crops with differing rooting characteristics. Clawson and Blad's (1982) criterion for irrigation scheduling (namely, CTV = 0.8 K) may not be equally effective under all field conditions, particularly in clayey soils.

In studying the effect of spatial variability of soil hydraulic properties on a bare soil temperature, Lascano and van Bavel (1982) found the temperature variabilities to be generally less than 1.5 K for a silty clay loam soil. This lead them to conclude that the current technology of infrared remote sensing would not be able to detect the effect of soil hydraulic variability. The observations of Clawson and Blad (1982) and the present simulation show that canopy temperature variability could be in excess of 4K for sandy soils. Such high variability resulting from soil heterogeniety should be detectable by the current infrared technology. The present simulation results for the clay loam soil would, however, concur with Lascano and van Bavel's conclusion. A further point addressed by Lascano and van Bavel is the accuracy with which the average hydraulic characteristics of the soil needs to be known to make model predictions compatible in accuracy with remote sensing observations. For their silty clay loam soil, which gave a temperature variability generally less than 1.5K, an order of magnitude accuracy in the hydraulic conductivity was suggested. The present simulation indicates that the hydraulic conductivity of sandy soils needs to be known with a better accuracy than for clayey soils.

SUMMARY AND CONCLUSIONS

A soil-plant-atmosphere model for corn together with the scaling theory were used to study the sensitivity of spatial variation of canopy temperature to soil texture and crop rooting characteristics. The temperature variability was shown to be more pronounced in a sandy soil as opposed to a clayey soil, and in more deeply rooted crop as opposed to a shallow rooted crop. If irrigation scheduling is done based on a fixed canopy temperature variability then the level of depletion of available water would vary among fields differing in soil texture and crop rooting characteristics. Sandy soils would appear to be more amenable to irrigation scheduling via canopy temperature

variability as compared to clayey soils if 70% depletion of available water is recognized as a criteria for need of irrigation.

In clayey soils the spatial variability of canopy temperature would generally be less than 1 K, suggesting that infrared radiometric observations with differing spatial resolutions (for example, via ground based and air-borne radiometers) should be comparable directly. The spatial variability of canopy temperature in sandy soils could be significant enough to require more prudence in comparing radiometric data with differing spatial resolutions. In attempting to 'calibrate' space-borne radiometric observations having a coarser resolution by a ground-based observation one needs to be cautious about the higher order heterogenieties of soil moisture which could be induced by a rainfall event, in addition to the canopy type variations and the presence of bare soils. The effect of these higher order (or forced) heterogenieties will be discussed elsewhere.

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CAPTION TO THE FIGURES

Figure 1. Schematic illustration of the soil-plant-atmosphere model used in the present simulation. The root water uptake is modeled by the van den Honert's (1948) equation; the resistance analogue model of Federer (1979) is used for changes in plant water storage; Monteith's (1965) equation is used for transpirational flux. The plant water potential (ψ) is calculated as the potential which conserves the water flux in the system. Arrows indicate the direction of water flow. Successive steady states are simulated with dynamic equations for soil water and plant water storage.

Figure 2. Comparison of simulated (solid line) and observed diurnal trends of the leaf water potential. The observations in (2a) are from Reicosky *et al.* (1975), and in (2b) from Reicosky and Lambert (1978). Concurrently observed microclimatic data are also shown. Plant-to-plant differences in the observed potentials are indicated by 'error' bars.

Figure 3. Simulated relationships between leaf and soil water potentials at 1300 hour. The microclimatic data in figure 2b is used in this and all other simulations. The results are for two soil textures and two rooting characteristics. Z_{eff} and L_A refer to effective rooting depth and root length per unit area, respectively.

Figure 4. Dependence of the plant water stress index (PWSI, defined in eqn. 10) on the soil water potential. The depletion levels of 65% and 70% of available water are annotated on the figures, (a) for clay loam, and (b) for loamy sand.

Figure 5. The simulated relationship between leaf and soil water potentials at 0600 hour (just before sunrise) for the clay loam soil. The meaning of R1 and R2 are clarified in Figure 3. A 1:1 line is drawn to show that the leaf water potentials are generally lower than the soil water potential.

Figure 6. Simulated leaf stomatal resistances and soil water potentials at 1300 hour for various days of the simulation. For the meaning of rooting characteristics, R1 and R2, refer to figure 3.

Figure 7. Simulated relationships of canopy-air temperature differences with soil water potentials at 1300 hour. For the meaning of rooting characteristics, R1 and R2, refer to figure 3.

Figure 8. A simulated range of canopy temperatures at 1300 hour of various days in the simulation. A depletion of 70 percent of available water is indicated in the figures. The rooting characteristics R1 and R2 are clarified in figure 3.

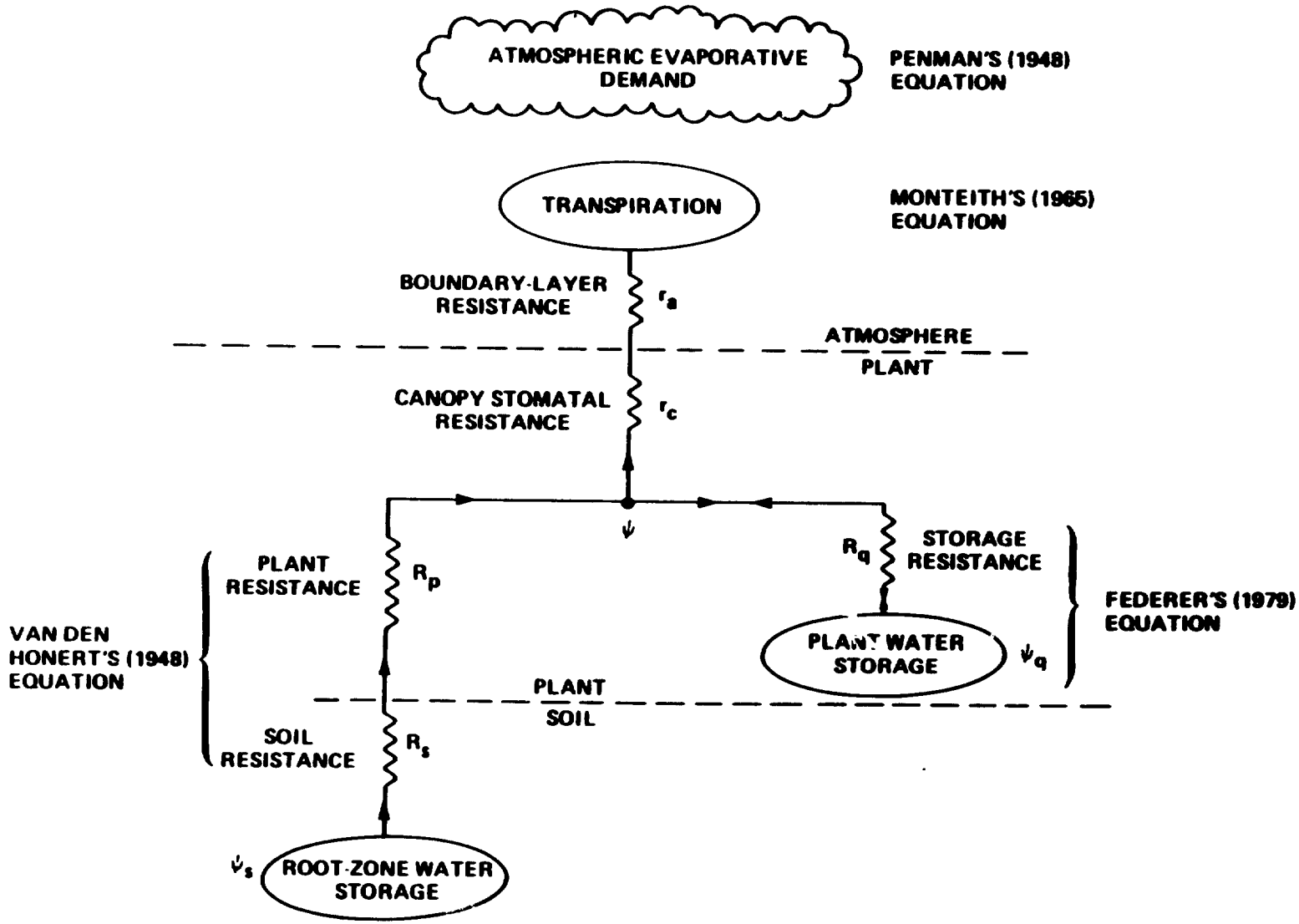

Figure 1.

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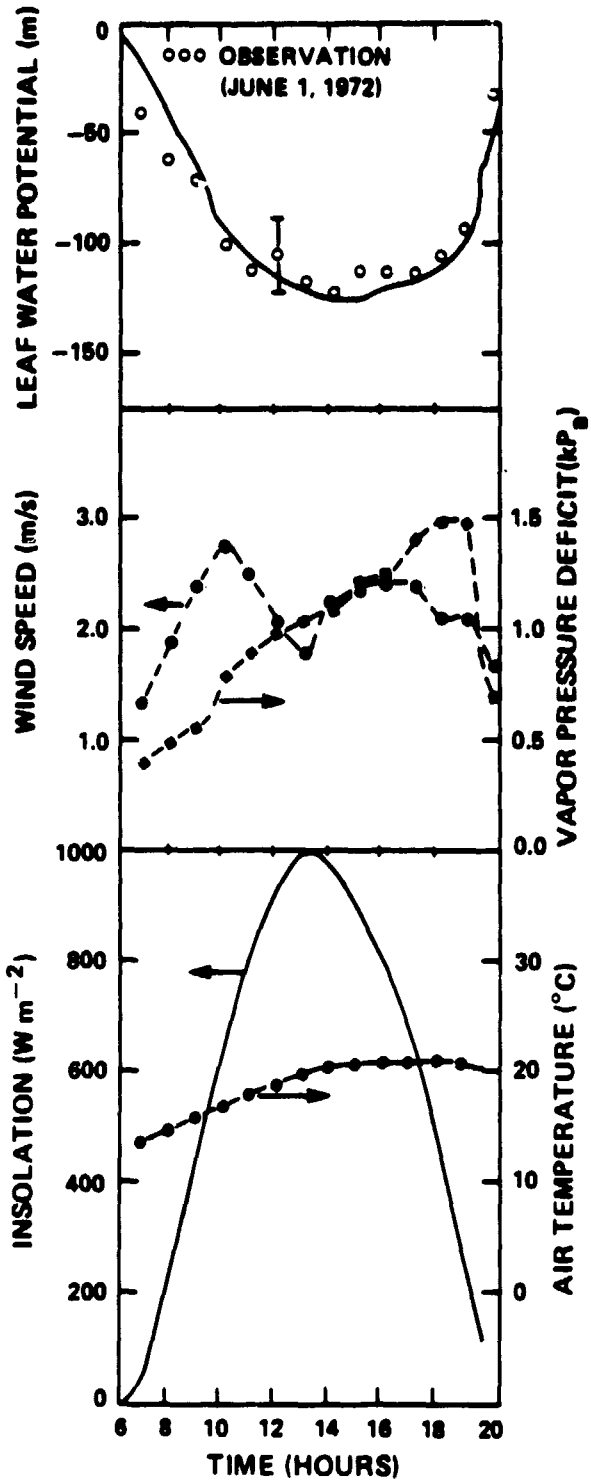


Figure 2a.

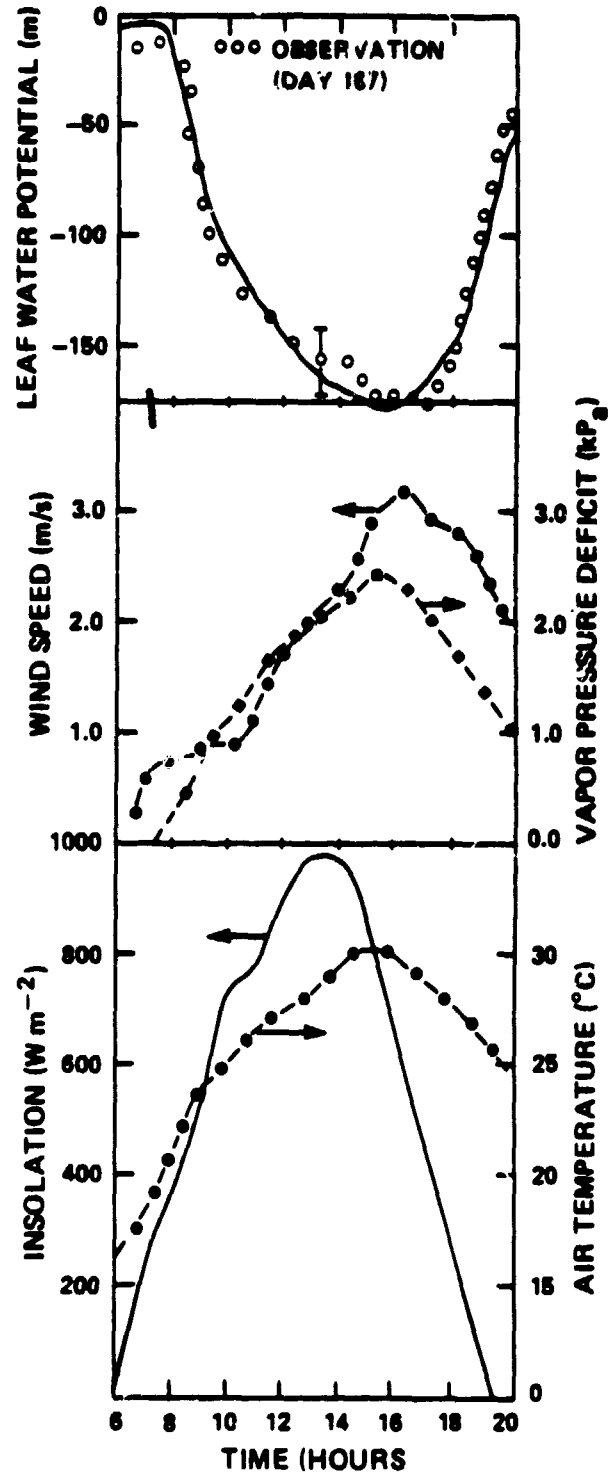
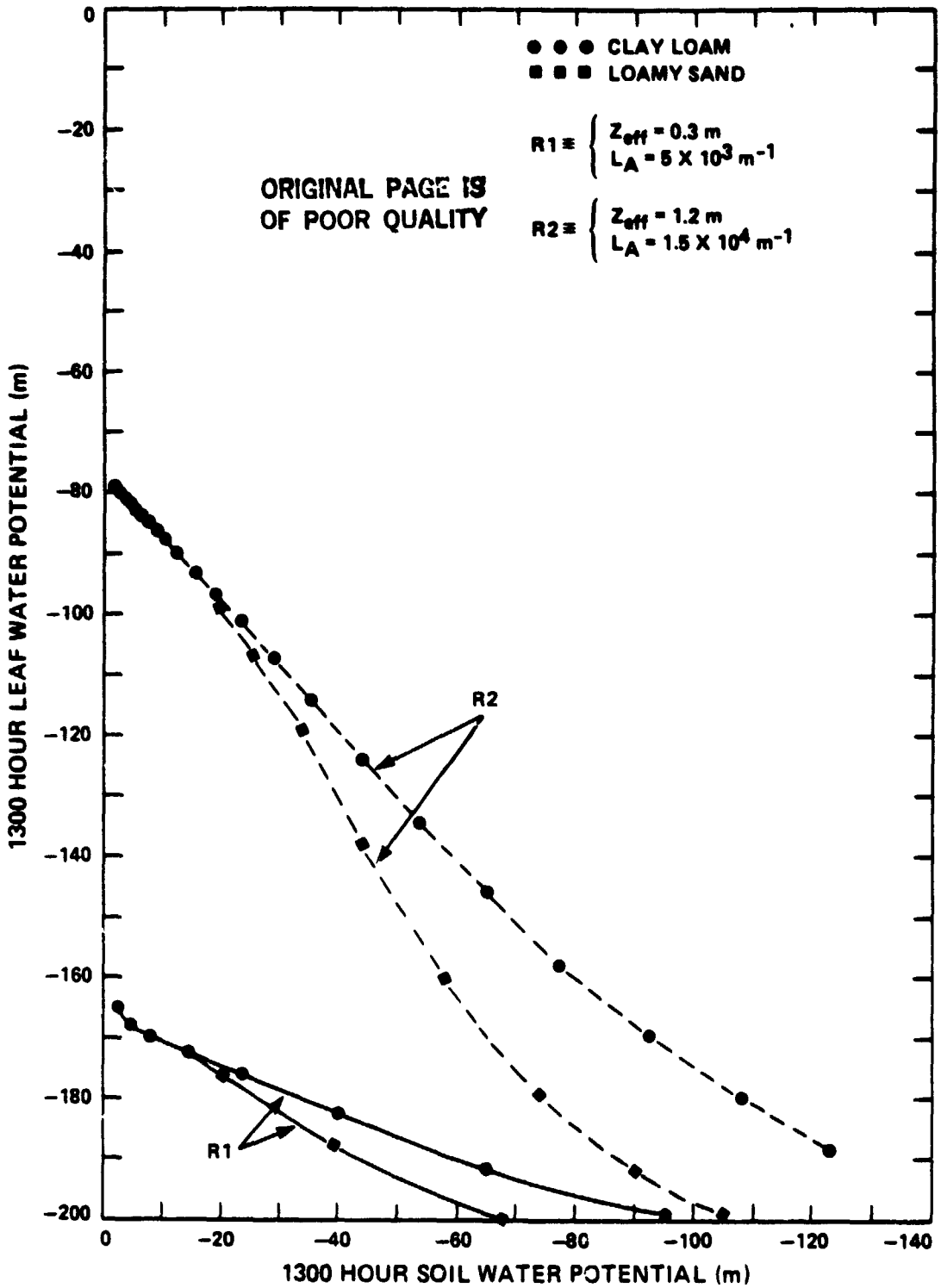


Figure 2b.


CLAY LOAM
LOAMY SAND
R1 ≡ { Z_eff = 0.3 m, L_A = 5 X 10^3 m^-1
R2 ≡ { Z_eff = 1.2 m, L_A = 1.5 X 10^4 m^-1
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R2
R1
1300 HOUR LEAF WATER POTENTIAL (m)
1300 HOUR SOIL WATER POTENTIAL (m)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200

Figure 3.

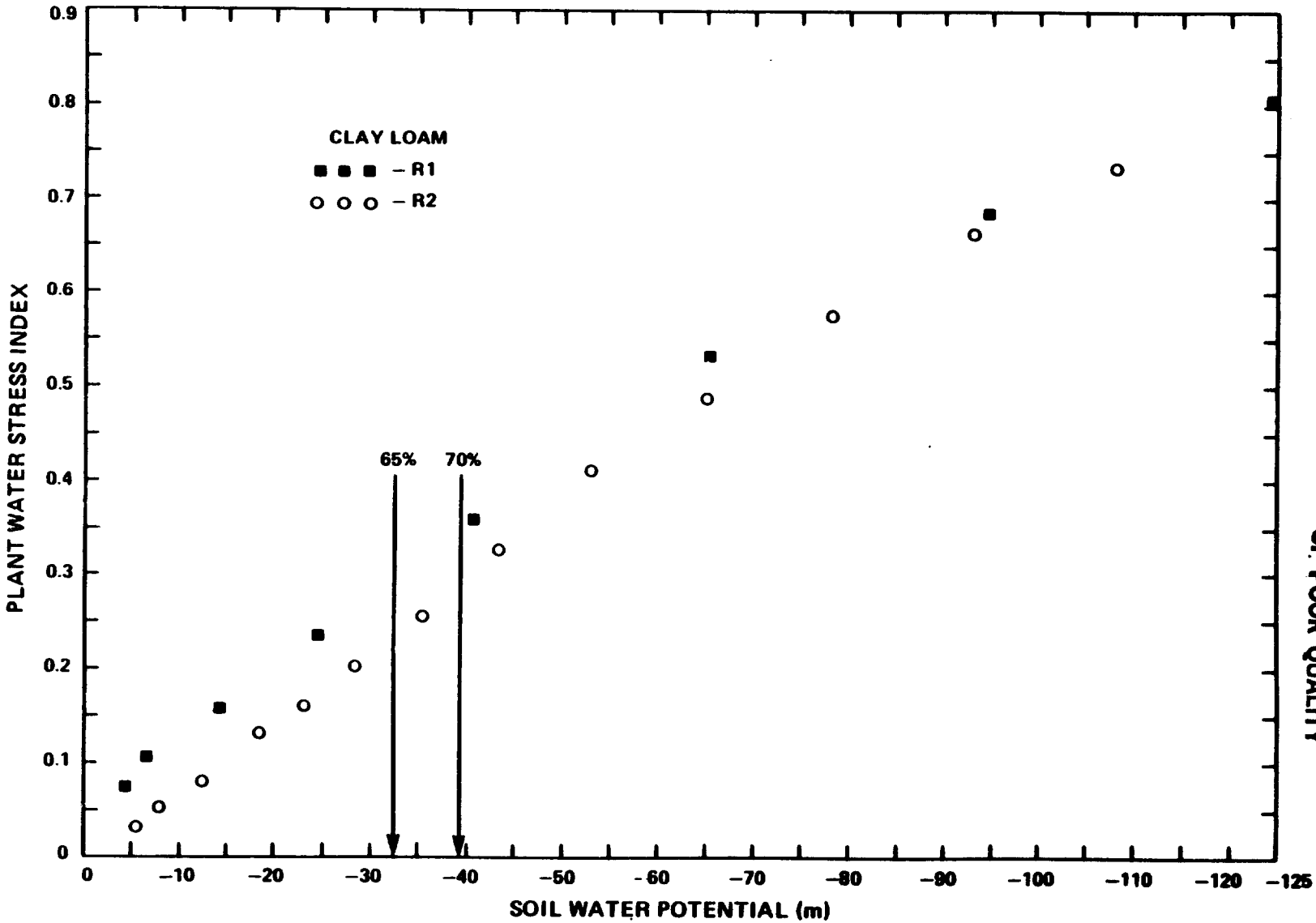

Figure 4a.

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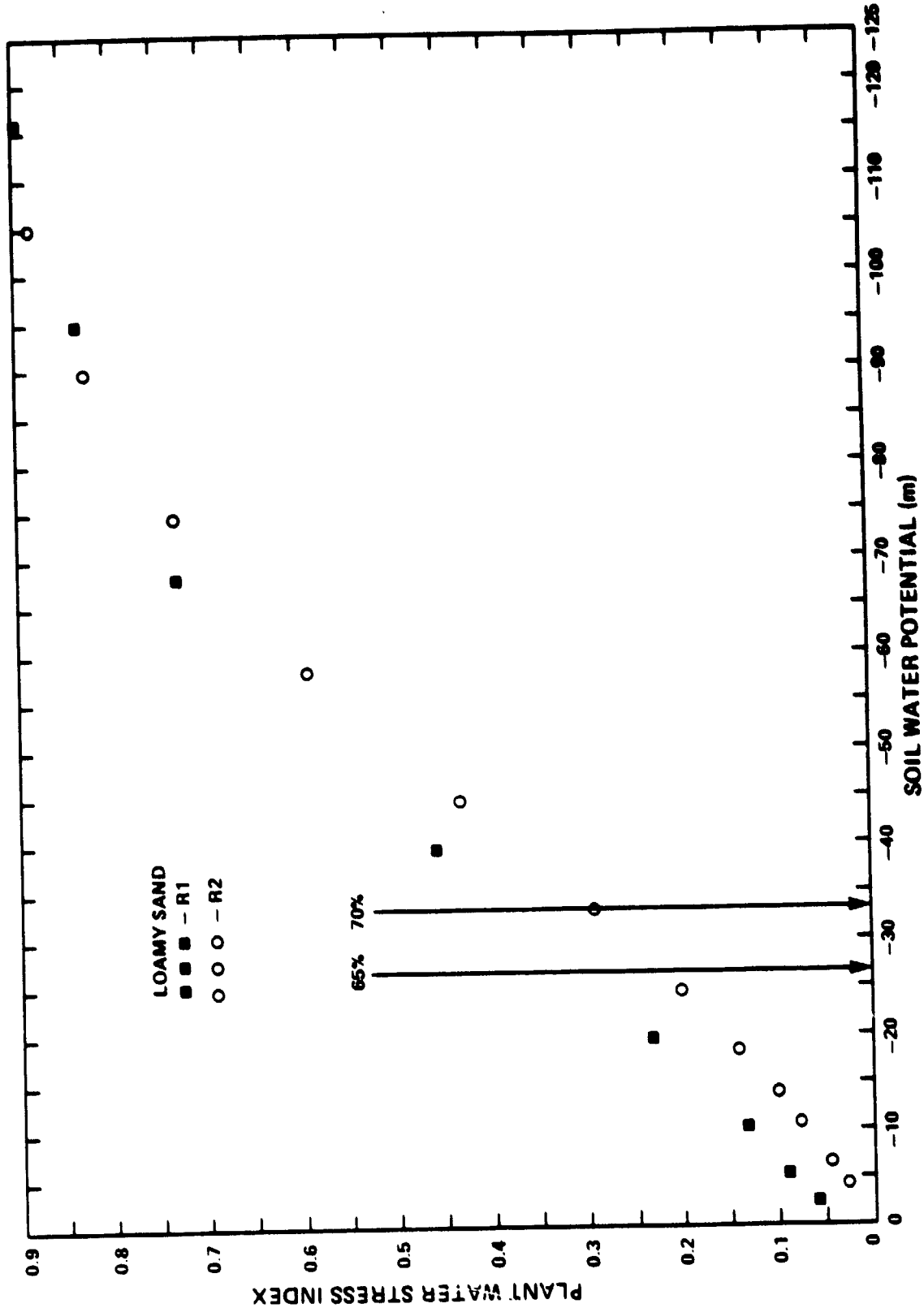

Figure 4b.

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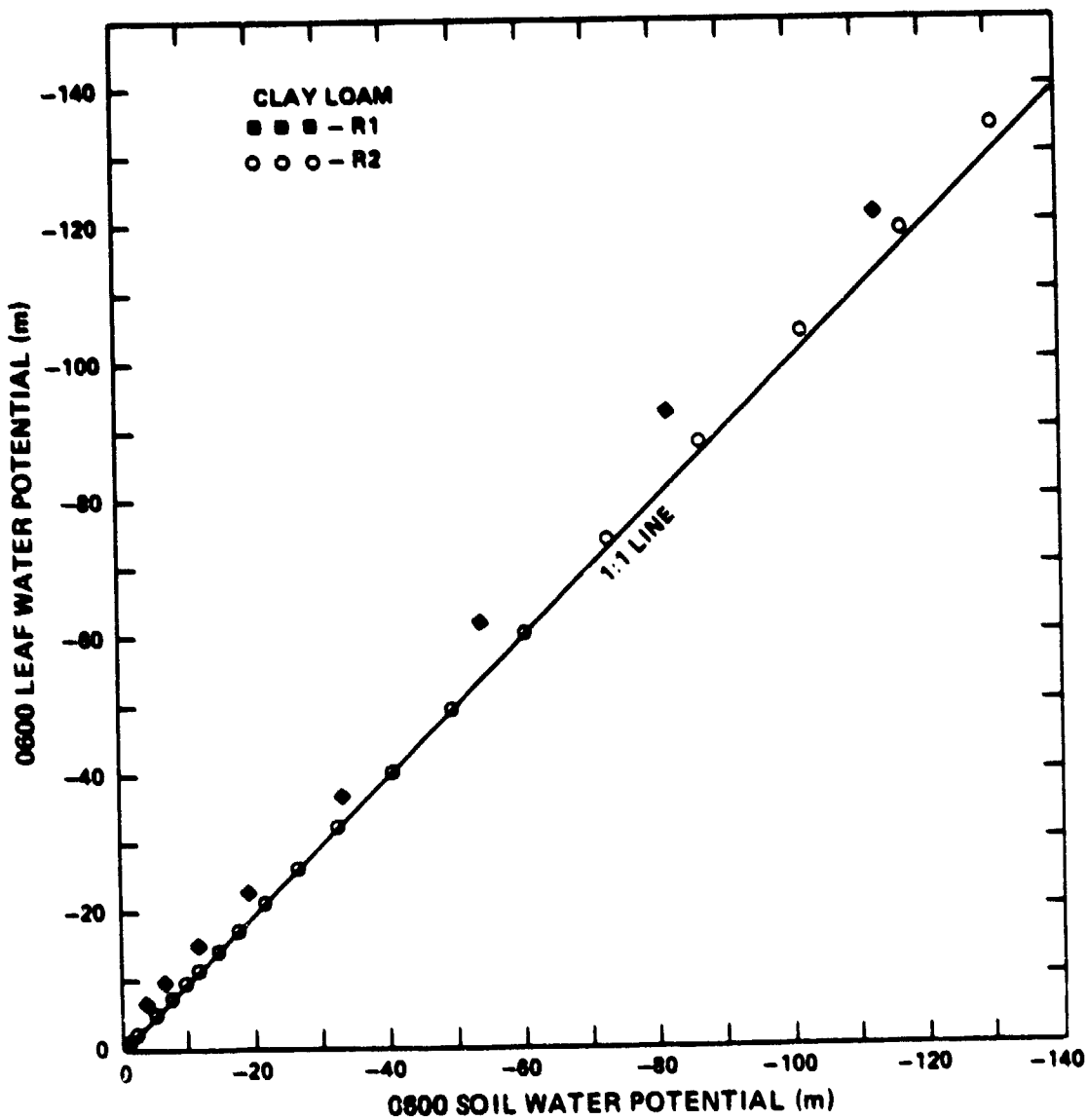

Figure 5.

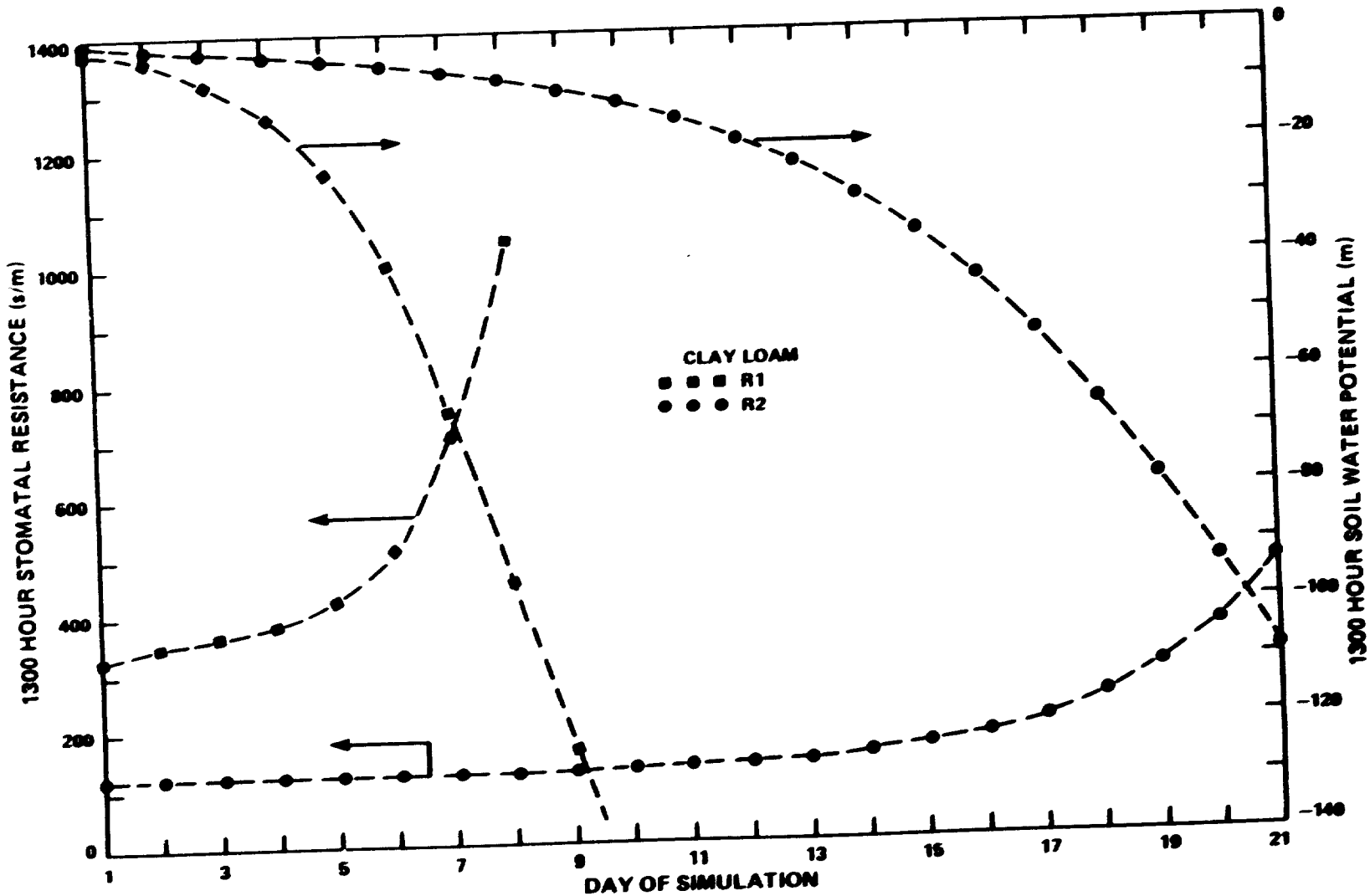

Figure 6.

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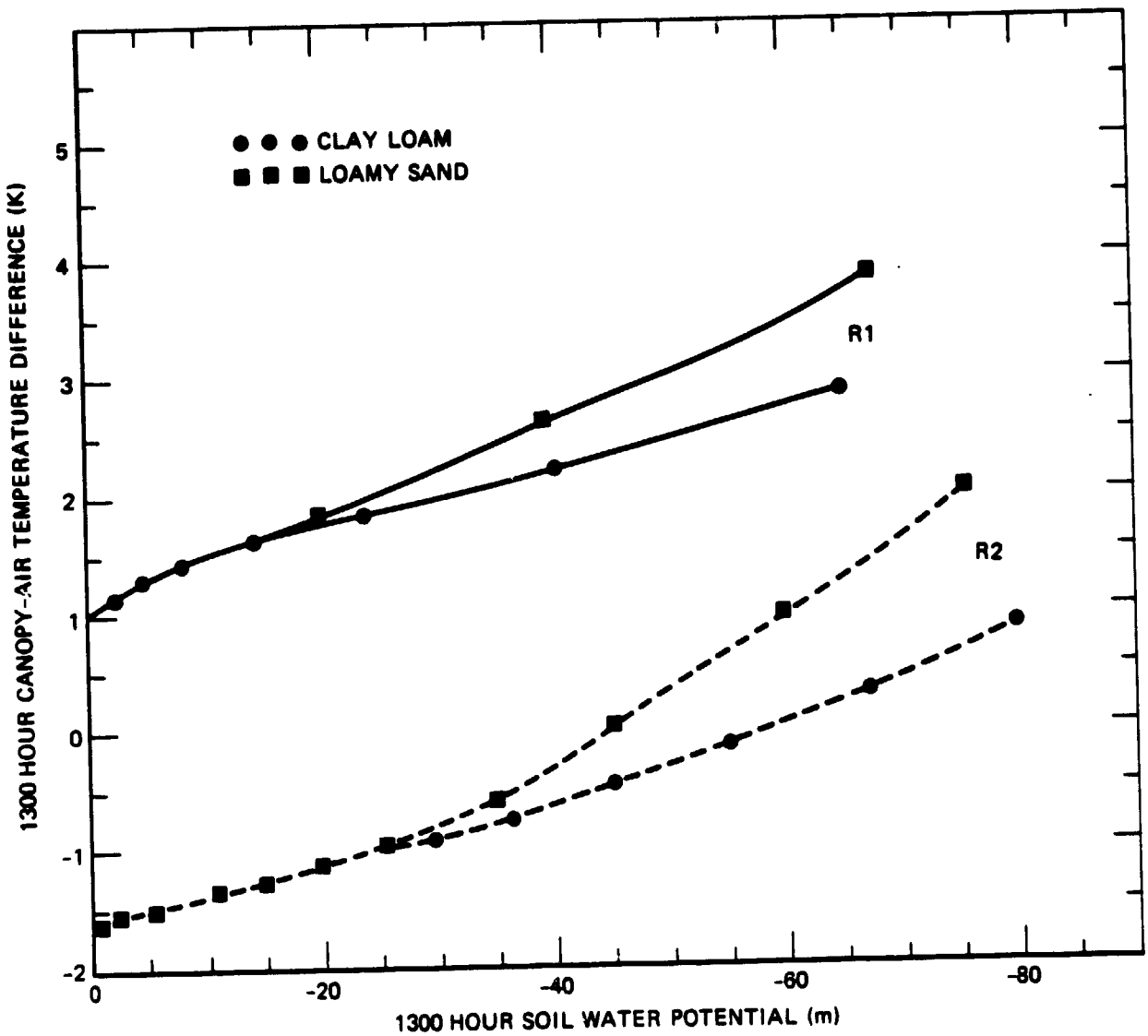

Figure 7.

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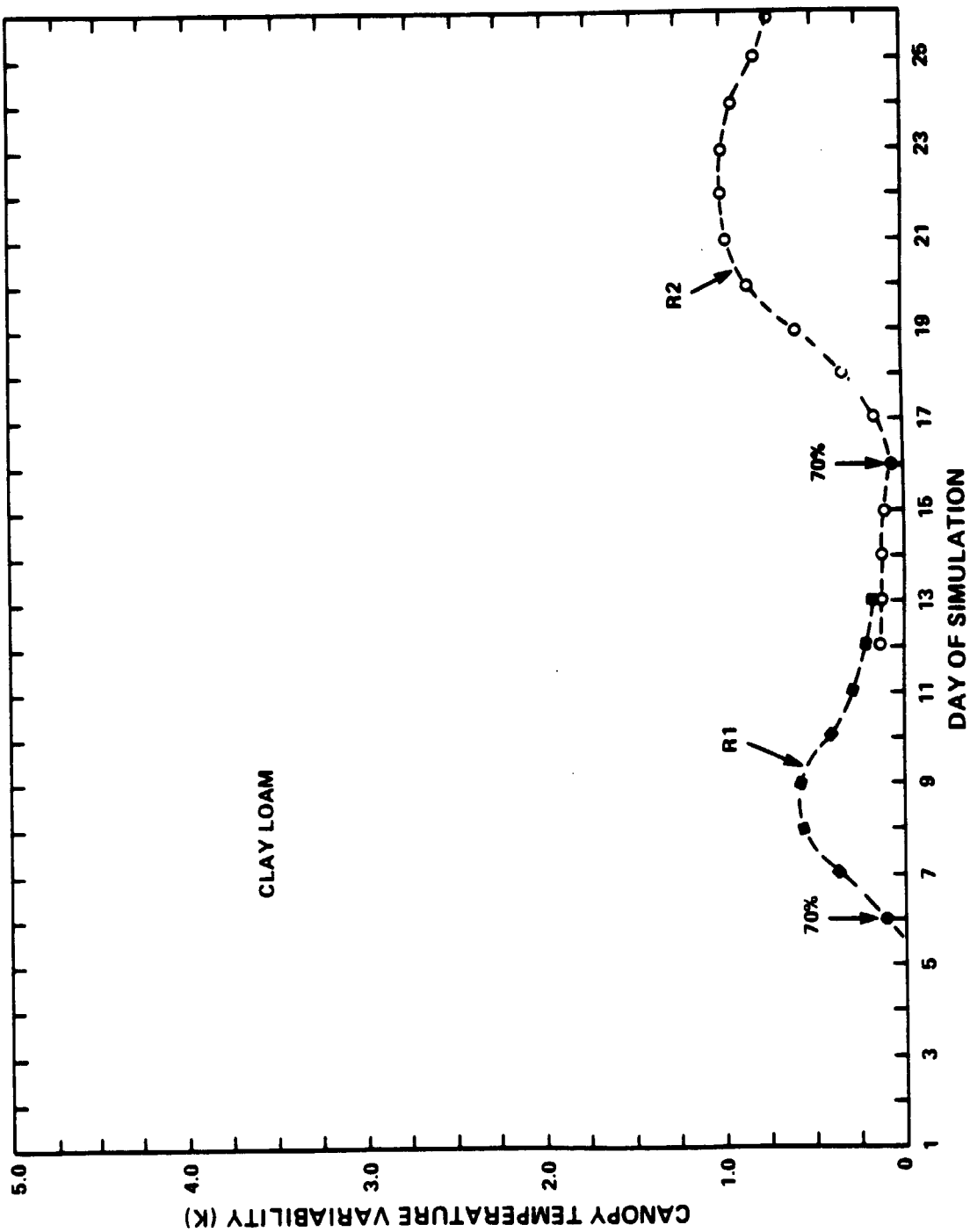

Figure 8a.

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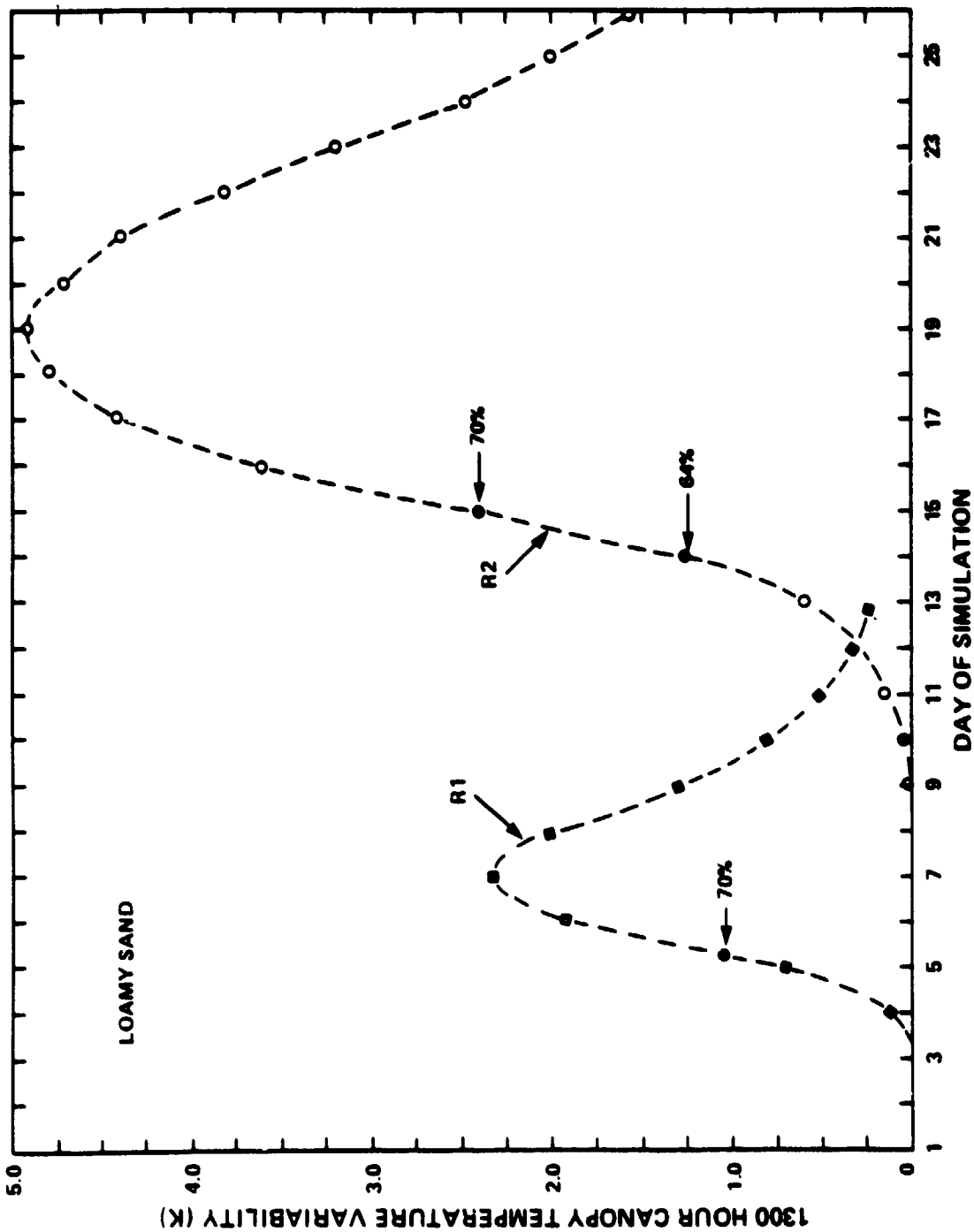

Figure 8b.