communications in
soil science
and
plant analysis

Communications in Soil Science and Plant Analysis

Communications in Soil Science and Plant Analysis presents current and important papers, symposia, and reviews in all areas of crop production, devoting particular attention to the mineral content of soils and plants and plant nutrition. This unique publication fully examines soil chemistry, minerology, fertility, soil testing, soil-crop nutrition, plant analysis, mineral metabolism and plant physiology, methods of soil and plant analysis, liming and fertilization of soils, and techniques for correcting deficiencies. International in scope and application, the journal considers plants and soils of all climates, including subtropical and tropical. In addition, its direct reproduction format permits rapid publication of important developments, keeping readers abreast on research at the frontiers of their field.

Whether engaged in basic or applied investigations or in communicating techniques and information directly to growers, **Communications in Soil Science and Plant Analysis** provides an excellent source and forum for agronomists, horticulturalists, floriculturalists, and foresters concerned with increasing crop yields.

COMMUN. IN SOIL SCI. PLANT ANAL., 15(9), 1111-1134 (1984)

MEASUREMENT VARIABILITY IN SOYBEAN WATER STATUS AND SOIL-NUTRIENT EXTRACTION IN A ROW SPACING STUDY IN THE U.S. SOUTHEASTERN COASTAL PLAIN

KEY WORDS: Infrared thermometer, microclimate, pressure chamber, pressure bomb, diffusive resistance, canopy temperature

R. E. Sojka
Soil Scientist

C. R. Camp and J. E. Parsons
Agricultural Engineers

D. L. Karlen
Soil Scientist

USDA-ARS
Coastal Plains Soil and Water
Conservation Research Center
Florence, SC 29502
In cooperation with the
South Carolina Agricultural Experiment Station
Clemson, SC 29631

ABSTRACT

Full-season determinate soybean [Glycine max (L.) Merrill] was grown in the field in a humid climate for three seasons (1979-81). The objective was to examine variability in several methods of determining basic relationships between soil and plant water status in a range of canopy configurations and to examine treatment effects on soil-nutrient extraction. In each year, two cultivars, "Davis" (group VI) and "Coker 338" (group VIII) were planted in four row spacings. In 1980 and 1981 the experiment was expanded and split for irrigation and row orientation (N-S or E-W). Post-harvest soil samples were collected and analyzed to determine if irrigation, row spacing, or cultivar influenced K, Ca, and Mg extraction patterns.

0010-3624/84/1509-1111$3.50/0

During the growing seasons, parallel leaf diffusive resistance (R_s) was poorly correlated with xylem pressure potential (Ψ_x), canopy temperature (T_c), canopy minus air temperature (ΔT), leaf vapor pressure deficit (LVPD), and atmospheric vapor pressure deficit (VPD) in single factor correlations. Xylem pressure potential was highly correlated with T_c, ΔT, VPD, and LVPD, but was poorly correlated with soil water potential. Both Ψ_x and T_c were significantly affected by the imposition of shade from a 60% shading cloth within as little as 1 minute of shade imposition. The impact of cultivar on seasonal Ψ_x was significant and was nearly half the magnitude of the observed difference caused by irrigation. Irrigation raised Ψ_x by only 2.2 bars over the two-year observation period, in spite of large differences in soil water potential when irrigation was imposed. The impact of canopy configuration was not measureable in any water relations parameter except infrared-determined T_c. Correlation of T_c and Ψ_x was significantly more reliable when limited to a single variety, row spacing, and row orientation. Aspect of infrared temperature measurement also significantly affected observed T_c.

Analysis of post-harvest soil samples indicated that narrow (50 cm) row spacing in 1980 and irrigation in 1981 significantly decreased post-harvest Mehlich No. I extractable K, but none of the cultural practices influenced extractable Ca or Mg at P(0.05). In 1980, extractable K within soybean rows was significantly greater than between rows. Similar trends were observed for Ca and Mg in 1980 and for all 3 nutrients in 1981, but those differences were not significant at P(0.05). Overall, these measurements quantify the difficulty in relating soil and plant water status and identifying nutrient extraction patterns in sandy soils within the humid U.S. Southeastern Coastal Plain.

INTRODUCTION

Crop water status and nutient management in the Southeastern Coastal Plain are greatly affected by numerous factors. Water-holding capacity of the major soils is commonly 10-15 cm or less of available soil water per meter of profile[36,39]. Soil cation exchange capacity is usually below 5 meq/100 g of soil. Rainfall, though frequently intense, is generally intermittent, often resulting in frequent cycles of drought and flooding. Wet periods can readily leach the weakly adsorbed cations. Growing season mean daily relative humidity is generally high and is accompanied by a nearly total absence of cloudless days. Various measurements have been used to assess the impact of irrigation or other cultural or environmental factors on the resulting water status of crops.

In recent years, three commonly reported measurements of plant water status have included measurements of: (1) leaf diffusive resistance (R_s) using diffusion porometers, (2) xylem pressure potential (Ψ_x) using pressure chambers or plant water potential (ψ_p) using psychrometers, and (3) canopy temperature (T_c) using thermistors, thermocouples, or noncontact infrared thermometers. These techniques have been developed in predominantly dry environments, and only limited data have been reported for field results with determinate soybean grown under humid conditions. Only limited work has been undertaken to identify the sources and quantify the magnitude of error associated with these techniques when employed in the field under humid conditions such as those which prevail in the U.S. Southeastern Coastal Plain and other humid soybean production areas worldwide.

The relative insensitivity of these techniques in discriminating large differences in field water regime in determinate soybean has proven puzzling to researchers. Reicosky and Deaton[45] reported observational anomalies in Ψ_x of irrigated 'Davis' and 'McNair 800' soybean associated with transient cloudiness during a typical diurnal study. There was no response, however, in the nonirrigated Davis and only partial response in nonirrigated McNair 800. In addition, even though the midday T_c of the nonirrigated Davis was 7 C higher than the irrigated, Ψ_x was not appreciably different between the irrigation regimes for either variety. Sojka et al.[53] showed that except for a small rise in Ψ_x shortly after irrigation, 'Lee 74' soybean quickly reached Ψ_x levels similar to their nonirrigated counterparts. A similar response was observed by Jung and Scott[29] for 'Forrest' soybean. Mean seasonal midday leaf diffusive resistance in Jung and Scott's study were 0.6 sec cm^{-1} and 2.7 sec cm^{-1} for irrigated and nonirrigated treatments, respectively. They found that irrigation had only a small effect on Ψ_x as well. Mean seasonal predawn Ψ_x was -4.2 and -5.2 bars and midday values were -11.6 and -12.9 bars for irrigated and nonirrigated treatments in each case, respectively. These differences are quite small in view of the large differences in soil water availability among treatments. In general, field determinations of R_s have seldom been cited for determinate soybean, particularly from humid environments.

In the southern U.S., aeration problems frequently arise with excess rainfall or unwanted rain following irrigation, or with fluctuating shallow water tables[7,8,21,31]. Greenhouse data recently collected for Lee soybean[48] indicate that R_s increases in response to low soil O_2 diffusion rates even in the presence of optimum soil water regimes. The same response has been documented for numerous other species[43,47,40,34,16,50]. Therefore, new concern must be expressed regarding interpretation of this traditional water-deficit related physiological indicator.

Since mean daily relative humidity (RH) in the Southeastern Coastal Plain is high during the growing season, often above 80%, it is conceivable that R_s may be more difficult to assess under field conditions where large vapor pressure deficits (VPD) are less common[49]. A better understanding of the impact of high humidity (low VPD) on other water status indicators could help assess the applicability of various meteorologically-based evapotranspiration models as they relate to irrigation scheduling in the Coastal Plain.

Jackson et al.[27] and Ehrler et al.[13] have demonstrated significant correlations between T_c and Ψ_x and have proposed using ΔT (T_c minus ambient temperature, T_A) integrated over time as an indicator of crop stress levels. While they have recently described methods for normalizing data from diverse experimental and environmental conditions[24,25,26], the impact of some simpler considerations on these relationships, such as canopy configuration or measurement aspect, have not yet been thoroughly investigated. The impact of haziness and intermittent cloudiness on the individual measurements and their interrelationships were analyzed theoretically[23], and a few shaded baselines reported[22], but extensive validation in field-grown crops has not been reported. A thorough evaluation of IR techniques has yet to emerge from humid locations. The latter point is especially important since Linacre[35] and Geiser et al.[15] suggest that the relationship of ΔT to VPD under well-watered conditions is not unique across environments, but is affected by both RH and radiation intensity. Such an effect could have a significant impact on the stress evaluation method proposed by Idso et al.[24,25] and Jackson et al.[26].

Despite these unknowns, there is already great interest in the use of the IR thermometer and the stress degree-day concept for consultant and on-farm use in the Southeast. Canopy configuration, transmissivity of the atmosphere (and thus radiation flux density at the leaf), RH, or aspect of measurement may influence either the observed values of Ψ_x, T_c, ΔT or the relationships of these factors to one another. Therefore, substantial error may result in accurately determining and integrating stress levels in the absence of simple, yet appropriate precautions.

Soil and plant water status ultimately influences nutrient extraction, absorption, and accumulation because of its effect on plant growth. DeMooy[12] stated that nutrient accumulation by soybean was proportional to the length of effective drought during a growing season and the portion of the root system located in water-depleted soil. Cation absorption is especially responsive to soil-water status because K is dependent upon diffusion and Ca and Mg are dependent upon mass flow for movement to soybean roots[37]. Uptake patterns for these cations showed different responses to water stress[30] presumably because those movement mechanisms differed. Uptake of K was much more responsive to soil water status[30] and has also been shown to be influenced by soybean root morphology[41]. However, information showing that field cultural practices which influence plant water status also influence post-harvest extractable nutrient concentrations is not readily evident within the literature.

It was with concern for these kinds of limitations that data were collected and evaluated from three years of soybean water relations studies conducted at Florence, South Carolina. Numerous observations of Ψ_x, R_s, T_c, ΔT, and VPD were recorded and related to one another under a variety of soybean conditions. The impact of those cultural management practices on the observations and on the relationship of the parameters to one another are presented and discussed. Post-harvest extractable nutrient concentrations are also related to the cultural management practices because of the influence that water status has on plant growth, development, and nutrient uptake in this physiographic region.

MATERIALS AND METHODS

Soybean were grown from 1979 to 1981 at the Coastal Plains Soil and Water Conservation Research Center in Florence, S. C. Determinate cultivars, 'Davis' (group VI) and 'Coker 338' (group VIII), were planted in a randomized complete block design with a split-block arrangement of treatments in four replicates on 1 May 1979. Four row spacings (102, 76, 51, and 36 cm) were used, with row spacing whole plots split for cultivar. Each cultivar subplot was 10.7 m long and 4 rows wide, except in the 36-cm row spacing, which had 5 rows per subplot. Rows were aligned in a NE-SW direction. The soil, a Norfolk loamy sand (fine-loamy siliceous thermic Typic Paleudults), was fallowed the previous year and prepared in the spring with cross-subsoiling to 45-cm depth and disking twice before planting. Fertilizer applied was 5-10-30 at 225 kg/ha. Weed control was achieved by pre-plant incorporation of trifluralin (α, α, α,-trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine) at 1.75 l/ha and timely cultivation and/or hand weeding. Plant population was 204,000 plants/ha. Soil matric potential (Ψ_s) was monitored with tensiometers in the row at 30-, 60-, and 90-cm depths which were read and serviced 2-3 times weekly.

In 1980, the experiment was expanded to include additional splits of row orientation (N-S and E-W) and irrigation. Plots were subsoiled and disked as in 1979 and were fertilized with 0-9-27 at the rate of 246 kg/ha. Weed control was the same as in 1979. Planting was on 7 May 1980, and population was 213,000 plants/ha. Tensiometers in 1980 were located in all Davis plots only, at 30-, 60-, 90-, and 120-cm depths both in the row and midway between the rows and were serviced and read 2-3 times weekly. Irrigation was initiated at bloom (1 August) and was accomplished by use of bi-wall drip tubing between plant rows at 36-cm spacing throughout the experiment. When operated at 0.69 to 0.83 bar pressure, water was uniformly "sprinkled" on the ground surface in a pattern approximately 50-cm wide (25 cm to each side of the drip line) giving a uniform distribution of water in the irrigated plots. In 1980 the plots were irrigated whenever the 30-cm tensiometers read 250 mb or whenever tensiometers at any depth read 500 mb. In 1981 irrigation was scheduled by a computerized water balance, but soil water tensions were not allowed to exceed 500 mb at any soil depth.

MEASUREMENT VARIABILITY IN SOYBEAN WATER STATUS

In 1981, experimental design was similar to that used in 1980. The 36-cm row spacing was deleted and drip tubing was moved to 50-cm spacing in the irrigated plots. Tillage was as in previous years. Fertilizer applied was 0-20-20 at 280 kg/ha. Weed control was with trifluralin at 1.75 l/ha, tank-mixed with metribuzin [4-Amino-6-(1, 1-dimethylethyl)-3 -(methylthio)-1,2,4-triazin-5(4H)-one] at the rate of 0.68 l/ha. Planting was on 12 May 1981. Plant population was 192,000 plants/ha. Tensiometer placement was as in the previous year, but in both cultivars in 1981.

Meteorological data were monitored automatically all three years with a computer-based data aquisition system[49]. Data were integrated over 30-min periods and printed at 30-min intervals. The weather station was located on turf approximately 100 m from the experimental site.

Canopy temperatures were measured in 1979 using thermistors taped to the abaxial mid-vein of the center leaflet of the most recently-matured trifoliate leaf not directly exposed to sunlight. In 1980 and 1981, canopy temperatures were measured using a Raynger II IR thermometer[1]. Temperatures by the IR thermometer were determined on cloudfree days or portions of days. Caution was exercised to bring the instrument into equilibrium with T_A before measuring T_c. An emissivity of 1.00 was used for all readings. The instrument was aimed at shallow angles and care was exercised to prevent inclusion of soil or other non-plant material in the instrument viewing field.

Xylem pressure potential (Ψ_x) was measured using a specially-built pressure chamber apparatus which allowed rapid sample changing and minimum tissue distortion at the point of sealing. Standard sampling involved selecting the uppermost, fully-expanded, fully sun-exposed mainstem trifoliate for pressurization. Petioles supporting the trifoliates were excised with a razor blade approximately 2 cm above their point of attachment to the mainstem. Samples were immediately placed in moistened plastic bags upon excision from the mainstem for transport from the individual plots to the pressure chamber. A standard pressurization rate of approximately 13.8 bars/min was used, and total time from excision to determination of end point seldom exceeded 2 min/sample.

Diffusive resistances of abaxial and adaxial leaf surfaces (R_{ab} and R_{ad}, respectively) were determined on the first and third leaf blades of each trifoliate, monitoring one surface per leaf blade[49]. Parallel leaf diffusive resistance (R_s) was calculated for each trifoliate using the equation:

$$1/R_s = (1/R_{ab}) + (1/R_{ad}) \qquad [1]$$

Leaf diffusive resistances were determined on the same trifoliates subsequently excised for determination of Ψ_x. The R_s determinations were made only in 1979.

To quantify the effect of fluctuating illumination on Ψ_x and infrared measurements of T_c, both Ψ_x and infrared determined T_c were measured on side-by-side plants before and after the imposition of shade on the canopy. The shading effect was created by positioning one of two 1.5 m x 1.5 m square shades in the canopy at right angles to the incoming rays of the sun. One shade was fully opaque (full shade); the second shade was made of a single thickness of commercial greenhouse 60% shade cloth (half-shade). Shade effects on response of the two cultivars were determined on different days for each cultivar.

Effects of cultural practices on post-harvest extractable K, Ca, and Mg concentrations were measured in 1980 and 1981. Soil samples were collected from within and between soybean rows which were spaced 50 or 100 cm apart in the N-S-oriented blocks in December of each year. Samples from 0-15-, 15-30-, 30-60-, and 60-90-cm depths were air dried, crushed to pass a 2 mm screen, extracted with Mehlich I solution, and analyzed for K, Ca, and Mg concentrations using atomic absorption spectrophotometry. Data were analyzed statistically using analysis of variance for a split, split, split, split plot design.

RESULTS AND DISCUSSION

Rainfall and irrigation for 1979, 1980, and 1981 are presented in Fig. 1. Rainfall during the growing season was 679, 461, and 453 mm, respectively, for 1979, 1980, and 1981. In addition, 355 and 220 mm of irrigation water was applied in 1980 and 1981, respectively, the two years when an irrigation treatment was included in the experiment. Abnormally high rainfall in 1979 was primarily caused by a hurricane in September which produced 169 mm of rainfall in one event. Incoming radiation, humidity, air temperature, and pan evaporation for 1979, 1980, and 1981 are presented in Fig. 2. Daily incoming radiation and pan evaporation were similar for the three years of the study, but

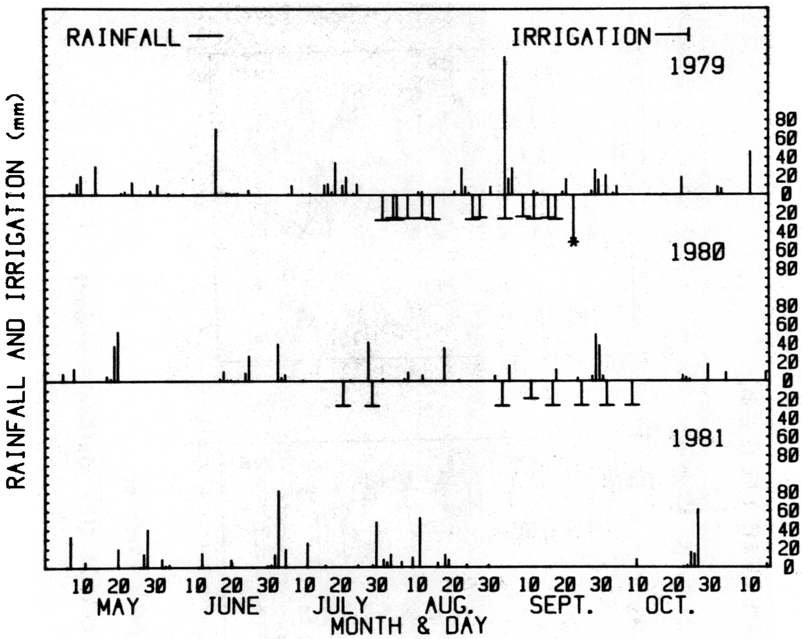

Fig. 1. Rainfall and irrigation for the 1979, 1980, and 1981 growing season for Florence, S.C. Asterisk on the September 1980 irrigation indicates an approximate value resulting from an irrigation metering error.

extremely variable, reflecting the high incidence of cloudy and hazy conditions during the growing season. Mean daily air temperature was similar for all three years except that it was slightly higher during the last half of the growing season in 1980 than for the other two years. Mean daily relative humidity was slightly higher in 1979 (averaging about 80%) than in the other two years when it averaged about 70%. Overall, the weather during 1979-81 reflected normal conditions prevailing in the Southeastern Coastal Plain.

Diffusive Resistance

In our observations, R_s did not correlate well with atmospheric vapor pressure deficit (VPD) or leaf vapor pressure deficit (LVPD), as defined by Burrows and Milthorpe[6]. In addition, R_s could not be satisfactorily correlated with any other single plant water status

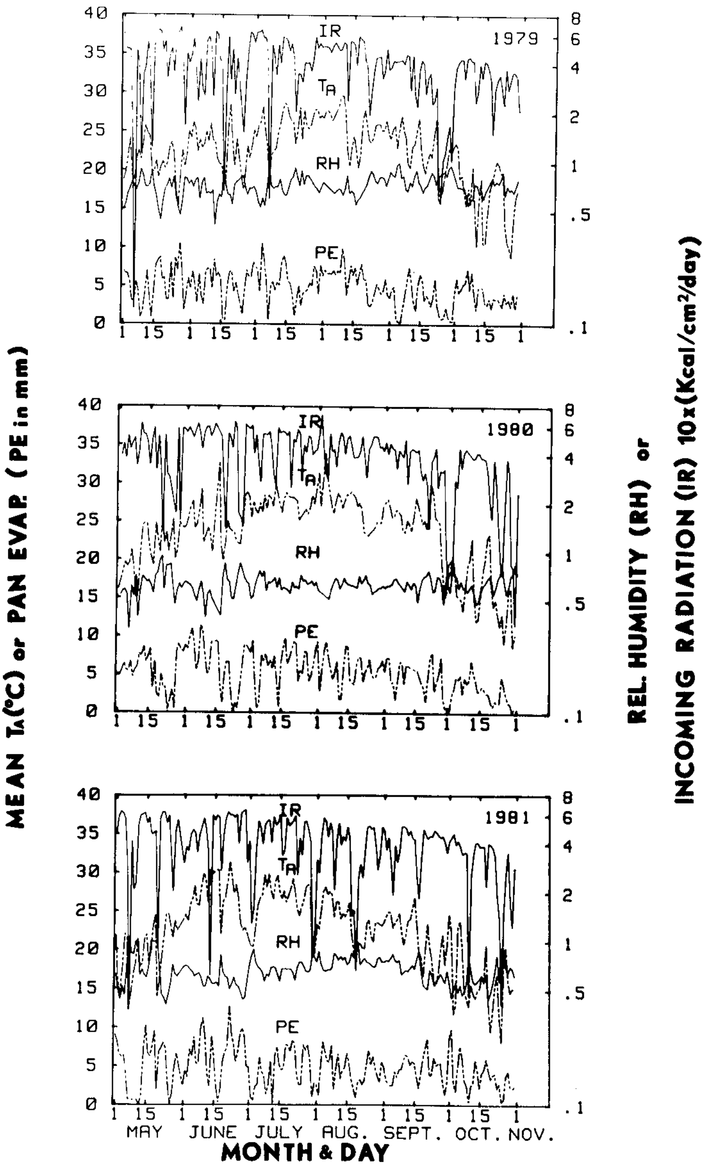

Fig. 2. Temperature (T_s), pan evaporation (PE), relative humidity (RH), and incoming radiation (IR) for the 1979, 1980, and 1981 (top to bottom) growing season for Florence, S.C.

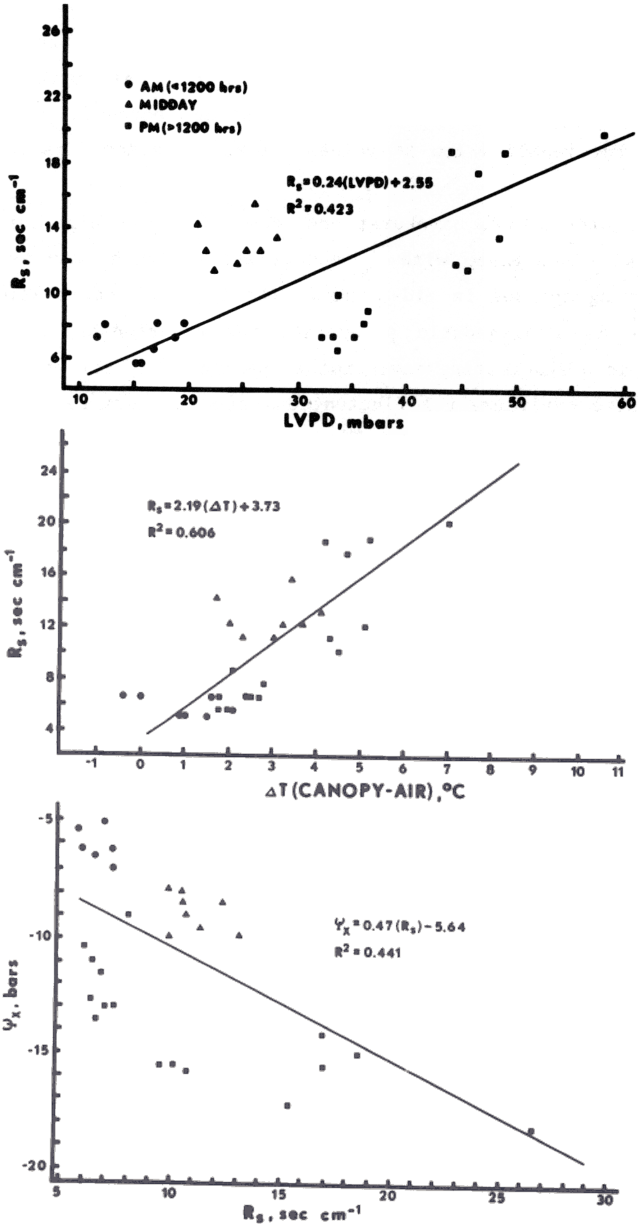

Fig. 3. The relationship between parallel leaf diffusive resistance (R_s) and leaf vapor pressure deficit (LVPD) and canopy temperature minus air temperature (ΔT) and between xylem pressure potential (Ψ_x) and R_s.

indicator (Fig. 3) or with Ψ_s. Successful correlation of R_s with other factors in the environment has not been widely reported for field observations with soybean. Brady et al.[5] fit curves to relationships of R_s with soil water potential and potential evapotranspiration, but reported low R^2 values for the relationships (all below 0.4).

In a later study, Sivakumar and Shaw[46] reported high correlation of stomatal conductance with Ψ_s and relative growth rate using data from a drying episode in mid-summer. But for this correlation to be meaningful as a diagnostic parameter, the relationship must remain good even in a fluctuating environment, particularly for physiographic regions where environmental fluctuations are the norm rather than the exception. Hatfield and Carlson[18] presented data which showed that R_s remained almost unchanged as photosynthetic photon flux density varied from 25 to 200 NE cm^{-2} sec^{-1}. In another paper, Carlson et al.[9] presented several sets of data relating leaf conductance to leaf water potentials, none of which resulted in satisfactory R^2 values when considering the two factors alone. Turner and Begg[57] point out that stomatal closure is also affected by species, preconditioning, and humidity.

Substantial scatter has been reported for field observations of R_s in a number of species for various reasons[58,51,52,28,54,32,33]. Various problems relative to porometer performance, and design, and to application of theory have been investigated[4,17,2,3,10]. Raschke[42] reported stomatal closure does not occur gradually in response to stress, but rather occurs abruptly upon reaching a stress threshold. Similar conclusions were drawn by Stange et al.[55], Turner and Begg[57], and Zur et al.[60].

In addition, various nonwater-stress related stomatal stimuli (e.g. light intensity, plant growth regulating chemicals, soil O_2, etc.) interfere with and complicate interpretation of R_s. O'Toole and Chang[38] concluded unequivocally that measurement of R_s in the field was subject to too much intrinsic variability and artifactual confounding to be a useful stress indicator in their rice program. It would seem that in view of the difficulty in relating R_s to other water status indicators reported in field experiments that R_s, at best, should be measured and interpreted with great caution with reference to water stress in humid environments. This is particularly true where numerical values of R_s are used outside the limited comparative context of the individual experiments from which they were derived.

Xylem Pressure Potential

In this study Ψ_x was poorly correlated with soil matric potential (Ψ_s) for the pooled irrigated and nonirrigated data, which represented a Ψ_s range of from nearly 0 to -800 mbars. Regression analysis was performed separately for the two varieties and the two years, 1980 and 1981. Correlation of individual Ψ_x values with the mean Ψ_s of the 30-and 60-cm depths for the row and row-middle tensiometer locations was attempted. Results were similar for all cases, with R^2 values ranging from 0.18 to 0.20. Reicosky et al.[44], while working on the same soil with corn under similar environmental conditions, also suggested that Ψ_x was a poor indicator of plant water stress. They found that with corn R_s was more sensitive than Ψ_x to changes in Ψ_s. In a greenhouse soybean study, Heatherly et al.[19] found a high correlation of Ψ_x with pre-sunrise Ψ_s when data were analyzed for single, dry-down periods. As with R_s, correlation of Ψ_x with Ψ_s can only be truly useful if it can be generalized over a prolonged time period in a fluctuating environment.

Xylem pressure potential (Ψ_x) was highly correlated with T_c, ΔT, and VPD with R^2 values of 0.84, 0.67, and 0.90 for the three relationships, respectively, in 1979[49]. The Ψ_x values used to compile these correlations were taken from a highly restrictive set of environmental conditions which limited observation to unusually clear days or portions of days. Additional observations of Ψ_x made in 1980 and 1981, however, indicate that Ψ_x measurements can be subject to significant errors due to factors in the field environment which are difficult to control and are often overlooked when making large numbers of observations on a routine basis. One such factor is the obstruction of sunlight by haziness or the occurrence of transient cloudiness To estimate the possible magnitude of such errors, Ψ_x was determined for side-by-side plants before and after the imposition of shade on the canopy. The effect of shade imposition for 0-, 1-, and 5-min durations on observed Ψ_x is presented in Table 1. As little as one

TABLE

Effect of intensity and duration of shade on Ψ_x and IR-determined T_c; and effect of illumination aspect (I = illuminated side of canopy; S = shaded side of canopy) on IR-determined T_c. Each cultivar was observed on different days. Each value is the mean of 9 observations.

Cultivar	Davis		Coker 338	
Shade intensity	½ shade	full shade	½ shade	full shade
Duration (min)				
0	-6.1 a	-6.2 a	-8.0 a	-7.7 a
1	-5.8 ab	-5.2 b	-7.0 b	-6.7 b
5	-4.9 b	-4.8 b	-6.2 c	-6.0 b
*DMRT @	10%	1%	5%	5%

Canopy temperature (T_c) °C

Cultivar	Davis		Coker 338	
Shade intensity	½ shade	full shade	½ shade	full shade
Duration (min)				
0_I	26.9 a	26.4 a	29.3 a	29.7 a
0_S	26.0 b	25.4 b	28.4 b	28.9 b
1^S	24.1 c	24.3 c	27.1 c	26.7 c
5	24.0 c	23.6 c	26.6 c	25.5 d
DMRT @	5%	5%	10%	5%

*Duncan's multiple range test at the specified level of probability. Values in the same column with common letters are not statistically different.

minute of half-shading was enough to create significant deviations of Ψ_x from the nonshaded determination. Recovery times were estimated (nonquantitatively) to be approximately 5 min. These results parallel the earlier limited findings of Reicosky and Deaton[45]. It should be noted that the number of days each growing season with acceptably uniform observing conditions are severely limited under the cloudy afternoon skies of the Southeast. Although afternoons correspond with maximum stress, they also generally correspond with the onset of scattered-to-total cloud coverage resulting from the rise of the humid local air masses upon midday heating of the ground surfaces.

At least two other facets of the Ψ_x observations made over the three-year course of the study point to problems of interpreting and utilizing Ψ_x measurements in determinate soybean. The overall mean seasonal Ψ_x for irrigated and nonirrigated plots were -8.6 and -10.8 bars, respectively, averaged over the two years of the irrigation split. This small (2.2 bar) Ψ_x difference points to poor resolution of water deficits, particularly in view of the severity of the drought in 1980. In addition, the resolution of actual water deficit is worse than immediately apparent from the 2.2 bar difference, since pressure chamber observations were not made shortly after rainfall, but were, in fact, delayed until higher stresses could be expected in the non-irrigated treatment, as reflected by Ψ_s monitoring.

Various explanations have been offered to explain the poor resolution of plant water status indicators in the face of dramatic differences in soil water regimes among treatments. Jung and Scott[29] proposed that stomatal closure under water stress reduced water loss rates sufficiently to maintain relatively high Ψ_x even in the face of severely limiting soil water regimes in soybean. The mean seasonal R_s of 2.7 s cm^{-1} of nonirrigated soybean reported in their work, however, is quite low, raising some question as to the degree to which it could limit transpiration. Zur et al.[60], for example, showed that in soybean R_s had a narrow range (from slightly less than one to nearly 4 s cm^{-1} over a Ψ_p range of -10 to -18 bars; only at the -18-bar stress level was significant stomatal closure apparent from R_s measurements. Several researchers[20,11,56,14] have shown that as transpirational demand increases, plants experience a reduction in root diameter in response to the increased xylem tension. This can occur at relatively high Ψ_s, bringing about reduction in root to soil water-film contact, and, they proposed, lower Ψ_x due to the increased resistance to water entry into the root. Such a response would cause well-watered plants to have lower Ψ_x than otherwise expected. Furthermore, the effect of reduced root diameter on well-irrigated roots would be much more pronounced than an equal loss of diameter in dry soil since once the soil is dry, very little root-to-water film contact remains. The net result would be to impair the resolution of irrigation treatment differences.

Up to this point, our discussion of results has pooled the observations for the two cultivars used. However, each year, the cultivar 'Coker 338' produced a signficantly lower Ψ_x. The mean seasonal Ψ_x of the cultivars 'Davis' and 'Coker 338' for the three-year period were -10.9 and -12.0 bars, respectively. This is particularly disturbing when one recognizes that the magnitude of cultivar differences in Ψ_x is half the magnitude of irrigation induced differences in Ψ_x. Sojka and Parsons[49] also reported that Coker 338 had a lower osmotic potential than Davis.

Canopy Temperature

Factors found to influence Ψ_x also generally affected T_c as determined with the IR thermometer. In addition, canopy geometry and aspect of IR temperature determination were found to contribute to error as well. Table 1 shows that as with Ψ_x, T_c is rapidly affected by shading. Leaf temperatures decline rapidly even upon imposition of only half-shade. In addition to shading, it was found that aspect of the measurement, -i.e. aiming the thermometer at the illuminated side of the canopy (sun at one's back) vs. aiming at the shaded side of the canopy (sun at one's face), had a significant effect upon the temperature determination. In these comparisons, ΔT was not calculated because sensible heat of the atmosphere remained stable over the brief period of observation, and thus, any change in ΔT would be governed by the magnitude and direction of change in T_c.

As Fig. 4 demonstrates, the relationship between IR-determined T_c and Ψ_x is best defined over a limited range of canopy geometry. When combining all data pairs for the 1980 season, a poor R^2 value of 0.44 was obtained. By singling out a limited set of conditions (such as the 'Davis' cultivar at 102-cm row spacing), the relationship was substantially improved, giving an R^2 of 0.71. Similar results were also observed in 1981.

Vapor Pressure

Both VPD and LVPD are highly active in bringing about plant water status responses[6,19,59,60]. Sojka and Parsons[49] found that VPD and LVPD gave the highest correlations with any other single indicator of plant water status. They concluded for this reason that VPD and LVPD were the best parameters for characterizing plant water status in humid environments. Burrows and Milthorpe[6] cautioned that characterization of crop water status from VPD could result in misleading con-

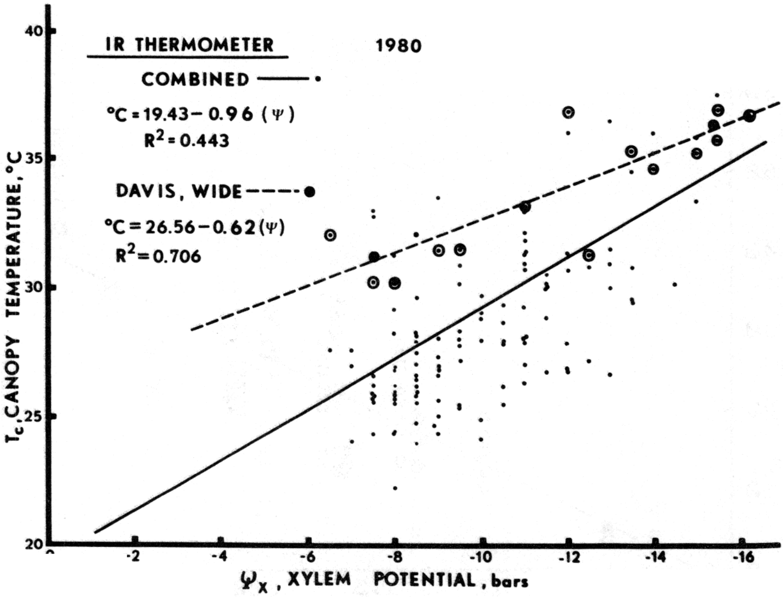

Fig. 4. The effect of pooling diverse canopy conditions on the relationship between infrared-determined canopy temperature (T_c) and xylem pressure potential (Ψ_x) versus limiting observations to a single variety and canopy geometry.

clusions regarding the severity of stress. They proposed that LVPD integrated both the plant and atmospheric contribution to the vapor pressure difference driving transpiration. A similar rationale is employed in the "normalized plant water stress index" (NSI) which employs both VPD and LVPD to interpret canopy-air temperature differentials for stress assessment. The NSI, however, has not been verified in humid environments. Sojka and Parsons[49] pointed out that empirical evidence presented by Geiser et al.[15] could affect the validity of the NSI due to the apparent influence of relative humidity on ΔT, an effect which could impair the accurate establishment of the NSI's nonstressed baseline. In a practical sense, use of the NSI may be difficult to adopt in humid environments even in the absence of theoretical problems. This is due to the inability to rely on occurrence of acceptable cloud conditions on a daily basis for regular assessment of canopy temperature. Furthermore, no method has been

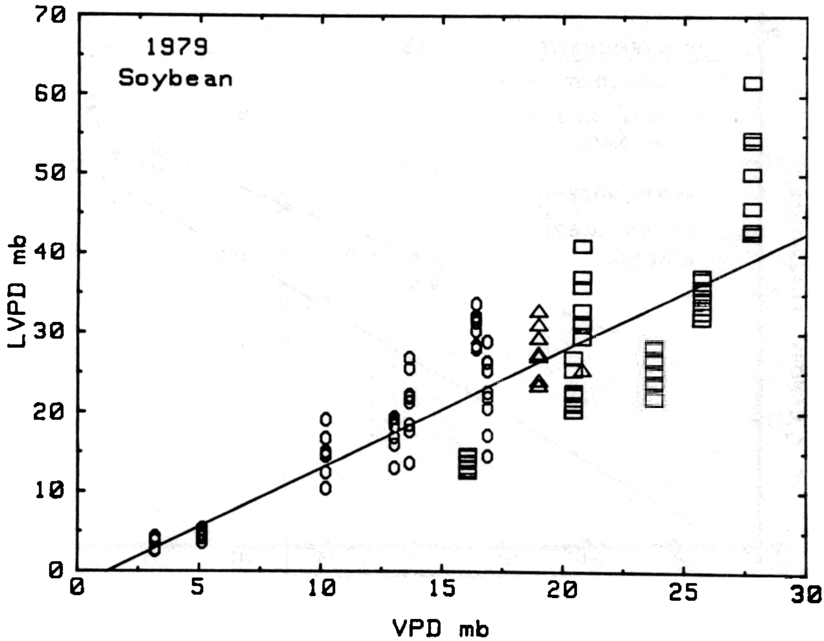

Fig. 5. The relationship between leaf vapor pressure deficit (LVPD) and vapor pressure deficit (VPD) for three time periods: circles (0800-1200 hr), squares (1200-1300 hr), and triangles (1400-1800 hr).

devised to cope with the influence of sensible heat in row crops with incomplete canopy coverage.

In this study, VPD and LVPD were highly correlated (Fig. 5) with LVPD being approximately double the value of VPD. Determination of LVPD ultimately has the same practical limitations as the NSI since both rely on accurate assessment of ΔT. If a simple relationship exists between VPD and LVPD, however, it is conceivable that VPD alone could serve as a reliable indicator of stress.

Nutrient Extraction Patterns

Chemical analysis of post-harvest soil samples showed lower average extractable K concentrations (39 vs. 45 mg/kg in 1980, and 44 vs. 50 mg/kg in 1981) in narrow (51 cm) compared to wide (102 cm) row soybean, but this difference was significant at P(0.05) only in 1980. Irrigation significantly reduced average profile K concentrations from

TABLE 2

Post-harvest Mehlich I extractable K, Ca, and Mg as influenced by depth, row spacing, sampling position, and year.

Sampling depth	Row spacing	Sampling position	1980 K	1980 Ca	1980 Mg	1981 K	1981 Ca	1981 Mg
------cm--------			------------------mg/kg					
0-15	50	M	49	410	76	72	435	122
0-15	50	R	57	385	72	68	445	124
0-15	100	M	38	355	64	64	410	101
0-15	100	R	75	430	84	82	449	108
15-30	50	M	29	123	24	33	143	36
15-30	50	R	31	169	26	37	218	57
15-30	100	M	34	116	25	41	160	35
15-30	100	R	36	164	28	38	207	55
30-60	50	M	42	152	43	46	250	69
30-60	50	R	43	152	44	40	198	58
30-60	100	M	58	221	64	56	223	66
30-60	100	R	55	193	57	49	186	58
60-90	50	M	30	230	53	28	273	73
60-90	50	R	31	218	55	32	292	77
60-90	100	M	30	245	64	36	250	63
60-90	100	R	36	252	64	34	276	66
LSD(0.05)			10	116	15	10	77	18

Sampling position M indicates between soybean rows while R indicates within the rows.

49 to 45 mg/kg in 1981, but although a similar trend occured in 1980, the difference was not significant.

In 1980, extractable K within soybean rows was significantly greater than between rows. Similar trends were observed for Ca and Mg in 1980 and for all three nutrients in 1980 and for all three nutrients in 1981, but those differences were not significant at P(0.05). Those measurements suggest, however, that plant nutrients may naturally become more concentrated within rows. This could have management implications, especially if conservation tillage and controlled traffic patterns were utilized for several consecutive growing seasons.

Concentrations of extractable K, Ca, and Mg differed significantly ($P<0.001$) with depth in both years. Mean values for each depth reflected zones of eluviation (15-30 cm) and illuviation (30-60 cm) within the profile. Interactive effects of sampling depth, row spacing, and sampling position are presented in Table 2. For K, this interaction was significant at P(0.01) both years, but for Ca and Mg, the interaction F values were nonsignificant.

CONCLUSIONS

Satisfactory relationships between R_s and any one of the other observed parameters were not found. Based on these findings and those reported elsewhere in the literature, reliability and utility of R_s measurements of field-grown soybean as a lone indicator of stress appear questionable. This seems especially true of R_s measurements made in humid environments.

A number of water stress indicators were highly correlated with VPD and/or LVPD. Therefore, VPD and/or LVPD may be the best indicators of stress in soybean canopies in humid regions, provided the observer has the capacity to make accurate estimates of T_c (needed to calculate LVPD). The factors LVPD and VPD were highly correlated.

Pressure chamber determinations of Ψ_x are well correlated with various other indicators of plant water status in soybean, but display only small magnitudes of difference even in the presence of substantial differences in soil water regime. Measurement of Ψ_x also appears subject to substantial systematic error where cultivar differences are not accounted for. Cultivar Ψ_x differences over the three-year observation period were found to be nearly half as large in magnitude as differences created by irrigation treatments. The impact of shading on Ψ_x can be nearly as large as that of irrigation and can have an effect on observations in as little as 1 to 5 minutes for even partial shading. This suggests that extreme caution must be exercised not to combine Ψ_x determinations from different illumination intensities during periods of transient cloud cover or haziness.

Infrared determination of T_c is subject to the same systematic errors resulting from shading as is Ψ_x. Caution should be exercised to compare readings from a single canopy geometry, and measurement should be consistently made from the same aspect for maximum accuracy. A simple universal convention of making all IR temperature measurements with the sun at one's back would seem well advised.

Finally, these data show that cultural and management practices strongly influence plant water relations in this physiographic region.

This subsequently influences plant growth, development, and nutient accumulation, but quantifying those effects on nutrient extraction patterns require extensive and positional soil sampling procedures.

REFERENCES

1. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the production by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.
2. Bell, C. J. and L. D. Incoll. 1981. A handpiece for the simultaneous measurement of photosynthetic rate and leaf diffusive conductance II. Calibration. J. Expt. Bot. 32:1135-1142.
3. Bell, C. J. and G. R. Squire. 1981. Comparative measurements with two water vapour diffusion porometers (dynamic and steady state). J. Expt. Bot. 32:1143-1156.
4. Berkowitz, G. A. and N. W. Hopper. 1980. A method of increasing the accuracy of diffusive resistance porometer calibrations. Ann. Bot. 45:723-727.
5. Brady, R. A., S. M. Goltz, W. L. Powers, and E. T. Kanemasu. 1975. Relation of soil water potential to stomatal resistance of soybean. Agron. J. 67:97-99.
6. Burrows, F. J. and F. L. Milthorpe. 1976. Stomatal conductance in the control of gas exchange. p. 102-152. In T. T. Kozlowski (Ed.) Water deficits and plant growth. Academic Press, NY.
7. Campbell, R. B. 1973. Flue-cured tobacco yield and oxygen content of soils in lysimeters, flooded for various periods. Agron. J. 65:783-796.
8. Campbell, R. B. and C. J. Phene. 1977. Tillage, matric potential, oxygen, and millet yield relations in layered soils. Trans. ASAE 20:271-275.
9. Carlson, R. E., N. N. Momen, O. Arjmand, and R. H. Shaw. 1979. Leaf conductance and leaf-water potential relationships for two soybean cultivars grown under controlled irrigation. Agron. J. 71:321-325.
10. Chapman, D. C. and R. L. Parker. 1981. A theoretical analysis of the diffusion porometer: steady state diffusion through two finite cylinders of different radii. Agric. Meteorol. 23:9-20.
11. Cole, P. J. and A. M. Alston. 1974. Effects of transient dehydration on absorption of chloride by wheat roots. Plant and Soil 40: 243-247.
12. DeMooy, C. J., J. Pesek, and E. Spaldon. 1973. Mineral nutrition. In C. B. Caldwell (ed.) Soybeans: Improvement, production, and uses. Agronomy 16:267-352. Am. Soc. of Agron., Madison, Wis.
13. Ehrler, W. L., S. B. Idso, R. D. Jackson, and R. J. Reginato. 1978. Wheat canopy temperature: Relation to plant water potential. Agron. J. 70:251-256.
14. Faiz, S. H. A. and P. E. Weatherly. 1978. Further investigations into the location and magnitude of the hydraulic resistances in the soil plant system. New Phytologist 81:1028.
15. Geiser, K. M., D. C. Slack, E. R. Allred, and K. W. Stange. 1982. Irrigation scheduling using crop canopy - air temperature difference. Trans. ASAE 25:689-694.

16. Gomes, A. R. Sena and T. T. Kozlowski. 1980. Response of melaleuca quinquenervia seedlings to flooding. Physiol. Plant. 49:373-377.
17. Hack, H. R. B. 1980. The uptake and release of water vapour by the foam seal of a diffusion porometer as a source of bias. Plant, Cell and Environment 3:53-57.
18. Hatfield, J. L. and R. E. Carlson. 1978. Photosynthetically active radiation, CO_2 uptake, and stomatal diffusive resistance profiles within soybean canopies. Agron. J. 70:592-596.
19. Heatherly, L. G., W. J. Russell, and T. M. Hinckley. 1977. Water relations and growth of soybeans in a drying soil. Crop Sci. 17:381-386.
20. Huck, M. G., B. Klepper, and H. M. Taylor. 1970. Diurnal variations in root diameter. Plant Physiol. 45:529-530.
21. Hunt, P. G., R. B. Campbell, R. E. Sojka, and J. E. Parsons. 1981. Flooding-induced soil and plant ethylene accumulation and water status response of field-grown tobacco. Plant and Soil 59:427-439.
22. Idso, S. C. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteorol. 27:59-70.
23. Idso, S. B., and R. D. Jackson. 1968. Significance of fluctuations in sky radiant emittance for infrared thermometry. Agron. J. 60:388-392.
24. Idso, S. B., R. D. Jackson, P. J. Pinter, Jr., R. J. Reginato, and J. L. Hatfield. 1981a. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteor. 24:45-55.
25. Idso, S. C., R. J. Reginato, D. C. Reicosky, and J. L. Hatfield. 1981b. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J. 74: 826-830.
26. Jackson, R. D., S. B. Idso, R. J. Reginato, and P. J. Pinter, Jr. 1981. Canopy temperature as a crop water stress indicator. Water Resources Research 17:1133-1138.
27. Jackson, R. D., R. J. Reginato, and S. B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Resources Research 13:651-656.
28. Jones, C. A., D. Pena, and A. Carabaly. 1980. Effect of plant water potential, leaf diffusive resistance, rooting density, and water use on the dry matter production of several tropical grasses during short periods of drought stress. Trop. Agric. (Trinidad) 57:211-219.
29. Jung, P, K. and H. D. Scott. 1980. Leaf water potential, stomatal resistance, and temperature relations in field-grown soybean. Agron. J. 72:986-990.
30. Karlen, D. L., P. G. Hunt, and T. A. Matheny. 1982. Accumulation and distribution of K, Ca, and Mg by selected determinate soybean cultivars grown with and without irrigation. Agron. J. 74:347-354.
31. Karlen, D. L., R. E. Sojka, and M. L. Robbins. 1983. Influence of excess soil-water and N rates on leaf diffusive resistance and storage quality of tomato fruit. Comm. Soil Sci. Plant Anal. 14:699-708
32. Kaufmann, M. R., 1982a. Leaf conductance as a function of photosynthetic photon flux density and absolute humidity difference from leaf to air. Plant Physiol. 69:1018-1022.

33. Kaufmann, M. R., 1982b. Evaluation of season, temperature, and water stress effects on stomata using a leaf conductance model. Plant Physiol. 69:1023-1026.

34. Kozlowski, T. T. and S. G. Pallardy. 1979. Stomatal responses of Fraxinus pennsylvanica seedlings during and after flooding. Physiol. Plant. 46:155-158.

35. Linacre, E. T. 1967. Climate and the evaporation from crops. J. Irrig. Drainage Div. Am. Soc. Civil Eng. 93:61-79.

36. Long, F. L., H. F. Perkins, J. R. Carrecker, and J. M. Daniels. 1969. Morphological, chemical, and physical characteristics of eighteen representative soils of the Atlantic Coast Flatwoods. Georgia Agric. Exp. Stn. Res. Bull. 59.

37. Oliver, S. and S. A. Barber. 1966. An evaluation of the mechanisms governing the supply of Ca, Mg, K, and Na to soybean roots (Glycine max L.). Soil Sci. Soc. Am. Proc. 30:80-86.

38. O'Toole, J. C. and T. T. Chang. 1978. Drought and rice improvement in perspective. IRRI Res. Paper Ser. No. 14. Int. Rice Res. Inst., Manila, Phillipines. 27 p.

39. Peele, T. C., O. W. Beale, and F. F. Lesesne. 1970. The physical properties of some South Carolina soils. South Carolina Agric. Exp. Stn. Tech. Bull. 1037.

40. Pereira, J. S. and T. T. Kozlowski. 1977. Variations among woody angiosperms in response to flooding. Physiol. Plant. 41:184-192.

41. Raper, C. D., Jr., and S. A. Barber. 1970. Rooting system of soybeans. II. Physiological effectiveness as nutrient absorption surfaces. Agron. J. 70:585-588.

42. Raschke, K. 1975. Stomatal action. Ann. Rev. Plant Physiol. 26:309-340.

43. Regehr, D. L., F. A. Bazzaz, and W. R. Boggess. 1975. Photosynthesis, transpiration, and leaf conductance of Populus deltoides in relation to flooding and drought. Photsynthetica 9:52-61.

44. Reicosky, D. C., R. B. Campbell, and C. W. Doty. 1976. Corn plant water stress as influenced by chiseling, irrigation, and water table depth. Agron. J. 68:499-503.

45. Reicosky, D. C. and D. E. Deaton. 1979. Soybean water extraction, leaf water potential and evapotranspiration during drought. Agron. J. 71:45-50.

46. Sivakumar, M. V. K. and R. H. Shaw. 1978. Relative evaluation of water stress indicators for soybean. Agron. J. 70:619-623.

47. Smucker, A. J. M. 1975. Interactions of soil oxygen and water stresses upon growth, disease, and production of navy beans. Report of the Bean Improvement Cooperative. pp. 72-75.

48. Sojka, R. E. 1984. Diffusive resistance, stomatal density, K, Ca, and Mg concentrations, and growth of Lee soybean as influenced by soil-oxygen diffusion rate. Soil Sci. [redacted] (In [redacted] Review).

49. Sojka, R. E. and J. E. Parsons. 1983. Soybean water status and canopy microclimate relationships at four row spacings. Agron. J. 75:961-968.

50. Sojka, R. E. and L. H. Stolzy. 1980. Soil-oxygen effects on stomatal response. Soil Sci. 130:350-358.

51. Sojka, R. E., L. H. Stolzy, and R. A. Fischer. 1979. Comparison of diurnal drought response of selected wheat cultivars. Agron. J. 71:329-335.

52. Sojka, R. E., L. H. Stolzy, and R. A. Fischer. 1981. Seasonal drought response of selected wheat cultivars. Agron. J. 73: 838-845.
53. Sojka, R. E., H. D. Scott, J. A. Ferguson, and E. M. Rutledge. 1977. Relation of plant water status to soybean growth. Soil Sci. 123: 182-187.
54. Squire, G. R. and C. R. Black. 1981. Stomatal behavior in the field. In P. G. Jarvis and T. A. Mansfield (Eds.) Soc. for Expt. Bio. Seminar Series, Vol. 8, Stomatal Physiology: Meeting, Lancaster, England. Dec. 19-20, 1979. Cambridge Univ. Press. p. 223-245.
55. Stange, K. W., D. C. Slack, E. R. Allred, and K. M. Geiser. 1981. Relationship between canopy-air temperature differences and stomatal diffusion resistance. Paper #81-2010, Am. Soc. Ag. Eng.
56. Tinker, P. B. 1976. Roots and water. Transport of water to plant roots in soil. Philos. Trans. R. Soc. London, Series B 273:445-461.
57. Turner, N. C. and J. E. Begg. 1981. Plant-water relations and adaptation to stress. Plant and Soil 58:97-131.
58. Turner, N. C. and J. Y. Parlange. 1970. Analysis of operation and calibration of a ventilated diffusion porometer. Plant Physiol. 46:175-177.
59. Wien, H. C., E. J. Littleton, and A. Ayanaba. 1979. Drought stress of cowpea and soybean under tropical conditions. p. 283-301. In H. Mussell and R. C. Staples (Eds.) Stress Physiology in Crop Plants. Wiley Interscience, NY.
60. Zur, B., J. W. Jones, and K. J. Boote. 1983. Field evaluation of a water relations model for soybean I. Validity of some basic assumptions. Agron. J. 75:272-280.

communications in

soil science
and
plant analysis