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COMPARISON OF CAMPBELL LEAF-PRESS WITH STANDARD PLANT WATER STRESS MEASUREMENTS FOR FOUR SPECIES

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ABSTRACT

The Campbell-Brewster (J-14) leaf press is a compact alternative to the pressure chamber for plant water potential determination. Data comparing the J-14 with the pressure chamber (Ψ_x) or with canopy temperatures (Tc) and crop water stress index (CWSI) are limited. All three J-14 end points (exudation from cut or uncut leaf edges or darkening of interveinal areas) were highly correlated among themselves for the four species studied. Correlations of J-14 end points with other stress indicators from unstable diurnal periods were poor. Our data showed a species-related reliability of the J-14. The J-14 produced r^2 values above 0.7 for soybean for all but comparisons with CWSI or Tc minus air temperature (ΔT), and for corn for Ψ_x only. The J-14 did not perform well for tomato or rapeseed. Failure of J-14 or Ψ_x to correlate well with CWSI suggests difficulty with CWSI measurement under humid southeastern conditions.

INTRODUCTION

Plant water status can be inconvenient in the field because of technique or equipment limitations. The pressure chamber (Scholander, et al. 1964) has been widely used for field assessment of plant xylem pressure potential (Ψ_x) which is closely related to total plant water potential (Ψ_p) in the absence of significant osmotic potential (Ψ_π). Most pressure chambers are either excessively bulky or have inadequate gas capacity for copius measurements. Psychrometric determination of Ψ_p (Savage et al. 1981) is poorly suited to field use because of time required and sensitivity to environmental variation. A highly portable method, requiring little or no equipment maintenance and no material resupply is the Campbell-Brewster hydraulic leaf press (Campbell and Brewster 1975).

The Campbell-Brewster (J-14)[1] press, however, is gaining acceptance slowly because only limited data comparing it to established plant water status indicators are available and the physical meaning of the J-14 end points is uncertain. Comparisons of the J-14 press have to date been only with the Scholander-type pressure chamber (Bristol et al. 1981; Campbell et al. 1979; Grant et al. 1981; Hicks et al. 1986; Jones and Carabaly 1980; Radulovich et al. 1982; Rajendrudu et al. 1983; Renard 1979; Shayo-Ngowi and Campbell 1980; Yegappan and Mainstone 1981), relative water content (relative turgidity) technique (Campbell et al. 1979; Grant et al. 1981; Rhodes et al. 1976), and thermocouple psychrometry (Grant et al. 1981, Rajendrudu et al. 1983). The authors are unaware of published comparisons of the J-14 end points with leaf temperature (T_c), leaf minus air temperature (ΔT), the derived crop water stress index (CWSI), or measurements of leaf diffusive resistance, leaf transpiration, or micrometeorologically-derived canopy parameters.

The J-14 end points generally observed are: free exudation from either the cut or uncut leaf edge (Ψ_{Jc} or Ψ_{Ju}, respectively) or darkening of leaf interveinal areas (Ψ_{Jd}). Frequently, Ψ_{Jc} and Ψ_{Ju} are further defined as exudation at or near a xylem element from either a cut or uncut edge. In the authors' experience, this distinction is difficult.

The majority of papers reporting a good relationship between Ψ_J and Ψ_x found that Ψ_J over-estimated Ψ_x -- i.e., a more negative potential was measured for Ψ_x than for the corresponding value of Ψ_J (Bristow et al. 1981; Grant et al. 1981; Radulovich et al. 1982; Rajendrudu et al. 1983; Yegappan and Mainstone 1981). Three factors may have contributed to this. One is the subtlety of the Ψ_J endpoint; Hicks et al. (1986) over-estimated Ψ_x if the first exudation of sap was taken as the Ψ_J endpoint. A one to one relationship existed if Ψ_J was taken to be the pressure at which sap exuded from all leaf veins. Also, in none of the Ψ_x vs Ψ_J comparisons did the authors report wrapping leaves with moist gauze or with plastic during chamber pressurization as recommended by Gandar and Tanner (1976) and Turner and Long (1980) to combat the rapid rise in chamber temperature and vapor pressure deficit (Puritch and Turner 1973, and Wenkert et al. 1979). Grant et al. (1981) also suggested that with the J-14, measurement of the xylem osmotic component is not measured, which upwardly biases Ψ by an amount which decreases as the plant progressively dries toward plasmolysis.

Other limitations of the J-14 have been noted. Good correlation of Ψ_J with Ψ_x and Ψ_p from pressure chamber and psychrometers respectively have been limited to readings from stable (midday) periods (Bristow et al. 1981; Radulovich et al. 1982) and in some species to partially stress-hardened plants (Yegappan and Mainstone 1981). Furthermore, Shayo-Ngowi and Campbell (1980) caution that all J-14 end points include the pressure required to deform the tissue and increase the matric potential to zero, and that these pressures alter matrix pore structure which can artifactually affect the end points in all but pre-frozen samples.

The objectives of this study were to compare Ψ_{Jc}, Ψ_{Ju}, and Ψ_{Jd} with one another, with the standard pressure chamber measurement of Ψ_x using plastic-wrapped leaf samples, and with the crop water stress index (CWSI) as developed by Jackson et al. (1981) and Idso et al. (1981). Unlike most other similar comparisons these comparisons were conducted under humid southeastern conditions.

[1] Names of equipment manufacturers and suppliers are provided for the benefit of the reader and do not imply endorsement by the Department of Agriculture.

METHODS AND MATERIALS

Ongoing field studies with irrigation treatments, providing a range of plant water status from non-stressed to moderately stressed, were monitored in Florence and Charleston, South Carolina. Corn (*Zea mays*), soybean (*Glycine max*), and rapeseed (*Brassica napus L.*) were grown on Norfolk loamy sand (fine-loamy, siliceous, thermic, Typic Paleudult) in Florence, and tomato (*Lypersicum esculentum*) was grown on Hockley loamy fine sand (fine-loamy, siliceous, thermic Plinthic Paleudult) in Charleston. Crops were grown using conventional standard cultural practices for each crop in the region, including in-row subsoiling to 0.45 m. Tomato was grown on 1.22-m staked rows. Soybean, corn, and rapeseed were grown on 0.76-m rows. Rapeseed was in a twin-row configuration with 0.28 m between twin rows.

Xylem pressure potential (Ψ_x) was determined using a pressure chamber specially designed with a high chamber-mass to internal-volume ratio to minimize compression-decompression related temperature changes and allowing rapid insertion and sealing. Leaves were excised, immediately placed in plastic bags containing wet paper towels, and quickly inserted into the pressure chamber for pressurization. Two to three cm of excised petiole (or corn leaf) were left protruding from the plastic bag. With a constant pressure increase rate of 1300 kPa min^{-1}, total time from excision to decompression seldom exceeded two minutes. Pressure chamber end points were taken as the first free flow of sap from conductive tissue at leaf excision points. For rape, soybean, and tomato chamber samples, excision was at the point of petiole attachment to the mainstem and entire compound leaves were inserted into the pressure chamber. For corn, excision was at mid-leaf. All leaves selected were most-recently-matured, fully-expanded sun-exposed leaves. For pressure chamber vs J-14 comparisons, matched pairs of leaves were selected from side-by-side plants (one for the chamber, one for the J-14).

The J-14 was pressurized at approximately double the chamber rate. Each J-14 leaf was excised from the plant with a sharp razor blade so that uncut or cut-edge exudation could be watched simultaneously. All three end points (Ψ_{Jc}, Ψ_{Ju}, Ψ_{Jd}) were noted on the same leaf sample. Each leaf was backed with white filter paper to facilitate detection of exudate.

Crop temperatures obtained with an Everest model 110 Infrared thermometer using an emissivity setting of 0.98. It was aimed obliquely at the crop canopy taking care to include only foliage in the target area. Air temperatures were determined from automated weather stations immediately adjacent to the plots. The Florence stations were described by Sojka and Parsons (1983) and Sadler and Camp (1984). The Charleston data were collected with CR21 data loggers for all but the rape data. Vapor pressures above the canopy (at 1 m height) were calculated from relative humidity measured with a Beckman Humi-Chek II precision hygrometer.

The CWSI was calculated using the empirical formulas derived by Idso et al. (1981) and summarized by Clawson et al. (1987). Results were confirmed using the computer program of Carney and Pinter (1986).

The equations used were as follows:

$$CWSI = (Tc-Tcl)/(Tcu-Tcl)$$

where Tc is crop temperature (C) and subscripts u and l indicate upper and lower limits, respectively.

$$Tcu = Ta + a0 + a1 * (esa-esa')$$

Ta is air temperature (C), a0 and a1 are intercept (C) and slope (C/kPa) of the well-watered baseline (see Table 1 for values), esa is saturation vapor pressure at Ta (kPa), and esa' is saturation vapor pressure (kPa) at (Ta+a0). This last is an estimate of Tc at zero transpiration.

$$Tcl = Ta + a0 + a1 * (esa-ea)$$

where ea is actual vapor pressure (kPa). The term (esa-ea) is recognized as the vapor pressure deficit (VPD).

Table 1. Slopes and intercepts of well-watered baselines used in calculations. Data taken from Idso (1982).

Crop	Scientific name	Intercept C	Slope C/kPa
Tomato	Lypersicum esculentum	2.86	-1.96
Soybean	Glycine max	1.44	-1.34
Rape*	Brassica napus L.	1.94	-2.26
Corn	Zea mays	3.11	-1.97

*Idso (1982) reported no data for rape. Data for turnip (B. rapa) were used.

Upon completion of each plant water status determination a record of Ta, Tc, ΔT, RH (relative humiditiy), VPD, Ψ_x, Ψ_{Jc}, Ψ_{Ju}, Ψ_{Jd}, and CWSI existed for correlation-regression analysis for the date and time. Regression analysis was accomplished using the PROC RSQUARE subroutine of SAS.

RESULTS AND DISCUSSION

A statistical summary of the relationship between physically measured parameters for all four crops is presented in Table 1. Soybean provided uniformly good correlations of J-14 parameters with all measured water status indicators except ΔT, which confirms and expands the findings of Grant et al. (1981). The relationships between Ψ_{Ju}, Ψ_{Jc}, or Ψ_{Jd} and Ψ_x or Tc are shown in figures 1a and 1b. In addition to the relationships between these parameters, it should be noted that the three J-14 end points for soybean are closely related. Under southeastern conditions, some problems have been noted with ΔT determinations under fluctuating radiation. Despite efforts to minimize this, some haziness may have affected the ΔT determination.

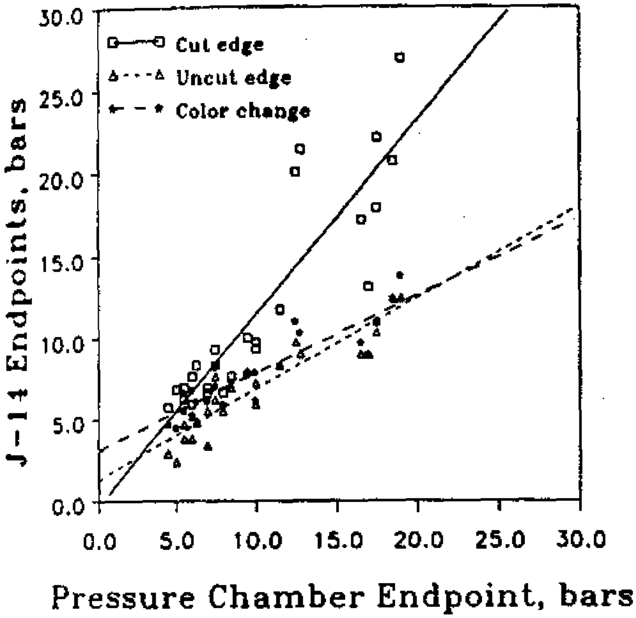
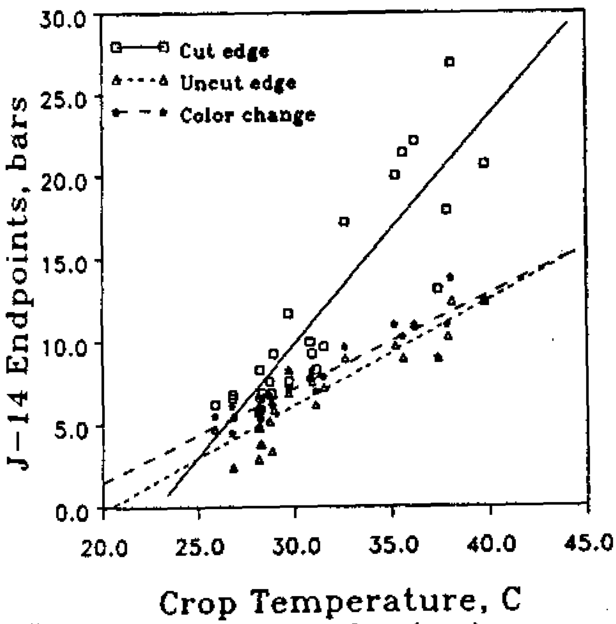


Figure 1a. Comparison of J-14 press with pressure chamber for soybean.



Fibure 1b. J-14 press data plotted against crop temperature for soybean.

Corn had moderately good correlations between Ψ_x and either Ψ_{Ju}, Ψ_{Jc}, or Ψ_{Jd} (fig.2). A good relationship was also reported for sorghum (*Sorghum bicolor* L. Moench) by Hicks et al. (1986), which has similar leaf structure and veination. The only comparison of the J-14 using corn previously reported was for matric potential determination (Shayo-Ngowi and Campbell 1980). As seen in Table 2, Ψ_{Jc} correlated measurably better with Ψ_x than did either Ψ_{Ju} or Ψ_{Jd}. Correlations between the J-14 end points were poorer than for soybean but did indicate they were strongly related.

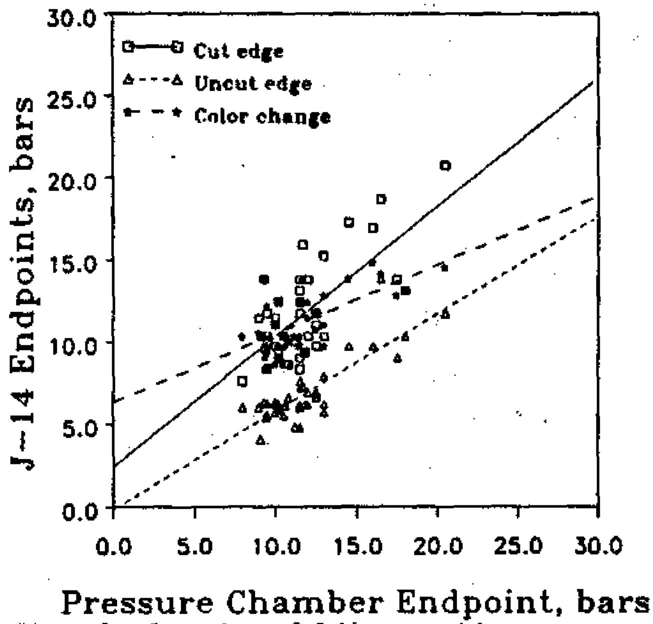


Figure 2. Comparison of J-14 press with pressure chamber for corn.

Evaluations of the J-14 have not been reported for tomato or rapeseed. Table 2 suggests there is no acceptable relationship between the J-14 and any other traditionally measured indicator of stress for these two species. Indeed, the J-14 parameters are only moderately correlated among themselves in rapeseed and in tomato. By contrast, wrapped and unwrapped Ψ_x measurements for soybean, rapeseed, and corn are significantly correlated (Table 3). The wrapped Ψ_x determinations were a subset of Table 2. Data not presented was used to relate Ψ_x, Ψ_{Ju}, Ψ_{Jc}, and Ψ_{Jd}, to parallel leaf diffusive resistance of tomato and corn. No good relationships were found. This may be an artifact, however, of several factors. The stable midday data pairs were few and were from a narrow range of well watered plant potentials with fluctuating radiation levels.

The crop water stress index (CWSI) was regressed on the four variables Ψ_x, Ψ_{Ju}, Ψ_{Jc}, and Ψ_{Jd}, for midday readings (0900-1500 hrs) for all four crops (Table 4). Tomato showed the closest correlation of CWSI (with Ψ_x) and soybean and corn showed some correlation with CWSI, however, correlations were poor (r^2 below 0.5). Again the problem appears related to the limited plant water potential ranges. Figure 3 illustrates this with plots of CWSI vs Ψ for tomato, corn and soybean. There have been indications that the CWSI may not perform well under

Table 2. Regression equations and coefficients of determination for relationships between measured plant water stress indicators for four species in bars (= kPa x 100) for Ψ and degrees C for T.

Crop	Dep. var	Ind. var	#Pairs	Slope	Intercept	r^2	Prob>F	Dep. min	Dep. max	Ind. min	Ind. max
Tomato	ΨJu	ΨJc	41	0.884	2.393	0.557	0.0001	3.4	9.0	2.1	6.6
	ΨJu	Ψx	"	0.158	4.666	0.065	0.1063	3.4	9.0	4.7	11.9
	ΨJu	Tc	"	0.177	1.657	0.176	0.0063	3.4	9.0	13.0	31.2
	ΨJu	ΔT	"	0.255	5.715	0.171	0.0072	3.4	9.0	-7.1	6.6
	ΨJc	Ψx	"	0.127	2.974	0.059	0.1249	2.1	6.6	4.7	11.9
	ΨJc	Tc	"	0.127	0.920	0.128	0.0219	2.1	6.6	13.0	31.2
	ΨJc	ΔT	"	0.169	3.842	0.106	0.0379	2.1	6.6	-7.1	6.6
	ΨJd	ΨJc	"	0.502	3.418	0.505	0.0001	4.0	6.9	2.1	6.6
	ΨJd	ΨJu	"	0.424	2.908	0.505	0.0001	4.0	6.9	3.4	9.0
	ΨJd	Ψx	"	0.081	4.780	0.048	0.1688	4.0	6.9	4.7	11.9
	ΨJd	Tc	"	0.080	3.481	0.102	0.0414	4.0	6.9	13.0	31.2
	ΨJd	ΔT	"	0.138	5.310	0.141	0.0154	4.0	6.9	-7.1	6.6
Soybean	ΨJu	ΨJc	25	1.974	-2.094	0.814	0.0001	5.7	26.9	2.4	12.4
	ΨJu	Ψx	"	1.179	-0.396	0.804	0.0001	5.7	26.9	4.5	19.0
	ΨJu	Tc	"	1.375	-31.394	0.797	0.0001	5.7	26.9	25.9	39.8
	ΨJu	ΔT	"	1.241	11.653	0.268	0.0081	5.7	26.9	-5.6	3.8
	ΨJc	Ψx	"	0.559	1.253	0.866	0.0001	2.4	12.4	4.5	19.0
	ΨJc	Tc	"	0.638	-13.031	0.823	0.0001	2.4	12.4	25.9	39.8
	ΨJc	ΔT	"	0.392	6.974	0.128	0.0790	2.4	12.4	-5.6	3.8
	ΨJd	ΨJc	"	0.836	2.097	0.928	0.0001	4.5	13.8	2.4	12.4
	ΨJd	ΨJu	"	0.379	3.509	0.912	0.0001	4.5	13.8	5.7	26.9
	ΨJd	Ψx	"	0.476	3.506	0.833	0.0001	4.5	13.8	4.5	19.0
	ΨJd	Tc	"	0.568	-9.867	0.865	0.0001	4.5	13.8	25.9	39.8
	ΨJd	ΔT	"	0.462	7.923	0.236	0.0139	4.5	13.8	-5.6	3.8
Rapeseed	ΨJu	ΨJc	30	0.805	2.713	0.493	0.0001	4.8	9.0	3.1	6.6
	ΨJu	ΨJx	"	0.388	3.682	0.269	0.0033	4.8	9.0	3.8	8.5
	ΨJu	Tc	"	0.158	3.050	0.269	0.0033	4.8	9.0	12.9	23.9
	ΨJu	ΔT	"	-0.048	6.289	0.004	0.7567	4.8	9.0	-1.9	3.5
	ΨJc	Ψx	"	0.415	1.646	0.405	0.0002	3.1	6.6	3.8	8.5
	ΨJc	Tc	"	0.157	1.200	0.353	0.0005	3.1	6.6	12.9	23.9
	ΨJc	ΔT	"	-0.001	4.394	0.000	0.9933	3.1	6.6	-1.9	3.5
	ΨJd	ΨJc	"	0.780	2.828	0.443	0.0001	4.7	9.0	3.1	6.6
	ΨJd	ΨJu	"	0.946	0.340	0.858	0.0001	4.7	9.0	4.8	9.0
	ΨJd	Ψx	"	0.340	3.998	0.199	0.0135	4.7	9.0	3.8	8.5
	ΨJd	Tc	"	0.122	3.785	0.154	0.0322	4.7	9.0	12.9	23.9
	ΨJd	ΔT	"	-0.284	6.276	0.001	0.8571	4.7	9.0	-1.9	3.5
Corn	ΨJu	ΨJc	41	1.278	3.001	0.657	0.0001	7.6	20.7	4.1	13.8
	ΨJu	Ψx	"	0.789	2.405	0.499	0.0001	7.6	20.7	8.0	20.5
	ΨJu	Tc	"	0.539	-3.464	0.400	0.0001	7.6	20.7	21.6	35.3
	ΨJu	ΔT	"	1.062	13.701	0.166	0.0083	7.6	20.7	-4.4	0.0
	ΨJc	Ψx	"	0.592	-0.169	0.699	0.0010	4.1	13.8	8.0	20.5
	ΨJc	Tc	"	0.389	-4.146	0.519	0.0001	4.1	13.8	21.6	35.3
	ΨJc	ΔT	"	0.599	7.931	0.131	0.0201	4.1	13.8	-4.4	0.0
	ΨJd	ΨJc	"	0.683	6.574	0.548	0.0001	8.3	14.8	4.1	13.8
	ΨJd	ΨJu	"	0.521	5.130	0.793	0.0001	8.3	14.8	7.6	20.7
	ΨJd	Ψx	"	0.417	6.304	0.409	0.0001	8.3	14.8	8.0	20.5
	ΨJd	Tc	"	0.310	2.509	0.386	0.0001	8.3	14.8	21.6	35.3
	ΨJd	ΔT	"	0.651	12.449	0.182	0.0055	8.3	14.8	-4.4	0.0

humid conditions, particularly under variable radiation regimes, or where haziness limits maximum incoming radiation. Some feeling for the difficulty associated with using the CWSI may be gained from figure 4a, b, c, and d in which measured ΔT values are plotted against correspondence VPD values with points coded for hour of day for the four crops and showing the calculated baselines.

Table 3. Regression equations and coefficients of determination for relationships between Ψx values from unwrapped and wrapped samples for four species in a pressure chamber (unwrapped = dep. var.) in bars (= kPa x 100).

Crop	#Pairs	Slope	Intercept	r^2	Prob>F	Dep. min	Dep. max	Ind. min	Ind. max
Soybean	25	1.043	0.356	0.906	0.0001	4.5	22.5	4.5	19.0
Rapeseed	30	0.974	0.955	0.747	0.0001	4.5	10.7	3.0	8.5
Corn	11	0.831	3.348	0.700	0.0013	12.5	22.5	11.5	20.5

Table 4. Regression equations and coefficients of determination for relationships between CWSI (dependent variable) and pressure chamber or J-14 measurements of plant water potential for four species in bars (= kPa x 100) for midday observations (0900-1500 hrs).

Crop	Ind. Variable	#Pairs	Slope	Intercept	r^2	Prob>F	CWSI min	CWSI max	Var. min	Var. max
Tomato	Ψx	16	.172	-1.000	.605	.0004	-0.0	1.6	3.5	11.9
	ΨJu	"	.197	-0.743	.230	.0554	-0.0	1.6	5.0	9.0
	ΨJc	"	.112	-0.000	.079	.2917	-0.0	1.6	2.1	6.6
	ΨJd	"	.229	-0.753	.141	.1524	-0.0	1.6	4.0	6.9
Soybean	Ψx	25	.074	-.307	.344	.0020	-0.4	1.5	4.5	19.0
	ΨJu	"	.046	-.319	.472	.0002	-0.4	1.5	5.7	26.9
	ΨJc	"	.121	-.389	.328	.0028	-0.4	1.5	2.4	12.4
	ΨJd	"	.167	-.870	.472	.0001	-0.4	1.5	4.5	13.8
Rapeseed	Ψx	26	.002	.556	.000	.9492	0.2	1.1	4.5	8.5
	ΨJu	"	.020	.444	.011	.6175	0.2	1.1	4.8	9.0
	ΨJc	"	.040	.394	.032	.3845	0.2	1.1	3.1	6.6
	ΨJd	"	.018	.457	.009	.6437	0.2	1.1	4.7	9.0
Corn	Ψx	37	.081	-1.163	.498	.0000	-0.9	0.2	8.0	20.5
	ΨJu	"	.049	-.803	.222	.0033	-0.9	0.2	7.6	20.7
	ΨJc	"	.087	-.813	.292	.0006	-0.9	0.2	4.1	13.8
	ΨJd	"	.085	-1.178	.127	.0029	-0.9	0.2	8.3	14.8

Several observations can be made from these data about use of the CWSI in humid regions. The range of CWSI observed indicates that the empirical form of the CWSI may need local calibration, since values considerably outside the range 0-1 are found. This can be seen from values outside the envelope of the upper and lower limits in figures 4b and 4d, for soybean and corn. Most values outside the envelope for tomato are from early morning or late afternoon, and not within the 0900-1500 time period usually used for CWSI calculations. Values for rape are mostly within the envelope. The data for soybean corroborate those of Evans and Sadler (1987), who found values ranging from about 2 C above to 2 C below the envelope, and found both a time-of-day and radiation dependence of CWSI for soybeans on the same soil. Sojka and Parsons (1983) and Evans and Sadler (1987) reported a similar diurnal pattern.

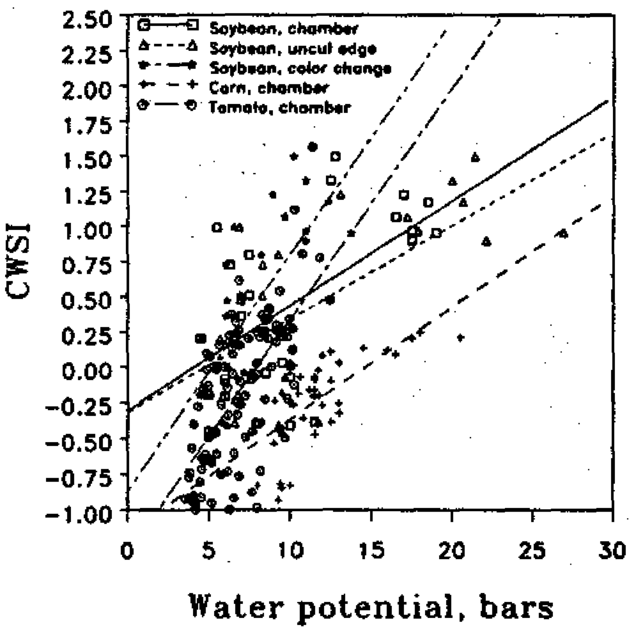
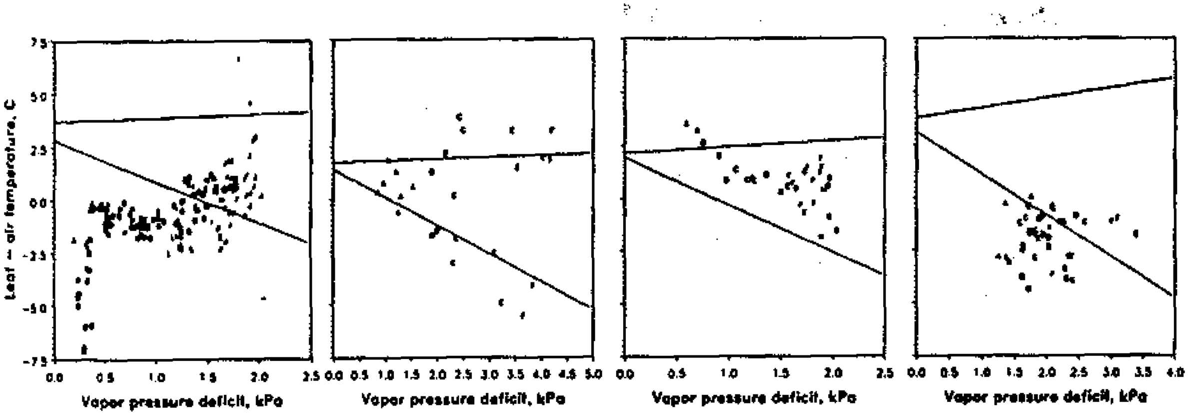


Figure 3. Comparison of CWSI to water potential for soybeans and corn.



(a) Tomato. A=5, Q=21. (b) Soybean. A=9, F=14 (c) Rapeseed. A=8, H=15 (d) Corn. A=9, G=15
Figure 4. Scatter of data within the CWSI envelope by hour of day (letter symbols are coded for time as indicated).

The current study lacks the time range to demonstrate the time-of-day dependence for soybean, though the range is similar. The trace for the tomato data is similar to the earlier soybean data, though generally lower in the envelope. These tomatoes were probably better watered than those soybeans.

Though the majority of work with CWSI has used cloud-free conditions near midday, such conditions seldom exist during the growing season in the Southeast. The comparisons among crops shown by Idso (1982) included sunlit and shaded baselines for five crops. The shaded crops had baselines 3.8 C lower than the sunlit crops. If thin clouds or haze reduce irradiance, it is within reason to assume some intermediate baseline applies. The dependence of these data on radiation could not be studied because all the weather stations integrated the irradiance, and the variability of irradiance precluded interpolation between hourly or half-hourly averages.

Previous investigators have shown that the relationship between J-14 parameters and other standard plant water stress indicators is diurnally affected (Hicks, et al. 1986; Radulovich, et al. 1982). The J-14 parameters apparently have different dynamics and therefore the ratio of J-14 parameters to other parameters changes until a diurnal plateau (a near-steady-state condition) is reached.

CONCLUSIONS

The Campbell-Brewster J-14 press appears to exhibit a species-related reliability. Our data confirm the inability to relate J-14 parameters to other water stress parameters during meteorologically dynamic diurnal periods. J-14 performed well with soybean for all but comparisons with ΔT or CWSI and it performed well with corn only for comparison of Ψ_x. The J-14 did not perform well for tomato or rapeseed. All three J-14 end points were highly correlated among themselves in all four species. Failure of CWSI to correlate highly with Ψ_x or J-14 parameters suggests inherent problems with the CWSI under high humidity/limited-radiation regimes.

LITERATURE CITED

Bristow, K. L., W. H. Van Zyl, and J. M. DeJager. 1981. Measurement of leaf water potential using J-14 press. J. Expt. Bot. 32:851-854.

Campbell, G. S., and S. F. Brewster. 1975. Leaf water potential and soil water content measured with a simple hydraulic press. Paper presented at the Western Regional Research Project W-67. Honolulu, Hawaii. January.

Campbell, G. S., R. I. Papendick, E. Rabie, and A. J. Shayo-Ngowi. 1979. A comparison of osmotic potential, elastic modulus, and apoplastic water in leaves of dryland wheat. Agron. J. 71:31-36.

Carney, B., and P. J. Pinter. 1986. A computer program to calculate the crop water stress index. 3rd Arid Lands Remote Sensing Workshop, 9-11 April. U of Ariz., Tucson, AZ.

Clawson, K. L., R. D. Jackson, and P. J. Pinter, Jr. 1987. Evaluating plant water stress with canopy temperature differences. Submitted to Agric. & For. Met.

Evans, D. E., and E. J. Sadler. 1987. Energy balance measurements for crop water status. ASAE Paper No. SER87-102. SE Region ASAE Meeting, Nashville, TN. Jan 30-Feb 4, 1987. American Society of Agricultural Engineers, St. Joseph, MI 49085-9659.

Gandar, P. W., and C. B. Tanner. 1976. Potato leaf and tuber water potential measurements with a pressure chamber. Am. Pot. J. 53:1-14.

Grant, R. F., M. J. Savage, and J. D. Lea. 1981. Comparison of hydraulic press, thermocouple, psychrometer, and pressure chamber for the measurement of total and osmotic leaf water potential in soybeans. S. Afr. J. Sci. 77:398-400.

Heathcote, D. G., J. R. Etherington, and F. L. Woodward. 1979. An instrument for non-destructive measurement of the pressure potential (turgor) of leaf cells. J. Exp. Bot. 30:811-186.

Hicks, S. K., R. J. Lascano, C. W. Wendt, and A. B. Onken. 1986. Use of a hydraulic press for estimation of leaf water potential in grain sorghum. Agron. J. 78:749-751.

Idso, S. B., R. D. Jackson, R. J. Pinter, Jr., R. J. Reginato, and J. L. Hatfield. 1981. Normalizing the stress degree day for environmental variability. Ag. Met. 24:45-55.

Idso, S. B. 1982. Non-watered stressed baselines: a key to measuring and interpreting plant water stress. Agricultural Meteorology, 27:59-70.

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.

Jones, C. A., and A. Carabaly. 1980. Estimation of leaf water potential in tropical grasses with the Campbell-Brewster hydraulic press. Trop. Agric. (Trinidad) 57:305-307.

Puritch, G. S., and J. A. Turner. 1973. Effects of pressure increase and release on temperature within a pressure chamber used to estimate plant water potential. J. Exp. Bot. 24:342-348.

Radulovich, R. A., C. J. Phene, K. R. Davis, and J. R Brownell. 1982. Comparison of water stress of cotton from measurements with the hydraulic press and the pressure chamber. Agron. J. 74:383-385.

Rajendrudu, G., M. Singh, and J. H. Williams. 1983. Hydraulic press measurements of leaf water potential in groundnuts. Expl. Agric. 19:287-291.

Renard, C., Flemal, J., and Barampama, D. 1979. Evaluation de la Resistance a la Secheresse Chez le Theier au Burundi. Cafe Caco The' 23:175-182.

Rhodes, P. R., and K. Matsuda. 1976. Water stress, rapid polyribosome reductions and growth. Plant Physiol. 58:631-635.

Sadler, E. J., and C. R. Camp, Jr. 1984. A remotely programmed and interrogated weather station for research facility. Agron. Abstracts. p. 18

Savage, M. J., Cass, A., and deJager, J. M. 1981. Measurement of water potential using thermocouple hygrometers. S. Afr. J. Sci. 77:24-27.

Scholander, P. F., Hammed, H. T., Hemmingsen, E. A., and Broadstreet, E. D. 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. Proc. Nat'l. Acad. Sci. 52:119-125.

Shayo-Ngowi, A., and G. S. Campbell. 1980. Measurement of matric potential in plant tissue with a hydraulic press. Agron. J. 72:567-568.

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

Turner, N. C., and M. J. Long. 1980. Errors arising from rapid water loss in the measurement of leaf water potential by the pressure chamber technique Aust. J. Plant Physiol. 7:527-37.

Wenkert, W., E. R. Lemon, and T. R. Sinclair. 1978. Changes in water potential during pressure bomb measurement. Agron. J. 70:353-355.

Yegappan, T. M., and B. J. Mainstone. 1981. Comparisons between press and pressure chamber techniques for measuring leaf water potential. Expl. Agric. 17:75-84