Crop Water Stress Index of Pecans

T. W. Sammis, W. R. Riley, D. G. Lugg
ASSOC. MEMBER
ASAE

This article is reprinted from APPLIED ENGINEERING IN AGRICULTURE (Vol. 4, No. 1, pp. 39-45, 1988)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

ABSTRACT

RESEARCH was conducted in New Mexico to develop the baselines needed to calculate the crop water stress index (CWSI) for pecans (*Carya illinoensis* (Wang) K. Koch) using infrared thermometry.

Leaflet temperature, canopy temperature, vapor pressure deficit and leaflet diffusion resistance (r_s) were measured on six-year-old trees in an open canopy that received four trickle irrigation water application rates. Similar measurements were made at a second site on 14-year-old trees flood irrigated in a closed canopy, and at a third site on eight small trees growing in 113-liter barrel lysimeters. The CWSI lower baseline relates canopy temperature minus air temperature, (T_c-T_a) to the vapor pressure deficit (V), for trees that are not stressed for soil water. This relationship was linearly related with a coefficient of determination of 0.75, and was independent of canopy tree size. The CWSI upper baseline for non-transpiring trees was independent of V but was affected by the canopy cover and had a T_c-T_a value of 6.0 and 4.0°C for trees growing in an open and closed canopy respectively. During three dry-down cycles, where soil water stress caused by soil moisture depletion occurred to the pecans in the barrel lysimeters, the calculated relative evapotranspiration (1-CWSI) was linearly related to the measured relative evapotranspiration (E_t/E_{tmax}) with a coefficient of determination of 0.78.

Pecan tree r_s was curvilinearly related to CWSI. During diurnal cycles, pecan tree r_s decreased early in the morning as light intensity increased, remained steady during the midday and increased late in the afternoon because of decreasing illumination. An error of 3.5% was made in estimating pecan tree r_s from measurements taken only on the abaxial leaflet surface. Leaflet diffusion resistance measurements taken on the edge of the canopy can only be used to represent an average value for the tree having open canopies.

INTRODUCTION

Pecans (*Carya illinoensis* (Wang) K. Koch) are irrigated in New Mexico, where rainfall averages 20 to 25 cm yr^{-1}, to provide sufficient soil water for nut production. Full-grown pecan trees use 100 to 130 cm of water each year in the Rio Grande valley of New Mexico and Texas (Miyamoto, 1983). Soil moisture stress from pollination in early May to shell-hardening in late July reduces nut size, while stress later in the season lowers nut quality (Kilby, 1980). Periods of drought may also limit pecan nut production in the southeastern United States, where normal rainfall is around 120 cm yr^{-1} (Daniell, 1979). In Georgia, nut yields from orchards where trickle irrigation was used to supplement rainfall were 356 kg ha^{-1} higher than in orchards receiving only rainfall Daniell, 1979). The quality of nuts grown in Georgia was also improved by using trickle irrigation to supplement rainfall (Worley, 1979). Accordingly, preventing water stress by proper irrigation management is essential for high yield and quality of nuts.

The crop water stress index (CWSI) has been proposed to help improve the efficiency of irrigation management (Idso et al., 1981a). The CWSI is calculated as a ratio between an upper and a lower baseline. The lower baseline is the relationship between canopy temperature minus air temperature (T_c-T_a) and vapor pressure deficit (V) when the crop is transpiring at the potential rate. This relationship was found to be linear, and has been determined for many crops under both sunlit and completely shaded conditions (Idso, 1982). The linear relationship between V and T_c-T_a appears to be applicable over a large geographic area (Idso et al., 1981a), but may be both species and variety dependent (Idso, 1982). The upper baseline is defined as the T_c-T_a when the crop is not transpiring, and has been found to be independent of V but dependent on air temperature and radiation (Idso et al., 1981b).

Transpiration rates are controlled, in part, by stomatal aperture. Cotton (*Gossypium hirsutm* L.) stomatal conductance declined as the CWSI increased, demonstrating that stomatal control of transpiration can be measured using infrared thermometry (Reginato, 1983).

The objectives of this experiment were to, (a) develop the relationships needed to calculate the CWSI for pecans using the method of Idso et al. (1982a), (b) determine the relationship between CWSI and leaflet diffusion resistance (r_s), (c) investigate the effect of time of measurement and location within the canopy on r_s.

MATERIALS AND METHODS

Experiment

The first experiment was conducted at the New Mexico State University Leyendecker Plant Science Research Center (PSRC), 12 km south of Las Cruces, NM. The soil type was an Armijo clay loam (fine, montmorillonitic, thermic Typic Torrert). The pecan trees (cv. 'Western Schley') were planted in 1978 in a small orchard, which

Article was submitted for publication in March, 1987; reviewed and approved for publication by the Soil and Water Div. of ASAE in June, 1987. Presented as ASAE Paper No. 86-2123.

Journal Article 1320, Agricultural Experiment Station, New Mexico State University, Las Cruces.

The authors are: T. W. SAMMIS, Associate Professor, and W. R. RILEY, former Graduate Student, Agronomy Dept.; and D. G. LUGG, Horticulture Dept., New Mexico State University, Las Cruces.

Acknowledgment: The work upon which this publication is based was supported in part by funds provided through the New Mexico Water Resources Research Institute by the U.S. Department of the Interior, Office of Water Research and Technology, as authorized upon the Water Research and Development Act of 1978, P. L. 95-467, under Project No. 1345669.

TABLE 1. SEASONAL PRECIPITATION AND IRRIGATION WATER APPLIED TO PECANS UNDER FOUR IRRIGATION TREATMENTS, LEYENDECKER PLANT SCIENCE RESEARCH CENTER, LAS CRUCES, NM, 1979-84

Year	Precipitation	Irrigation	Applied water*			
			1	2	3	4
	---- mm ----	---no.---	--------liter tree^{-1}----------			
1979	195	4	492	440	319	215
1980	227	7	3172	2532	1797	1388
1981	239	8	5337	4003	3092	2045
1982	260	13	4591	3205	2414	2115
1983	217	12	6266	4406	3669	2510
1984	335	22	7134	5178	3871	2787
Mean			4498	3294	2527	1843

*Includes yearly precipitation based on an area equal to the projected area of the crown of the trees.

consisted of six rows of 29 trees each. Only the four interior rows were used in this study. There was 5.3 m between the trees in each row, and 7.7 m between rows.

A trickle-irrigation system was used to apply four irrigation treatments from 1978 to 1985 to develop the relationship between CWSI and r_s and to develop the upper and lower baselines for the CWSI. Irrigation treatment 1 maintained the medium size trees under non-soil-water-stress conditions. The treatment consisted of applying a volume of water equal to the daily pan evaporation times the projected crown area of the largest tree in this treatment, then adding 10% to account for additional transpiration due to advective energy. Projected crown area was determined by measuring the canopy diameter in several directions. The irrigation treatments 2, 3 and 4 were 0.75, 0.50 and 0.25, respectively, of treatment 1 but the final irrigation amounts applied were 0.73, 0.56, and 0.43 of treatment 1 for treatments 2, 3, and 4, respectively (Table 1).

The trickle system consisted of 13 mm tubing with four clip-on emitters per tree in treatment 1 and two emitters per tree in the other treatments. The emitter rate was 3.78 L h^{-1} at a pressure of 103 kPa. From planting until the end of the 1983 growing season, all trees were irrigated when tensiometers in treatment 1 reached -40 kPa. Three tensiometers were placed 0.15 m from an emitter at a depth of 0.3 m. After stomatal resistance data in 1983 indicated that the trees were undergoing cycles of increasing moisture stress between irrigations, trees were watered twice a week in 1984 and 1985. Precipitation was measured with a standard 20 cm rain gauge located adjacent to the orchard. Precipitation, number of irrigations, and total amount of irrigation water applied to each tree in each irrigation treatment between 1979 and 1984 are shown in Table 1. All trees received limited water application in 1985 equal to the amount received in 1983.

The trees were fertilized with urea beginning in 1979 at the recommended rate (Herrera, 1983), and received 0.32 kg and 0.36 kg of N per tree in March 1983 and May 1984, respectively. Zinc fertilizer (applied as a formulation containing 15% N, 5% Zn as a metal, 6.2% Zn as ZnO) was sprayed on the leaves in early June 1983 and 30 May 1984 at a rate of 100 mL per 37.8 L of water.

In 1983 on 17 dates from 26 May to 29 July, the temperature of 40 leaflets on the outside edge of the canopy of each of two trees from each irrigation treatment was measured using an infrared thermometer (Everest Interscience Model 210 between 1130 and 1400 h (MDT). The thermometer was held 0.2 to 0.25 m from the leaflets at a 2 m height. Ten leaflets were measured on the north, south, east and west sides of each tree. The leaflets were sunlit except the northerly facing leaflets, which were shaded due to the sun orientation. In 1984, the temperature of 15 randomly selected leaflets from each of three trees in each treatment was measured between 1200 and 1400 h (MDT) on nine dates from 5 July to 21 August. The leaflets measured were located near the outer edge of the canopies and were both sunlit and shaded. Temperature measurements of 15 leaflets from each of four trees in treatment 1 were also taken from 0700 to 1900 h at 2 h intervals throughout the day to determine diurnal effects. Measurements were taken on 19 July, 26 July and 2 August 1984.

To simulate the effect of stomatal closure on canopy temperature of trees in an open canopy and to determine the upper baseline of the CWSI, a large limb with fully sunlit leaflets was severed from a main tree trunk, so that the leaflets would cease transpiration, on 1, 15 and 21 August 1984 and on 15 dates from 10 July to 27 August 1985. The limbs were tied to a pole using twine at the same height and angle as they had been on the tree. The limbs were placed 5 m from the tree so that the foliage was unshaded. After transpiration had become less than 0.5 g cm^{-2} s^{-1}, determined using a steady state porometer (Li-Cor Model 1600), canopy temperature (T_c) was measured by holding the infrared thermometer approximately 2 m from the foliage of the limbs. Ten readings each were taken from the east and west between 1200 and 1400 h (MDT). To simulate the effect of stomatal closure on T_c of trees in a closed canopy, a limb supporting dense foliage was severed from a tree on the same dates in 1985 as was done for the open canopy. The limbs were tied back in place on the tree. The limbs were selected because the foliage was partially shaded by the canopy of the tree and an adjacent tree. Measurements were taken in the same manner as for the open canopy.

An Assman psychrometer was used to measure wet (T_b) and dry (T_a) bulb air temperatures at the same time T_c was measured in order to determine the vapor pressure deficit (V). Net radiation was measured with a Fritschen net radiometer suspended approximately 0.3 m above the top of each tree. Solar radiation was measured at a nearby climate station using an Eppley pyranometer.

The relationship between CWSI and leaflet diffusion resistance (r_s) was developed using measurements of r_s taken using a steady state porometer for three trees in each of treatments 2, 3, and 4 between 1200 and 1400 h (MDT) in August 1984. The trees were the same as those used for leaflet temperature measurements. For each tree, r_s was measured on the abaxial surface of 10 randomly selected sunlit leaflets located at the outer edge of the canopy. In addition, r_s was measured from 0700 to 1900 h on 19 July, 26 July and 2 August 1984 for three trees in irrigation treatment 1 using the same procedure as described above. Although pecan leaflets lack stomata on their adaxial surfaces (Storey et al., 1979; Wetzstein and Sparks, 1984), r_s of the adaxial and abaxial surfaces of 50 leaflets on trees in irrigation treatment 1 were measured on 21 September and 1 October 1984 to determine the amount of error associated with measuring only the abaxial r_s.

The effect of leaflet location on r_s, was determined by measuring r_s of leaflets at the outer edge of the canopy and leaflets near the trunk of trees in open canopies. Trees ranged in trunk diameter from 5.2 to 29.1 cm. Measurements were taken in treatments 1 and 4 between 1300 and 1500 h (MDT) during selected days in July and August 1984. Similarly, r_s was measured for leaflets at the outer edge of the canopy and for leaflets near the trunk of trees in closed canopies. These trees were in a flood-irrigated orchard adjacent to the experimental one site. Mean trunk diameter was 21 cm, and measurements were taken between 1300 and 1500 h (MDT) on 2 and 14 August 1984.

Experiment 2

The second experiment was conducted in a 250 ha orchard at the Salopek Farm, 10 km south of Las Cruces, NM. The soil type was a Pajarito fine sandy loam (coarse-loamy, mixed, thermic Typic Camborthid). The trees were 14 years old in 1984. The fertilization, irrigation timing and all other cultural practices were determined by the farmer. Measurements were taken within the orchard in a border containing 136 trees. The orchard was flood irrigated, and the amount of water applied was approximately 56,000 L/tree during the 1984 growing season. On 6 October 1984, in order to determine the relationship between T_c-T_a and V for well-watered trees in a closed canopy, T_a, V and T_c were measured every 30 min from 1000 to 1600 hours. Mean T_c was estimated using 15 separate measurements taken by pointing the infrared thermometer at different portions of the fully sunlit canopy from a distance of 10 to 15 m. In this manner, canopy temperature of several trees was measured simultaneously. Measurements of V and T_a were taken as described previously. Net radiation was not measured at this site because of the height of the trees.

Experiment 3

A third experiment was undertaken at the New Mexico State University Fabian Garcia Horticulture Farm, located in Las Cruces, NM. To collect data to verify the CWSI developed using data from experiment one and two and to collect additional data relating r_s to CWSI. One pecan tree was planted in 1976 in each of eight 113-L lysimeter barrels containing a 1:1:1 mixture of peat moss, perlite and vermiculite. A trickle system with two emitters per barrel supplied water to the trees, which were located in an open sunlit area. Three dry-down cycle experiments were conducted, where the soil water content was depleted until relative transpiration (actual evapotranspiration (E_t) divided by maximum evapotranspiration (E_{tmax})) was 0.5, 0.37 and 0.11 for dry-down cycles 1, 2 and 3, respectively. Six barrels were irrigated to field capacity to start the dry-down experiments. Dry down cycle 1 was conducted on four trees. These trees were then irrigated and the soil maintained at field capacity for 2 days before the second dry-down cycle. The other two trees were allowed to dry from field capacity to permanent wilting point, referred to as dry down cycle 3. Measurements of r_s, T_c, T_a, V, and E_t were taken daily between 1430 and 1530 hours from 21 August to 5 September 1984 as the plant available water (PAW) was depleted during the three dry-down cycles. Canopy temperature and r_s were measured on 10 and 15 leaflets per tree, respectively, and the 24-hr weight change of the barrels was measured with a beam balance to estimate E_t during the dry-down cycles. The measurements of T_a and

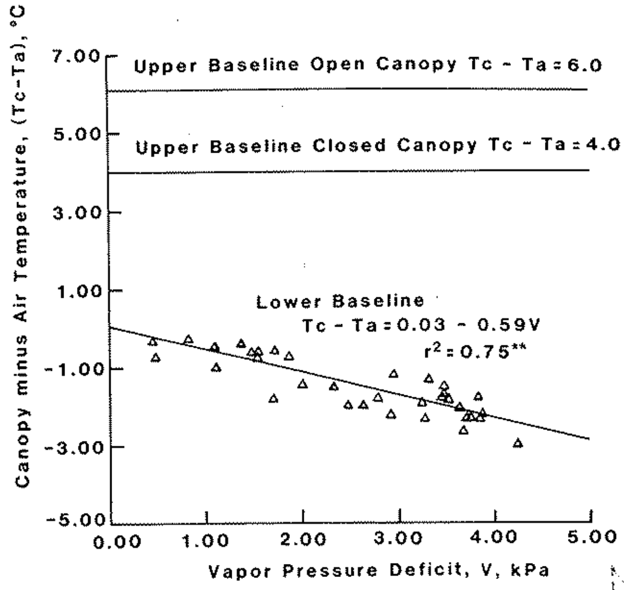

Fig. 1—Relationship between vapor pressure deficit (V) and canopy minus air temperature (T_c-T_a) for fully transpiring (lower baseline) and non-transpiring (upper baseline) pecan trees, Leyendecker Plant Science Research Center, Las Cruces, NM

V were taken as described previously. Two of the eight lysimeters were irrigated daily to maintain PAW near field capacity to measure E_{tmax}. Plastic trash bags covered the top of the barrel and were tightly wrapped and taped around the trunk of the tree to reduce evaporation losses.

Twenty-four hours after an irrigation, the barrels were weighed to determine field capacity (approximately 70% water on a volume basis). Moisture content at the permanent wilting point (PWP) (approximately 38% on a volume basis) was determined by allowing the two trees in the third dry-down cycle to deplete the PAW until leaflets shed.

RESULTS AND DISCUSSION

The relationship between canopy minus air temperature (T_c-T_a) and vapor pressure deficit (V) under non-soil-water-stress conditions is shown in Fig. 1. The data were taken between 1030 and 1330 h on 6 October 1984 for the flood-irrigated trees at the Salopek Farm (Table 2) and from part of the diurnal cycle on 19, 26 July and 2 August on treatment 1 at the Leyendecker Plant Science Research Center (Table 2). The reason for deleting late afternoon data and, early morning data on 2 August will be discussed later. Data were also taken on 11 periods between 26 May and 29 July 1983 and on five periods between 5 July and 21 August 1984 (Table 3). Because of the variability in leaflet temperatures of the trickle-irrigated trees growing in an open canopy, a seven-term and four-term running average were used in 1983 and 1984, respectively. Idso (1982) used a three-term running average to smooth T_c-T_a data. When temperature measurements were taken on leaflets and not the full canopy because of the open nature of the canopy, then a large sample size (greater than 40 measurements) or a form of running average is essential to calculate the CWSI. The large sample size can be accomplished by recording the output of the infrared thermometer using a portable data acquisition system.

TABLE 2. CANOPY TEMPERATURE MINUS AIR TEMPERATURE (T_c-T_a), VAPOR PRESSURE DEFICIT (V), NET RADIATION (R), AND SOLAR RADIATION (Q) AT THE LEYENDECKER PLANT SCIENCE RESEARCH CENTER AND THE SALOPEK FARM, LAS CRUCES, NM, 1984

Date	Time	T_c-T_a °C	V, kPa	R, W m^{-2}	Q, W m^{-2}
		Plant Science Research Center			
19 July	0700*	-0.70	0.49	38	128
19 July	0900*	-0.75	1.56	350	372
19 July	1100*	-2.20	2.93	565	739
19 July	1300*	-2.63	3.68	662	938
19 July	1500*	-2.97	4.25	565	895
19 July	1700	-4.27	4.44	331	642
19 July	1900	-4.64	4.02	38	220
26 July	0700*	-0.30	0.46	38	14
26 July	0900*	-0.97	1.13	155	269
26 July	1100*	-0.57	1.49	350	493
26 July	1300*	-1.76	1.69	448	702
26 July	1500	-2.17	2.13	233	550
26 July	1700	-2.06	2.39	233	407
26 July	1900	-1.41	1.79	19	138
02 Aug	0700	-2.68	0.51	38	9
02 Aug	0900	-1.43	0.72	136	243
02 Aug	1100*	-1.41	2.02	565	699
02 Aug	1300*	-1.78	2.80	662	885
02 Aug	1500*	-1.47	3.48	584	770
02 Aug	1700	-3.77	3.48	331	602
02 Aug	1900	-3.25	2.80	19	27
		Salopek Farm			
06 Oct	1000	-0.72	0.50	†	491
06 Oct	1030*	-0.23	0.84		
06 Oct	1100*	-0.44	1.11		606
06 Oct	1130*	-0.37	1.39		
06 Oct	1200*	-0.58	1.56		723
06 Oct	1230*	-0.55	1.73		
06 Oct	1300*	-0.70	1.88		776
06 Oct	1330*	-0.98	2.04		
06 Oct	1400	-0.36	2.19		761
06 Oct	1430	-0.17	2.34		
06 Oct	1500	-1.31	2.35		685
06 Oct	1530	-0.08	2.37		
06 Oct	1600	-0.85	2.34		381

*Used to calculate lower baseline of crop water stress index.
†No measurements were made because of the height of the trees.

There was a linear relationship between T_c-T_a and V for trees maintained under non-soil-water-stress conditions. This relationship had a smaller slope and intercept than that found for alfalfa (*Medicago sativa* L.) and spring barley (*Hordeum vulgare* L.) at Las Cruces, New Mexico (Abdul-Jabbar et al., 1985; Tubaileh et al., 1986). The baseline also had a smaller slope and intercept than found for fig trees (Idso, 1982).

The T_c-T_a for non-transpiring pecan leaflets in open and closed canopies (Table 4 and Fig. 1) was not related to V. The upper baseline for an open canopy where the leaves of adjacent trees did not shade each other was 6.0°C, and for a closed canopy was 4.0°C (Table 4). The mean solar radiation was 827 and 891 W m^{-2} when the upper baselines were determined for the open and closed canopies, respectively. The mean temperature of non-transpiring leaflets on limbs simulating open and closed canopies was 40.0 and 37.7°C, respectively. The (T_c-T_a) for the non-transpiring pecan leaflets was not dependent on air temperature or radiation load. Tubaileh et al. (1986) reported the same results for spring barley. Consequently, using an upper baseline of 4°C for a closed canopy of 6°C for an open canopy will result in the most accurated calculation of the CWSI.

Idso (1982) indicated that measurements of T_c-T_a and V every half-hour throughout the day could be used to derive the lower baseline. In this study, measurements

TABLE 3. CANOPY TEMPERATURE MINUS AIR TEMPERATURE (T_c-T_a), VAPOR PRESSURE DEFICIT (V), AND NET RADIATION (R) AT THE LEYENDECKER PLANT SCIENCE RESEARCH CENTER, LAS CRUCES, NM, 1983 AND 1984

Date	T_c-T_a, °C	V, kPa	R, W m^{-2}
1983: 7-term running average			
26 May - 13 June	-1.17	2.96	676.7
27 May - 21 June	-1.30	3.32	685.0
31 May - 22 June	-1.68	3.47	657.2
01 June - 24 June	-1.76	3.45	626.6
03 June - 28 June	-2.03	3.64	612.6
08 June - 29 June	-2.20	3.89	609.9
13 June - 08 July	-2.30	3.76	598.7
21 June - 15 July	-2.30	3.86	593.1
22 June - 19 July	-2.30	3.71	587.6
24 June - 27 July	-1.81	3.52	601.5
28 June - 29 July	-1.75	3.84	629.4
1984: 4-term running average			
05 July - 27 July	-1.90	3.25	609.2
16 July - 01 Aug	-2.30	3.28	584.8
23 July - 13 Aug	-1.96	2.65	575.0
27 July - 17 Aug	-1.96	2.49	565.3
01 Aug - 21 Aug	-1.47	2.35	594.5

TABLE 4. LEAFLET TEMPERATURE AND CANOPY MINUS AIR TEMPERATURE (T_c-T_a) MEASURED ON CUT LIMBS AND SOLAR RADIATION AT THE LEYENDECKER PLANT SCIENCE RESEARCH CENTER, LAS CRUCES, NM, 1984 AND 1985

Date	Leaflet temperature		T_c-T_a		Solar radiation
	Open canopy, °C	Closed canopy, °C	Open canopy, °C	Closed canopy, °C	W m^{-2}
1984					
01 Aug	41.7		8.9		934
15 Aug	35.4		6.0		501
21 Aug	37.8		7.8		905
1985					
10 July	44.2	40.2	6.6	4.5	927
11 July	40.7	38.7	6.0	3.0	853
17 July	41.1	39.1	4.7	3.0	924
18 July	42.3	40.5	5.1	3.3	904
02 Aug	36.2	38.4	4.5	6.5	917
05 Aug	36.8	38.2	2.9	3.7	922
06 Aug	40.7	39.5	7.4	6.2	925
07 Aug	40.5	38.8	6.3	4.1	910
08 Aug	41.2	38.8	8.2	5.0	860
12 Aug	33.6	32.0	5.0	3.4	895
16 Aug	38.1	36.0	6.4	4.3	920
21 Aug	35.3	31.8	5.0	1.5	791
22 Aug	37.9	36.8	3.8	2.7	902
23 Aug	41.1	38.4	9.0	5.4	894
27 Aug	35.5	34.1	4.4	3.0	833
Mean	40.0	37.4	6.0	4.0	827

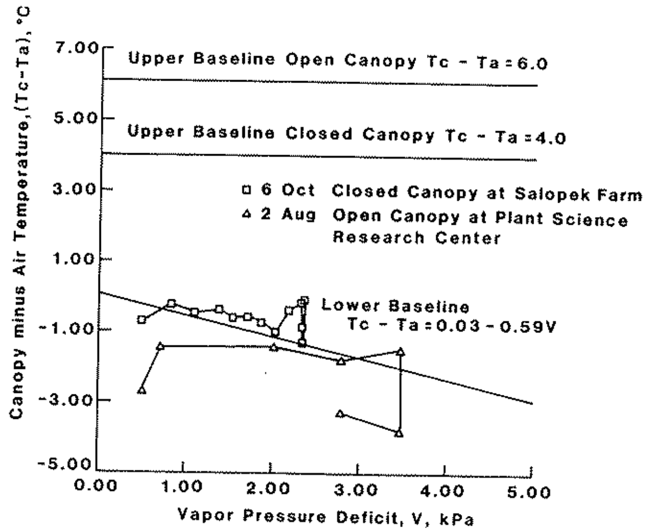

Fig. 2—Diurnal variation in the relationship between vapor pressure deficit (V) and canopy minus air temperature (T_c-T_a) for pecan trees, Las Cruces, NM, 1984.

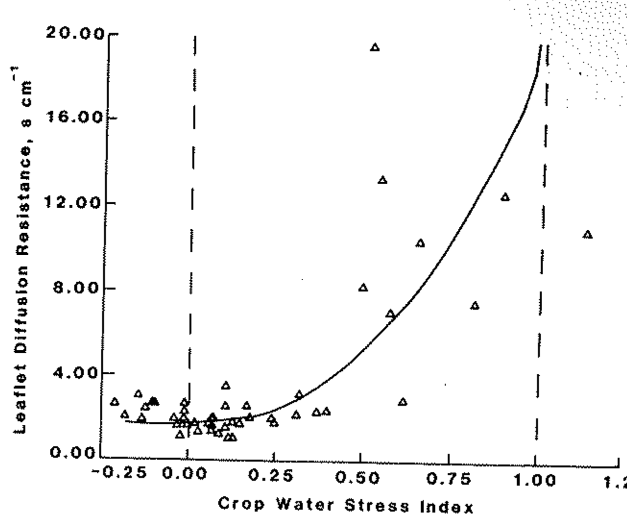

Fig. 4—The relationship between midday leaflet diffusion resistance and crop water stress index for pecan trees, Las Cruces, NM.

taken between 1100 and 1500 h fell on the lower baseline (Table 2, Fig. 2). Measurements taken before and after this time were off the baseline on some days but followed the baseline on other days (Table 2). Idso et al. (1981a) reported a similar trend for squash (*Cucurbita pepo* L.). The deviation from the baseline that occurs early in the morning is a function of stomatal aperture (Idso et al., 1981a). Leaf temperature drops at night and, at sunrise, radiant and convective heat exchange determine T_c-T_a until stomata open fully and transpiration occurs at the potential rate. The time of morning that this occurs depends on the radiation cooling that has occurred the night before. The departure from the lower baseline late in the afternoon is a response to decreasing illumination (Idso et al., 1981a), and T_c-T_a becomes more of a function of the night-time radiation balance. Cloud cover also caused a deviation from the baseline at 1500 h on 26 July.

To verify the upper and lower baselines, relative evapotranspiration, which is the ratio of actual evapotranspiration (E_t) to maximum evapotranspiration (E_{tmax}), and CWSI were calculated from data using the barrel lysimeters during each day of the three dry-down cycles. Maximum daily evapotranspiration was measured using the two control barrel lysimeters. Jackson et al. (1981) showed that E_t/E_{tmax} is equal to 1 minus CWSI (1-CWSI). As the soil water in the six barrel lysimeters used to measure E_t was depleted, E_t/E_{tmax} decreased as the CWSI increased. Relative evapotranspiration was linearly related to 1-CWSI (Fig. 3). Similar results wre found by Abdul-Jabber et al. (1985) for alfalfa.

Leaf diffusion resistance (r_s) measurements were taken on the abaxial surface of the leaflets at midday at the same time that CWSI was determined for trees in irrigation treatments 2 through 4 (experiment 1) at the Leyendecker Plant Science Research Center, and for trees in the barrel lysimeters (experiment 3) during the dry-down cycles. The relationship between CWSI and r_s is shown in Fig. 4. Leaflet r_s averaged 1.6 s cm^{-1} when the CWSI was 0. This r_s is higher than that reported for

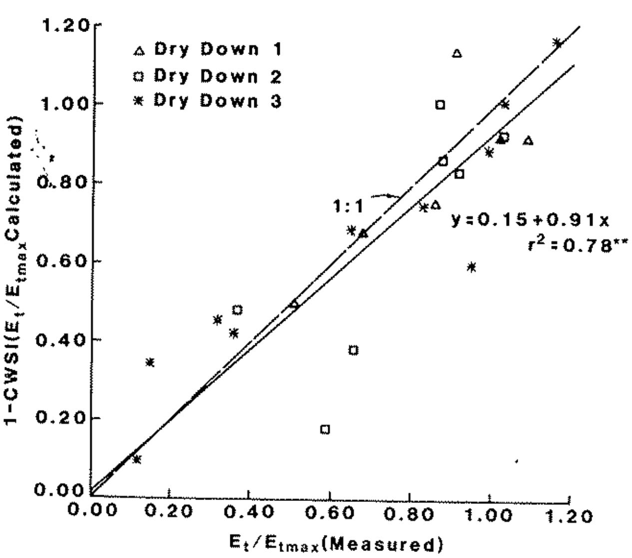

Fig. 3—Relationship between 1-CWSI (calculated E_t-E_{max}) and E_t-E_{tmax} measured for pecan trees in barrel lysimeters during three dry-down cycles at Las Cruces, NM.

TABLE 5. DIFFUSION RESISTANCE ON THE ABAXIAL AND ADAXIAL SURFACES OF PECAN LEAFLETS, LEYENDECKER PLANT SCIENCE RESEARCH CENTER, LAS CRUCES, NM, 1984

Date	Diffusion resistance			Error*, %
	Abaxial surface, s cm^{-1}	Adaxial surface, s cm^{-1}	Both surfaces, s cm^{-1}	
21 Sept	2.8	78.4	2.7	3.5
21 Sept	3.2	79.3	3.1	4.0
21 Sept	2.2	90.8	2.2	2.4
21 Sept	2.5	99.4	2.4	2.5
21 Sept	4.0	47.6	3.7	8.4
06 Oct	1.8	160.0	1.8	1.1
06 Oct	3.5	112.0	3.4	3.1
06 Oct	4.1	292.0	4.0	1.4
06 Oct	2.7	37.4	2.5	7.2
06 Oct	2.4	96.3	2.3	2.5
06 Oct	2.9	139.8	2.8	2.1
			Ave.	3.5

*Percent error between computing leaflet diffusion resistance using abaxial and adaxial surface of leaflet and using only abaxial surface of leaflet.

cotton (*Gossypium hirsutum* L.), which was 0.4-0.9 s cm^{-1} at a CWSI equal to 0 (Idso et al., 1982). The lack of stomata on the adaxial surface of pecan leaflets explain the greater r_s than found for cotton. However, the transpiration rate of the canoy of a mature pecan orchard with full leaf cover approaches that of potential evapotranspiration (Miyamoto, 1983) because, even though the r_s of pecans is high, the total number of leaflets on a tree is large.

Leaf diffusion resistance measurements were taken on the abaxial and adaxial surfaces of leaflets of non-soil-water-stressed trees at the Leyendecker Plant Science Research Center (Table 5). The error associated with measuring r_s on only the abaxial surface of the leaflets was 3.5% (Table 5). The r_s of the adaxial surface varied considerably depending on the placement of the porometer. However, in all cases, the adaxial surface r_s was more than 10 times that of the abaxial surface.

Daily changes in r_s are shown in Fig. 5. There was a high r_s early in the morning when the lack of solar radiation caused stomata to be closed. The r_s then levelled off and remained near a minimum value between 0900 and 1700 h, then increased again as light intensity decreased late in the day. Similar fluctuations in r_s have also been reported for cotton (Jordon and Ritchie, 1971), corn (Ritchie, 1973) and sorghum (Ritchie and Jordan, 1972). The r_s of soil-water-stressed cotton fell from 40 to 2.5 s cm^{-1} within 2 h after sunrise, and remained near this minimum valve between 0900 and 1700 h (Jordan and Ritchie, 1971).

The r_s measurements reported previously were taken on leaflets located at the outside of the canopy under sunlit conditions. To obtain an integrated r_s for the entire tree, measurements need to be taken not only on the outside of the tree but in the interior of the canopy where leaflets are shaded. In July and August 1984, r_s was measured on sunlit leaflets on the canopy edge and shaded leaflets near the trunk of small- and medium-size trees (Table 6). The ratio between r_s of sunlit leaflets and r_s of shaded leaflets was 0.81 for small trees in an open canopy, 1.0 for medium-size trees in an open canopy and 0.46 for medium-size trees in a closed canopy. The r_s measurements made on the canopy edge of medium-size trees in a closed canopy are not representative of the

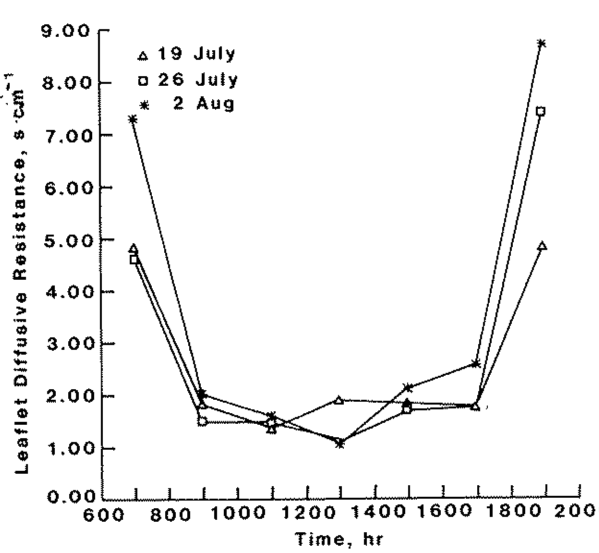

Fig. 5—Diurnal variation in leaflet diffusion resistance of pecan trees under non-soil-water-stress conditions, Las Cruces, NM, 1984.

TABLE 6. DIFFUSION RESISTANCE ON THE ABAXIAL SURFACE OF SUNLIT AND SHADED LEAFLETS, LEYENDECKER PLANT SCIENCE RESEARCH CENTER, LAS CRUCES, NM, 1984

				Leaflet diffusion resistance		
Date	Irrigation treatment	Trunk diameter, cm	Sample size	Sunlit leaflets, mean, s cm^{-1}	Shaded leaflets, mean, s cm^{-1}	Sunlit to shaded
			Small-size trees: Open canopy			
11 July	1	7.3	30	2.1	2.4	0.87*
11 July	4	5.2	30	1.7	2.0	0.86*
24 July	1	7.3	30	2.3	3.6	0.64*
24 July	4	5.2	30	1.8	2.6	0.70*
17 Aug	1	7.3	30	1.3	1.5	0.86*
21 Aug	1	7.3	20	1.5	1.6	0.96*
						0.81
			Medium-size trees: Open canopy			
30 July	1	23.6	10	1.2	1.1	0.91
14 Aug	1	29.1	10	1.2	1.1	1.09
						1.00
			Medium-size trees: Closed canopy			
02 Aug	Flood	21.6	20	1.9	4.8	0.39*
14 Aug	Flood	20.4	30	1.5	2.7	0.53*
						0.46

*Ratio statistically ($P \leq 0.05$) different from 1.

average r_s over the whole canopy, and would need to be adjusted accordingly. Leaflet diffusion resistance measurements can be used to schedule irrigation. Irrigation should be applied when midday sunlight r_s exceeds an average value of 1.6 s cm^{-1}.

CONCLUSIONS

The CWSI for pecans can be determined satisfactorily using the method presented by Idso et al. (1981a). The lower baseline was described by a linear relationship between T_c-T_a and V, and the upper baseline was 6.0°C for trees in an open canopy and 4.0°C for trees in a closed canopy. Pecan tree r_s increased as a curvilinear function of CWSI when measured under high light intensities at midday. An error of only 3.5% was made when r_s was measured on the abaxial leaflet surfaces only compared with measurements made on both the adaxial and abaxial leaflet surfaces. When r_s is measured at the outside of the canopy, it can be used to represent the mean r_s for the entire canopy as long as the trees are in open canopies. However, when trees are in closed canopies, a large portion of the leaflets are shaded and measurements must be taken from the outside to the inside of the canopy to obtain a mean r_s over the whole tree.

References

1. Abdul-Jabbar, A. S., D. G. Lugg, T. W. Sammis, and L. W. Gay. 1985. Relationships between crop water stress index and alfalfa yield and evapotranspiration. TRANSACTIONS of the ASAE 28(2):454-461.
2. Daniell, J. W. 1979. Trickle or drip irrigation of pecans. Proc. S.E. Pecan Grow. Assoc. 72:119-122.
3. Herrera, E. 1983. Pecan orchard fertilization. NMSU Coop. Ext. Serv. Guide H-602.
4. Idso, S. B., R. D. Jackson, P. J. Pinter, Jr., R. J. Reginato, and J. L. Hatfield. 1981a. Normalizing the stress degree day concept for environmental varibility. Agric. Meteorol. 24:45-55.
5. Idso, S. B., R. J. Reginato, R. D. Jackson, and P. J. Pinter, Jr. 1981b. Measuring yield-reducing plant water potential depression in wheat by infrared thermometry. Irrig. Sci. 2:205-212.
6. Idso, S. B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteorol. 27:59-70.

7. Idso, S. B., R. J. Reginato, and J. W. Radin. 1982. Leaf diffusion resistance and photosynthesis in cotton as related to a foliage temperature based plant water stress index. Agric. Meteorol. 27:27-34.

8. Jackson, R. D., S. B. Idso, R. J. Reginato, and P. J. Pinter, Jr. 1981. Canopy temperature as a crop water stress indicator. Water Resourc. Res. 17:1133-1138.

9. Jordan, W. R., and J. T. Ritchie. 1971. Influence of soil water stress on evaporation, root absorption and internal water status of cotton. Plant Physiol 48:783-788.

10. Kilby, M. W. 1980. Fall irrigation of pecans. Pecan South 7(4):38-39.

11. Miyamoto, S. 1983. Consumptive water use of irrigated pecans. J. Amer. Soc. Hort. Sci. 108:676-681.

12. Reginato, R. J. 1983. Field quantification of crop water stress. TRANSACTIONS of the ASAE 26(3):772-775.

13. Ritchie, J. T. 1973. Influence of soil water status and meteorological conditions on evaporation from a corn canopy. Agron. J. 65:893-897.

14. Ritchie, J. T. and W. R. Jordan. 1972. Dryland evaporative flux in a subhumid climate. IV. Relation to plant water status. Agron. J. 64:173-176.

15. Storey, J. B., P. N. Westfall, and M. W. Smith. 1979. Why do pecans need zinc? Pecan Quarterly 13:3-9.

16. Tubaileh, A. S., T. W. Sammis, and D. G. Lugg. 1986. The utilization of thermal infrared thermometry for detection of water stress in spring barley. Agr. Water Management 12:75-85.

17. Wetzstein, H. Y., and D. Sparks. 1984. A closer look at the pecan leaf. Pecan South (January) 11-17.

18. Worley, R. E. 1979. Drip irrigation for pecan trees. Proc. S. E. Pecan Grow. Assoc. 72:123-125.