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Non water-stressed baselines for sunflowers

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Abstract

Effective use of the Crop Water Stress Index (CWSI) to quantify water stress requires knowledge of a non water-stressed baseline (NWSB). This study was conducted to determine effects of plant population, plant development, leaf temperatures, canopy temperatures, and time of measurement on NWSB for sunflower (*Helianthus annuus* L., "Triumph 560-A, 822B-R"). Measurements of canopy and single leaf temperatures were made with an infrared thermometer (IRT) throughout the growing season on plants in three populations (2.6, 5.3, and 7.9 plants·m^{-2}) grown under full irrigation to provide a range of ground cover conditions. Plant population only affected NWSB based on canopy temperatures when leaf area index (LAI) was less than 2.0. Non water-stressed baselines based on single leaf temperatures were not affected by plant population. Slopes of NWSBs were similar during vegetative and flowering growth stages, but declined in absolute value during grain-filling. Non water-stressed baselines derived from midday temperature and vapor pressure deficit (VPD) measurements were not different from NWSBs derived from diurnal measurements. Measurements of single leaves of sunflower plants made with an IRT can be used to evaluate water stress early in the growing season before canopy closure occurs, or in non-irrigated production areas where canopy closure may not occur, and during grain-filling when heads become very warm and disrupt canopy temperature measurements.

Keywords: Sunflower; Infrared thermometry; Canopy temperature; Water stress

1. Introduction

Infrared thermometry can be used for rapid quantification of water stress in crop species by use of the Crop Water Stress Index (CWSI) (Idso et al., 1981; Gardner et al., 1992). Crop Water Stress Index in its empirical form requires a non water-stressed baseline (NWSB) relationship between vapor pressure deficit (VPD) and the canopy-air temperature difference (d*T*). These relationships have been determined for a number of crop species, generally under full canopy conditions. However, in many areas agricultural production in

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row crop situations never achieve full cover, and viewing of the soil surface by the infrared thermometer (IRT) greatly affects the measured canopy temperature. Wanjura et al. (1984), Hatfield et al. (1985), and Wanjura et al. (1990) found that the absolute value of the slope of the NWSB equation for cotton was smaller under partial canopy conditions than under full canopy conditions. Wanjura et al. (1990) found that the slope of the NWSB for cotton became more negative with plant development until canopy cover reached 70%. Even when care is taken to ensure that no soil is viewed by the IRT, the baselines may be different due to differences in aerodynamic roughness of the canopies and convective heat exchange.

Partial canopy conditions also occur early in the growing season of most crop species when plants are very small. Evaluation of water stress at these times with an IRT would be a valuable research and production tool, but elimination of viewed soil surface would be impossible except if single leaves sufficiently large to cover the entire IRT field of view were measured. Pinter and Reginato (1982) calculated CWSI from cotton leaf temperatures measured with an IRT and found results that suggested that a different NWSB might be needed early in the season compared with later. They attributed this not to viewing soil surface by the IRT when single leaf measurements were made, but to a closer coupling of the leaf temperatures of smaller plants early in the season to their thermal radiant environment than occurs with larger plants.

NWSB have generally been determined from diurnal, concurrent measurements of dT and VPD (Idso et al., 1981; Idso, 1982), although Gardner et al. (1992) suggest that a better method is to make measurements of dT and VPD throughout an entire growing season at the time of day that water stress measurements are most likely to be taken (typically early to mid afternoon). Wanjura et al. (1990) found that determining NWSB from diurnal data sets with early morning readings deleted improved the R^2 values of the linear regressions fit to the data and improved the seasonal behavior of the NWSB slopes.

Non water-stressed baselines have been shown to change with plant development. This shift may be the result of the appearance of nontranspiring reproductive structures, such as heads in small grains (Idso, 1982; Hatfield et al., 1984), or it may be a result of changing transpirational ability as leaves age (Burke et al., 1990). Wanjura et al. (1990) documented a shift in NWSB for cotton (lower slope) for the end of the season, but they did not speculate on the cause. Pinter and Reginato (1982) found that well-watered dT response of cotton to environmental conditions changed with age of the crop, probably due to such factors as osmotic potential, leaf diffusion resistance, and leaf thickness.

The objectives of this study were to:

(1) Determine NWSB for sunflowers based on either canopy or leaf temperatures made with an IRT under varying plant population conditions.
(2) Determine if NWSB determined from canopy measurements were different from NWSB determined from leaf measurements.
(3) Determine if seasonal shifts of NWSB occur concurrently with changes in plant growth stage.
(4) Determine if NWSB determined from diurnal data differ from NWSB determined from early afternoon data.

2. Materials and methods

This study was conducted during the 1990 growing season at the USDA-ARS Central Great Plains Research Station (40°9′N, 103°9′W, 1384 m a.m.s.l.), 6.4 km east of Akron, CO. The soil type at this location is a Rago silt loam (fine montmorillonitic mesic Pachic Argiustoll). Sunflowers were planted on 5 June 1990 at a population of 101300 plants·ha^{-1} in a solid set irrigation area. Row spacing was 38 cm and row direction was north-south. After sunflower emergence, treatment plots (3.05×6.10 m) were established by thinning stands to plant populations of 2.6, 5.3, and 7.9 plants·m^{-2} (hereafter designated as low, medium and high, respectively) to provide a range of canopy cover and exposed soil surface conditions. The plots were arranged in a completely random design with four replications of the three plant density treatments.

Non water-stressed conditions were maintained throughout the entire growing season by applying weekly irrigations (by overhead impact sprinklers) to replace evapotranspirational losses as calculated by the Penman equation utilizing weather data acquired from an adjacent automated weather station.

Leaf area index (LAI) measurements and plant height measurements were made periodically during the growing season. LAI was measured with a plant canopy analyzer (LAI-2000, Li-Cor, Inc., Lincoln, NE)* which employs a radiative transfer model to estimate LAI from readings of light interception by the crop canopy.

Copper-constantan thermocouple arrays of five thermocouples wired in parallel were placed in the center of the interrow space at a depth of 2.5 cm below the soil surface in one replication of each population treatment. The soil temperature data were logged with a data logger (CR21, Campbell Scientific, Logan, UT) every 60 s and 15-min averages were computed during the time that canopy and leaf temperature data were being collected.

Canopy and leaf temperatures were measured with hand-held IRT (Model 112 Agritherm, Everest Interscience, Fullerton, CA)*, each with a 3° field of view, detecting radiation in the 8- to 14-μm waveband. Spot size for the canopy measurements ranged from 0.14 to 0.42 m^2, depending on IRT height and canopy height as calculated by the program of Gardner et al. (1992). When spot size was largest, IRT measurements still came from only the four center rows of each 8-row plot to minimize border effects. Border effects due to differential soil water contents under the three plant populations were probably not a factor in any case due to the frequency of irrigations. Measurements were made every 45 min from 1015 to 1615 MDT whenever the sun was unobscured by clouds. Data were recorded with portable data loggers (Polycorder, Model 516B, Omnidata International, Logan, UT)*. The IRTs were checked against a portable blackbody reference before and after each set of readings, and readings were adjusted for differences. At the same time, air temperature and VPD were measured at a height of 1.5 m above the soil surface with an Assman-type psychrometer (Model 5230, WeatherMeasure, Sacramento, CA)* in an open area adjacent to the plots. The before and after measurements were averaged to give one set of air temperature and VPD readings per measurement period.

Canopy temperatures were made from the SE and SW corners of each plot, with six

* Trade names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

instantaneous measurements taken from each direction. Low viewing angles were used early in the season to minimize the amount of soil viewed by the IRT. Leaf temperatures were measured simultaneously with another IRT by measuring a single, upper-canopy, fully sunlit leaf on 12 plants per plot. The IRT was held as close to the leaf as possible without shading it (typically about 5 cm from the leaf). Spot size for the IRT held in this manner was measured following the technique of Jackson et al. (1980) in which a piece of aluminum foil is moved into the IRT field of view from around the perimeter of the viewed area until the signal from the IRT drops rapidly. Spot size remained nearly constant (approximately 15 cm^2) over a range of target distances varying from 4 to 37 cm.

For each set of measurements, one canopy temperature and one leaf temperature were computed as the averages of the 12 individual canopy and 12 individual leaf measurements, respectively, made in each plot. Measurements were averaged over replicated treatments.

3. Results

The primary factor influencing IRT-measured canopy temperatures early in the growing season and with low plant population conditions is viewed soil surface. Leaf area index development for the three plant populations is shown in Fig. 1. The boxes denote the five sampling periods during which canopy temperature measurements were made and the growth stages (Schneiter and Miller, 1981) during those periods. During the first sampling period (growth stage V13-R1, 13–18 July) LAI was quite low for all three plant populations, with LAI approximately twice as large in the high population as in the low population. The population difference created large differences in soil temperature during this period, with midday soil temperature in the low population about 11°C warmer than in the high population (Fig. 2). During the second sampling period (growth stage R2-R3, 23 July–3 August), LAI exceeded 3.0 for the high population, while the medium population reached a value of 3.0 during the middle of the period, and the low population had not yet reached a value of 3.0. The soil temperatures during this period were all below air temperature as more of the soil surface was being shaded than during the first period. The effect of plant population was still evident, but smaller (about 3.5°C at midday between high and low populations) than during the first period.

Leaf area index for the three populations during the third and fourth periods (growth stage R4-R5, 7–16 August; growth stage R6-R7, 21–31 August) were all greater than 3.0, resulting in soil temperatures much below air temperature. There was no difference in soil temperature between the medium and high populations and a small (2.0 to 2.5°C) difference between the low and high populations at midday. Leaf area index declined rapidly during the last period (R8), with all populations similar and less than 3.0. Soil temperatures were similar for all plant populations.

3.1. Diurnal measurements

Differences in LAI and soil temperature affected the NWSB equation coefficients derived from the linear regressions of dT on VPD for diurnal measurements (Table 1). To determine if NWSBs are different from one another, the combination of differences in both slope and

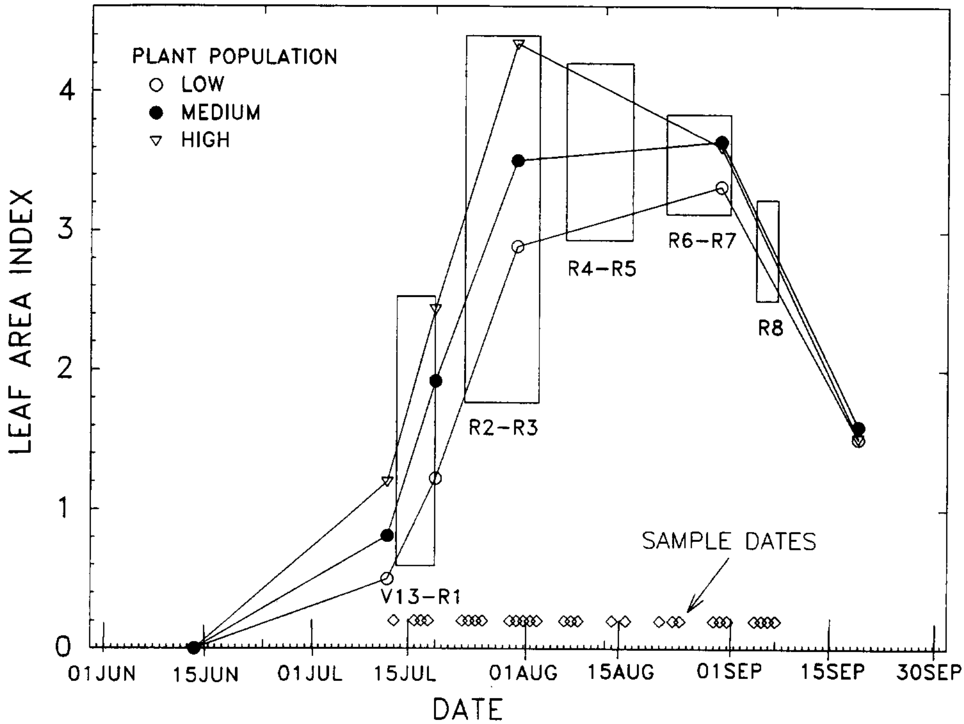

Fig. 1. Leaf area index for sunflowers grown at high, medium, and low plant populations (2.6, 5.3, and 7.9 plants·m^{-2}, respectively). Boxes denote sampling periods for NWSB determinations, with growth stage noted below box.

intercept must be considered. In this study, regressions were visually evaluated for significant differences based on overlap of 95% confidence intervals, similar to those shown in Fig. 3. The visual evaluation of NWSBs based on diurnal measurements (data not presented) showed that only for the canopy measurements during the first sampling period was there an effect of plant population on the NWSB equation. For all other canopy measurements and leaf measurements the data were combined over plant populations.

The effect of decreasing plant population during the first period (Table 1, Fig. 3) was to increase the absolute value of NWSB slope based on canopy measurements as a result of very warm soil being viewed by the IRT at low VPD during the first date of this period, and to a coupling of the canopy temperatures with the warm soil temperatures when the plants were small and closer to the soil surface (Pinter and Reginato, 1982). This is contrary to results of Wanjura et al. (1990) who found the absolute slope values of NWSBs of cotton increased with increasing LAI. This discrepancy may be due to the fact that during the first sampling period of the current experiment LAI was increasing rapidly, so that there probably was more soil viewed by the IRT during the first date of the first sampling period than a few days later. The VPD during this day was lower than on subsequent days, thereby making the intercept value of the NWSB higher. The confidence intervals (Fig. 3) for the first

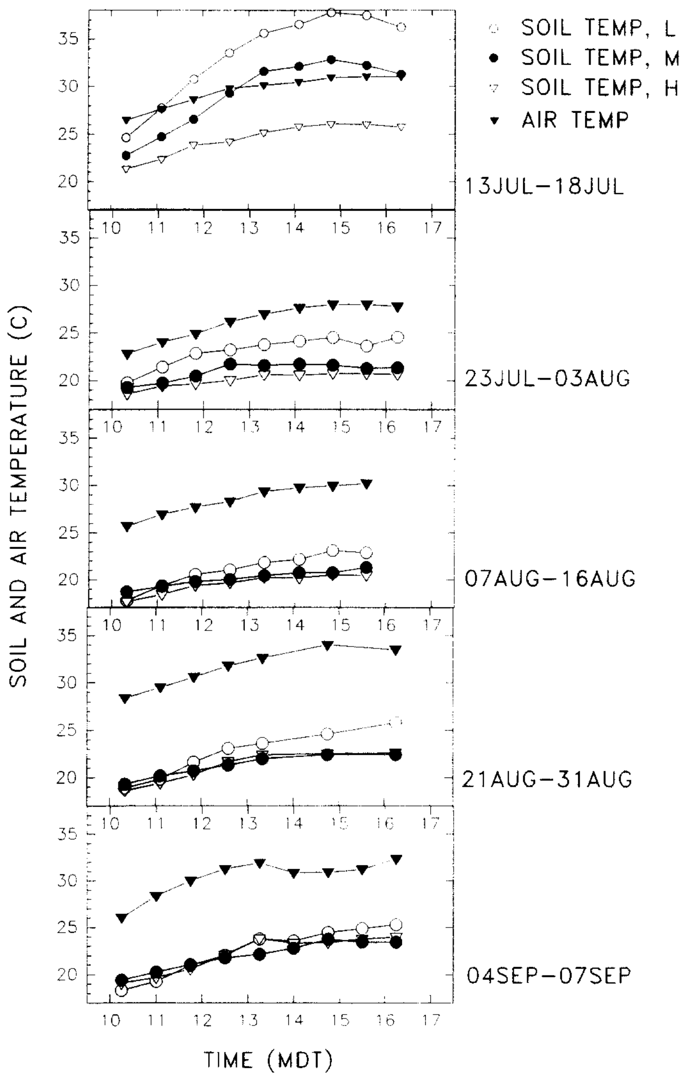

Fig. 2. Average diurnal air and soil temperatures under low, medium, and high plant populations (L, M, and H, respectively) for sampling periods when NWSB were determined.

period measurements show very little overlap for 1 < VPD < 3 kPa. Values of $T_c - T_a$ (dT) at VPD > 3 kPa were similar for all three plant populations during this period.

There was a small increase in the absolute value of the NWSB slope between the second and third periods. The confidence intervals of the NWSBs during these two periods show almost no overlap, but plots of the data showed points falling in the same general area. Differences in calculated slope and intercept values are probably due to the different VPD ranges during the two measurement periods, as suggested by Gardner et al. (1992).

There was a distinct change in the slope and intercept values for canopy measurements

Table 1
Sunflower stage, height and non water-stressed baseline (NWSB) equation coefficients determined from diurnal measurements of dT and VPD

Sampling period	Date	Stage[a]	Height (cm)	VPD range (kPa)	Treatment[b]	NWSB coefficients[c] a	b	R[d]	n[e]
1	13 July–18 July	V13-R1	36–70	0.98–4.60	C-L	10.66	−4.06	0.83	39
					C-M	7.96	−3.61	0.86	39
					C-H	5.27	−2.95	0.85	39
					L	5.37	−3.39	0.92	117
2	23 July–3 Aug.	R2-R3	90–140	0.65–2.93	C	2.52	−2.50	0.86	108
					L	3.67	−3.22	0.86	108
3	7 Aug.–16 Aug.	R4-R5	150–155	1.27–3.60	C	4.06	−2.84	0.88	60
					L	5.41	−3.95	0.88	60
4	21 Aug.–31 Aug.	R6-R7	155	1.91–4.96	C	0.17	−1.49	0.71	54
					L	−0.62	−1.65	0.85	39
5	4 Sept.–7 Sept.	R8	155	1.58–3.48	C	0.34	−1.64	0.50	51
					L	0.26	−1.76	0.55	50
	Idso (1982)[f]	–	–	0.80–4.10	C	0.66	−1.95	0.98	58

[a] Stage as described by Schneiter and Miller (1981).
[b] Treatment codes C-L, C-M, C-H denote canopy temperature measurements at plant populations of 2.6, 5.3, and 7.9 plants$\cdot m^{-2}$, respectively; C and L denote canopy and leaf temperature measurements, respectively, over all plant populations.
[c] a = the intercept of the dT axis (°C); b = the baseline slope dT (°C)/VPD (kPa).
[d] Coefficient of determination.
[e] Number of observations.
[f] Idso (1982) data were smoothed with a 3-point running average prior to fitting the linear regression.

beginning with the data collected on 21 August and continuing through 7 September (sampling periods 4 and 5), with shallower slopes and lower intercepts much lower than earlier in the growing season. This is probably a result of reduced transpiration as leaves aged, and measuring sunflower heads as well as leaves. A few periodic measurements of heads taken late in the growing season showed heads to be 6 to 10°C warmer than leaf temperatures. The slope of the NWSB reported by Idso (1982) for sunflowers grown in Kansas (Table 1) falls between the slopes reported here for periods 2 and 3 and periods 4 and 5. He did not report growth stage of plants measured. The NWSBs from periods 4 and 5 were not different, as determined by confidence interval overlap. Combining the data from periods 2 and 3 gives a NWSB for bud development through flowering (Table 2). The canopy data from period 1 are not included in this combined data set because they show a different relationship due to the population effect. Combining the data from periods 4 and 5 gives a NWSB for grain-filling. These NWSBs are shown graphically with 95% confidence intervals in Fig. 4.

Plots of NWSB regressions with confidence intervals for diurnal leaf temperature meas-

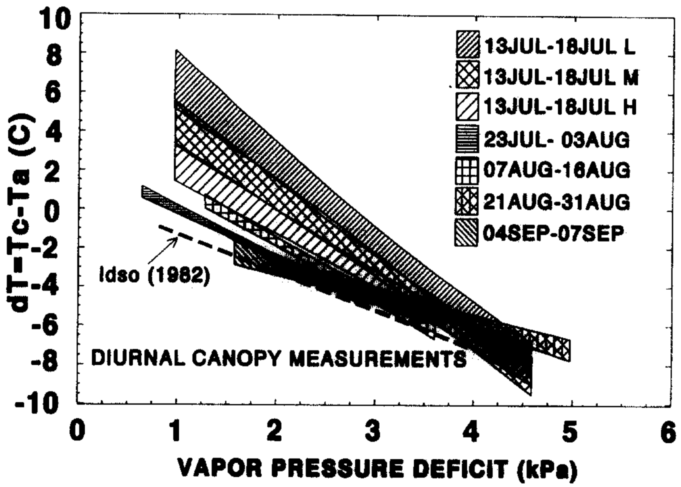

Fig. 3. Non water-stressed baselines (with 95% confidence intervals) based on diurnal canopy measurements. dT = temperature difference between sunflower canopy or leaves (T_c) and air (T_a) in °C.

Table 2

Sunflower stage, height and non water-stressed baseline (NWSB) equation coefficients determined from diurnal measurements of dT and VPD, data separated into two time periods covering vegetative to flowering and grain-filling growth stages

Date	Stage[a]	Height (cm)	VPD range (kPa)	Treatment[b]	NWSB coefficients[c]		R^{2d}	n^e
					a	b		
23 July–16 Aug.	R2-R5	90–155	0.65–3.60	C	2.91	−2.56	0.84	168
13 July–16 Aug.	V13-R5	36–155	0.65–4.60	L	3.91	−3.11	0.88	285
21 Aug.–7 Sept.	R6-R8	155	1.91–4.96	C	0.17	−1.49	0.71	54
			1.58–4.96	L	0.24	−1.83	0.75	89

[a] Stage as described by Schneiter and Miller (1981).
[b] C and L denote canopy and leaf temperature measurements, respectively, over all plant populations.
[c] a = the intercept of the dT axis (°C); b = the baseline slope dT (°C)/VPD (kPa).
[d] Coefficient of determination.
[e] Number of observations.

urements showed that there was no difference in NWSB due to plant population during any of the sampling periods, even when LAI was very low during the beginning of the first period. Therefore, the data generating NWSBs were combined over plant population for each of the five sampling periods to give one NWSB for each period based on leaf measurements (Table 1). A similar pattern was seen with the leaf measurements as with the canopy measurements, with the data falling into two distinct groupings: vegetative/bud development/flowering (V13-R5) and grain-filling (R6-R8). Non water-stressed baselines for leaves were determined for data separated into these two periods (Table 2, Fig. 4). Non

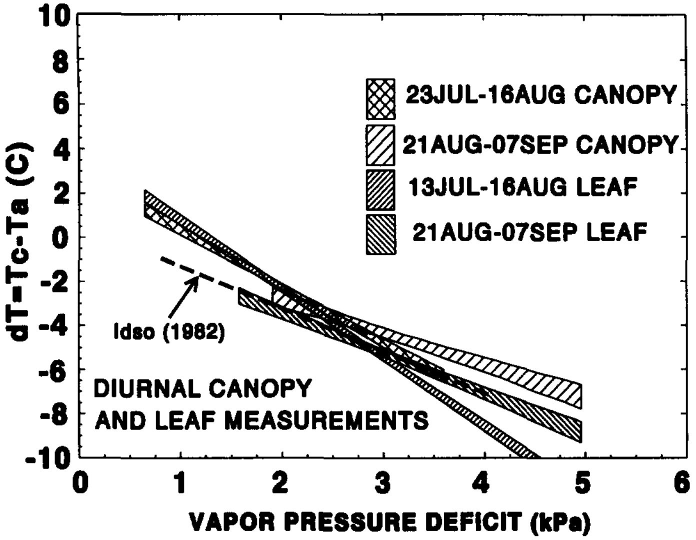

Fig. 4. Non water-stressed baselines (with 95% confidence intervals) based on diurnal canopy and leaf measurements. Data were separated into two time periods covering vegetative to flowering and grain-filling growth stages. dT = temperature difference between sunflower canopy or leaves (T_c) and air (T_a) in °C.

water-stressed baselines from leaf measurements have slightly steeper slopes than NWSBs from canopy measurements during both time periods, although the differences in measured dT over the VPD range common to both sets of measurements (0.65–3.60 kPa) is not large during the V13-R5 period. The NWSB for grain-filling has a much shallower slope than the NWSB based on earlier vegetative and reproductive stage data. Since this data was not acquired from any situations in which stems, heads, or soil was viewed, the reduction in response of dT to VPD must be related to reductions in transpirational ability of aging leaves. Since there was no effect of plant population on NWSB, especially during the first period, the NWSB based on single leaf measurements made during stages V13 to R5 could be used early in the season when plants are small and viewed soil would be a problem with canopy measurements. The NWSB of Idso (1982) is very similar to the NWSB for leaf measurements made during the R6-R8 period over the VPD range common to both sets of measurements (Fig. 4).

3.2. Midday measurements

Non water-stressed baselines were also derived from only midday measurements of dT and VPD at 1315 and 1400 MDT (Table 3, Fig. 5). This is the typical period for water stress measurements in the central Great Plains, corresponding to the time when VPD is large and just prior to the rapid development of convective cumulus clouds that disrupt canopy temperature measurements. The same pattern in relative slopes and intercepts of the NWSBs were seen with data derived from midday measurements as with diurnal measurements, except that there was no effect of plant population during any of the measurement periods for either canopy or single leaf measurements. The same shift in NWSB slope that

Table 3

Sunflower stage, height and non water-stressed baseline (NWSB) equation coefficients determined from midday measurements of dT and VPD, data separated into two time periods covering vegetative to flowering and grain-filling growth stages

Date	Stage[a]	Height (cm)	VPD range (kPa)	Treatment[b]	NWSB coefficients[c] *a*	*b*	R^{2}[d]	n[e]
13 July–16 Aug.	V13-R5	36–155	0.86–4.36	C	2.44	−2.19	0.82	87
				L	4.48	−3.21	0.89	92
21 Aug.–7 Sept.	R6-R8	155	1.91–4.96	C	1.01	−1.66	0.78	42
				L	0.08	−1.71	0.77	31

[a] Stage as described by Schneiter and Miller (1981).
[b] C and L denote canopy and leaf temperature measurements, respectively, over all plant populations.
[c] a = the intercept of the dT axis (°C); b = the baseline slope dT (°C)/VPD (kPa).
[d] Coefficient of determination.
[e] Number of observations.

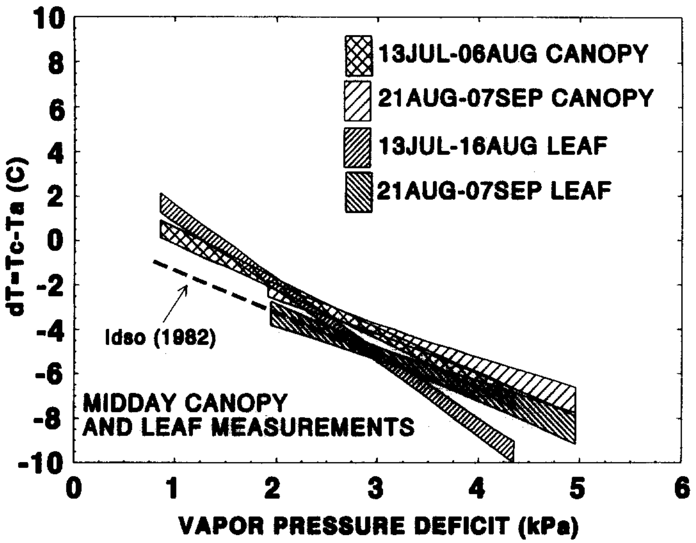

Fig. 5. Non water-stressed baselines (with 95% confidence intervals) based on midday canopy and leaf measurements. Data were separated into two time periods covering vegetative to flowering and grain-filling growth stages. dT = temperature difference between sunflower canopy or leaves (T_c) and air (T_a) in °C.

occurred at grain-filling noted with the diurnal measurements was seen in the midday data. Consequently, the data were combined across plant populations and divided into two time periods corresponding to growth stages V13 to R5 and R6 to R8, as was done for the diurnal measurements.

The NWSBs from midday measurements are remarkably similar to the NWSBs from diurnal measurements. The leaf NWSB during the vegetative through flowering stages was slightly steeper than the canopy NWSB. The slopes of both canopy and leaf NWSBs were similar during the grain-filling stages, but leaf temperatures were consistently lower than canopy temperatures.

Based on the confidence intervals associated with the NWSBs shown in Figs. 4 and 5, there is no difference in NWSBs derived from midday measurements of dT and VPD compared with diurnal measurements.

4. Conclusions

Non water-stressed baselines for sunflowers based on canopy temperature measurements were found to be affected by plant population only when LAI was less than about 2.0. Non water-stressed baselines based on single leaf temperatures were not affected by plant population. The absolute value of slopes of NWSBs based on both canopy and leaf measurements were fairly constant during the vegetative and flowering stages, but decreased as plants went into the grain-filling stage. Slopes of NWSBs based on leaf measurements were slightly steeper than for NWSBs based on canopy measurements during the vegetative and flowering stages. Slopes of NWSBs during the grain-filling stage were similar for both leaf and canopy measurements, although the leaf measurements were consistently cooler than the canopy measurements. Non water-stressed baselines derived from midday dT and VPD measurements were not different from NWSBs derived from diurnal measurements. Measurements of single leaves of sunflower plants made with an IRT can be used to evaluate water stress or schedule irrigations early in the growing season before canopy closure occurs, or in non-irrigated production areas where canopy closure may not occur, and during grain-filling when heads become very warm and disrupt canopy temperature measurements. The NWSBs derived from this study should be useful in calculating the CWSI for sunflower regardless of plant population, row spacing or developmental stage so that accurate evaluations of water stress effects on plant growth, development, and yield can be made. Additionally, the calculated CWSI can be used to schedule irrigations for sunflower similar to methods described previously for other crops (Nielsen and Gardner, 1987; Nielsen, 1990), thereby conserving water and minimizing production costs.

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