RESEARCH

Canopy Temperature Depression Sampling to Assess Grain Yield and Genotypic Differentiation in Winter Wheat

Maria Balota,* William A. Payne, Steven R. Evett, and Mark D. Lazar

ABSTRACT

Canopy temperature depression (CTD = air temperature [*T*a] – canopy temperature [*T*c]) has been used to estimate crop yield and to rank genotypes for tolerance to heat and drought, but when to measure CTD for breeding selection has seldom been addressed. Our objectives were to evaluate the suitability of CTD for the Texas High Plains environment and to determine optimal measurement times in relation to growth stage, time of day, and weather. Three years of CTD and weather data were used to assess regression models of grain yield in three wheat (*Triticum aestivum* L.) lines. Under dryland agriculture, long-term mean CTD at noon and yield were correlated in 2000 and 2001. The relation of short-term CTD readings to grain yield was highly variable. Poor correlation was associated with days of low solar irradiance, high wind speed, and rain events. Genotype effects on CTD were detected for all hours of day and night. Genotype × hour interaction was insignificant at night, suggesting that nighttime measurements may provide more stable conditions for CTD comparison among genotypes. In general, tree regression assessed grain yield from short-term CTD measurements better than linear regression and suggested that the best times to measure CTD were 0900, 1300, and 1800 h. Tree regression models provided a heuristic interpretation of crop water status under different scenarios of soil water availability.

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Abbreviations: CTD, canopy temperature depression; IRT, infrared thermometer.

CANOPY TEMPERATURE depression (CTD) is the difference between air (T_a) and canopy (T_c) temperatures and it is positive when the canopy is cooler than the air:

$$\mathrm{CTD} = T_a - T_c$$

Canopy temperature and CTD have been recognized as indicators of overall plant water status (Ehrler, 1972; Blum et al., 1982; Jackson et al., 1981; Idso, 1982) and used in such practical applications as evaluation of plant response to environmental stress (Ehrler et al., 1978; Idso, 1982; Howell et al., 1986; Jackson et al., 1981), irrigation scheduling (Hatfield, 1982; Pinter and Reginato, 1982; Evett et al., 1996; Wanjura et al., 1995), cultivar comparison for water use (Pinter et al., 1990; Hatfield et al., 1987), and tolerance to heat (Amani et al., 1996; Reynolds et al., 1998) and drought (Blum et al., 1989; Royo et al., 2002; Rashid et al., 1999). High CTD has been used as a selection criterion to improve tolerance to drought and heat (Amani et al., 1996; Ayeneh et al., 2002; Blum, 1988; Blum et al., 1989; Pinter et al., 1990; Rashid et al., 1999; Reynolds et al., 1994, 2001; Fischer et al., 1998) and has been associated with yield increase among wheat (*Triticum aestivum* L.) cultivars at CIMMYT (Fischer et al.,

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1998). The suitability of CTD as an indicator of yield and stress tolerance, however, must be determined for individual environments. For example, it can be a poor indicator where yield is highly dependent on limited amounts of soil-stored water (Idso et al., 1984; Winter et al., 1988; Royo et al., 2002; Sojka et al., 1981).

Studies that have used CTD have almost always relied on measurements taken during very short periods (seconds or minutes), in part due to instrumentation limitations. When to best measure CTD, however, has seldom been addressed. Under irrigated conditions in a hot environment of Mexico, Amani et al. (1996) found that correlations for CTD and yield among 24 spring wheat cultivars was highest when CTD was measured between 1200 and 1600 h at any crop growth stage between preheading and grain fill. Other studies, however, have been more vague and few other than that by Amani et al. (1996) provide supporting data. For example, Hofmann et al. (1984) measured CTD "after full crop establishment," Pinter et al. (1990) between 1000 and 1600 h, Reynolds et al. (1994) from 1200 to 1600 h, and Blum et al. (1989) and Royo et al. (2002) at 1200 h from anthesis to 2 wk postanthesis. Descriptions of suitable weather conditions for CTD measurement include "full sunshine" (Ayeneh et al., 2002), "clear days" (Blum et al., 1989; Idso et al., 1984), "cloudless days/periods" (Fischer et al., 1998; Rashid et al., 1999), "sunny days" (Royo et al., 2002), "clear sky and cloudy or shaded conditions" (Idso, 1982), "most non-raining days" (Pinter et al., 1990), "various light and wind conditions" (Ferguson et al., 1973), and "days with complete cloud cover and days with clear sky" (Jackson et al., 1981). None of the cited studies compared models using CTD data that were taken from other growth stages, at other times of the day, or during days with unsuitable weather conditions. Yet such comparisons would be useful to breeding programs that must balance the need to measure many entries with the need to minimize genotype × environment interaction due to changing weather conditions. Furthermore, more quantitative guidelines are needed on which climatic conditions to seek and which to avoid.

The advent of relatively inexpensive infrared thermometers (IRTs) that can take multiple and nearly continuous CTD measurements when coupled to a data logger (e.g., Evett et al., 1996) provides an opportunity to determine which measurement times and conditions provide the best statistical models for yield estimation and genotype ranking. The objectives of this study were (i) to evaluate CTD in statistical models that estimate yield and rank genotypes under arid to semiarid conditions of the Texas High Plains, and (ii) to determine optimal CTD sampling conditions in terms of growth stage, time of day, and environment to assess grain yield.

MATERIALS AND METHODS

Plant Material and Growth Conditions

Canopy temperature depression measurements were made on three winter wheat BC3-generation sister lines during three cropping seasons at the Texas Agricultural Experiment Station (35° N, 102° W, 1170-m elevation) near Bushland, TX. Soils at this site are classified as Pullman clay loam (Torrertic Paleustolls). The lines, TX86A5606, TX88A6880, and TX86A8072 (coefficient of parentage = 0.94), were categorized as having low, medium, and high tolerance to drought, respectively, based on multiple yield trials (Lazar et al., 1995). They have as pedigree TAM 105*4/Amigo*4//Largo (Lazar et al., 1996) and are related to TAM 107 (TAM105*4/Amigo), which is well adapted to High Plains growing conditions. The lines have identical phenology and similar plant height and tillering (Balota et al., 2005).

In 2000 wheat was planted on 1 October only under dryland conditions in a breeder's nursery. Seeds were planted at a rate of 6.5 g m^{-2} in north–south-oriented rows spaced 0.3 m apart. Plot size was 4.6 m^2. Heading, which was recorded when 50% of the spikes were headed, occurred on 22 April.

In 2001 wheat was planted on 13 October under both dryland and irrigated conditions, again in a breeder's nursery. Seeds were planted at a rate of 10 g m^{-2} in east–west rows spaced 0.2 m apart. Plot size was 3.3 m^2. Heading occurred on 30 April.

In 2002 wheat was planted on 9 October under dryland and irrigated conditions as part of an agronomic experiment (i.e., not in a breeder's nursery). Seeds were planted at a rate of 10 g m^{-2} in east–west rows spaced 0.2 m apart. Plot size was 39 m^2. Heading occurred on 28 April under dryland conditions and 2 May under irrigated conditions.

In 2000 neither fertilizer nor preplant irrigation was applied. In 2001, 18 g m^{-2} N, 10 g m^{-2} P_2O_5, and 76 mm of preplant irrigation were applied to all plots at the end of September. Irrigated plots received a total of 200 mm of water in two irrigations on 20 Apr. and 18 May 2001. In 2002, 17 g m^{-2} N and 76 mm of irrigation were applied preplant to all plots. Irrigated plots received a total of 410 mm in four irrigations on 27 Mar., 26 Apr., 10 May, and 6 June 2002. In all years, cultural operations for weed and pest control were applied as needed.

Each year, canopy temperature was measured with mast-mounted IRTs (Model IRt/c.2-T-80F, Exergen Corp., Watertown, MA) with a 2:1 (~35°) field of view. The height of each IRT was adjusted every few days to maintain a viewing angle of 45° to the horizontal, 0.5 m distance above the canopy layer and to target a calculated area of 0.7-m^2 in the middle of each plot. One IRT was allocated per plot, and positioned at one-third distance from the east end of the plot in 2000 and at one-third distance from the south end in 2001 and 2002. The IRTs faced north and were enclosed in white-painted plastic fixtures to minimize changes in sensor body temperature. The measurement starting dates were chosen so that soil was not viewed by the IRT. Wheat CTD was measured from the preheading stage to 20 d after anthesis in 2000 and to 40 d after anthesis in 2001 and 2002. Preheading occurred on 16 Apr. 2000, 26 Apr. 2001, and 5 Apr. 2002. Days of the year when heading occurred are given in Table 1. At maturity, total biomass and grain yield were measured.

Additionally, air temperature and relative humidity were measured every year with mast-mounted temperature and

Table 1. Summary of weather conditions before and during canopy temperature depression (CTD) measurements during three wheat (*Triticum aestivum* L.) cropping seasons at Bushland, TX.

Heading day of the year	Period	Day of the year†	Mean daily solar irradiance	Mean air temp.	Max. air temp.	Mean soil temp. at 10 cm	Mean wind speed	Precipitation	Pan evaporation
			W m^{-2}	——— °C ———			m s^{-1}	——— mm ———	
2000									
112	Fall planting to end of CTD measurements	274–135	407	10.8	19.9	12.7	5.9	178	
	Before CTD measurement	274–105	369	7.9	17.1	9.8	6.2	115	
	During CTD measurement	106–135	528	17	26.2	19.1	5.1	2	159
2001									
120	Fall planting to end of CTD measurements	286–164	373	8.0	15.7	9.7	4.1	389	
	Before CTD measurement	286–115	333	5.0	12.6	6.6	4.1	280	
	During CTD measurement	116–164	520	19.3	27.3	21.4	3.9	109	229
2002									
118/122‡	Fall planting to end of CTD measurements	292–163	414	9.7	18.8	11.7	4.8	152	
	Before CTD measurement	292–94	373	5.8	15	7.7	4.5	97	
	During CTD measurement	95–163	505	18.4	27.3	20.7	5.4	55	419

†Fall planting day of year is for previous year.

‡118 in dryland and 122 in irrigated plots.

relative humidity probes (Model HMP45C, Campbell Scientific, Logan, UT) at a height of 2 m in the center of each irrigated and dryland field. All IRTs and the HMP45C probe were tested at the beginning of each season with a black body (Model 1000, Everest Interscience, Tucson, AZ) as described by Peters and Evett (2004). The IRTs had interchangeability error, defined as the difference in reading between any two IRTs, <0.05°C and accuracy from the black body and the HMP45C temperature probe <0.1°C at 37°C. Repeatability error was <0.01°C.

In 2000 wind speed and solar irradiance data were collected from the USDA weather station located <1 km from the experimental plots. Sensors were located at a standard height of 2 m. In 2001 anemometers (03001-5 RM, Campbell Scientific) were used to monitor wind speed at 2 m above the ground in each environment starting 24 May. Before 24 May, weather station data were used. In 2002 wind speed and incoming shortwave solar irradiance were monitored at 2 m above the ground in one plot in each environment (i.e., irrigated and dryland) using the same anemometer and a pyranometer (Model CM3, Campbell Scientific). Because of the relatively small plot size and highly advective conditions in Bushland, temperature, humidity, irradiance, and wind data were considered to be representative of the environment in general, and not treatment-induced microclimates. All instruments were connected to data loggers (Models 21x and 23x, Campbell Scientific) that took sensor readings every 50 s, then stored the average reading every 10 min. The 10-min means were aggregated to 1-h means. Hours of the day reported here are based on CST, and were not adjusted for daylight savings time.

Experimental Design and Statistical Analysis

In each environment, the experimental design was a randomized complete block with four replications in 2000 and 2001 and three replications in 2002. To assess the effect of genotype on CTD and grain yield, analyses of variance were made using the GLM procedure of SYSTAT Version 10.2 (SYSTAT Software, 2002). To evaluate the suitability of CTD measurements for the Texas High Plains region, linear regression equations were fitted to mean CTD at 1200 h and grain yield for each environment. Simple linear regression equations were also fitted to 1200-h CTD and grain yield under dryland conditions to evaluate their relationship on days with contrasting solar irradiance, vapor pressure deficit, wind speed, and rain events. To determine the optimal time interval and stage of vegetation for CTD measurement for assessing grain yield variation and cultivar differentiation, stepwise linear regression and cluster analysis were used. These analyses identified natural groupings of hours of CTD values sampled 24 h a day within each stage of vegetation. Regression tree analysis was used as an alternative method of assessing grain yield variation and cultivar differentiation for stress tolerance from short-term CTD readings. Regression tree models are increasingly used instead of traditional linear models in ecological and agricultural sciences (Lobell et al., 2005; Moody and Meentemeyer, 2001).

RESULTS AND DISCUSSION

Weather

Large contrasts among the three cropping seasons were observed in terms of air temperature, pan evaporation, and precipitation (Table 1). In 2000, mean grain yield under dryland conditions was 310 g m^{-2}. Only 2 mm of precipitation was received between heading and the third week after anthesis, and 61 mm between heading and harvest. This was the coolest growing season, with only 9 d in which the maximum air temperature was >30°C, and the most humid, with only 159 mm total pan evaporation during CTD measurements. Mean wind speed was greatest in this year.

In 2001 mean grain yield was 563 g m^{-2} in dryland plots and 637 g m^{-2} in irrigated plots. Precipitation was greatest; during 48 d of CTD measurements, there were 12 d with rainfall >5 mm, 12 d with air temperatures >30°C, and 229 mm total pan evaporation. Wind speed was smallest.

In 2002 mean grain yield was only 271 g m^{-2} in dryland plots and 464 g m^{-2} in irrigated plots. Precipitation was least and temperatures were the highest, with 32 d >30°C. Total pan evaporation during CTD measurements (419 mm) was by far the largest.

Canopy Temperature Depression

Mean CTD diurnal patterns for the entire measurement period were relatively conservative within years under both dryland and irrigated conditions (Fig. 1). In all environments, CTD was most negative at 1200 h and most positive at 2000 h. Similarly, Ehrler et al. (1978) found that a single CTD measurement of wheat from 1300 to 1400 h could be used to characterize diurnal trends in Arizona. Their study, however, considered neither CTD–yield relationships nor genotypic differences in stress tolerance.

At 1200 h, CTD of dryland wheat ranged from −5 to 3°C in 2000, from −8.5 to 2°C in 2001, and from −10 to 3°C in 2002. Under irrigation, CTD at 1200 h ranged from −5.7 to 4.6°C in 2001 and from −5.5 to 8°C in 2002. The maximum depression at 2000 h was 9°C under both dryland and irrigated conditions.

Dryland data from Fig. 1 replotted across shorter time intervals reveal significant ($P < 0.0001$) genotypic effects on CTD and consistent genotype ranking from 1100 to 1500 h and, in 2000 and 2002, from 0300 to 0700 h (Fig. 2). Even in 2001, the same genotype ranking and significant genotype effect on CTD was observed from 0300 to 0700 h for several individual days (data not shown). The drought-resistant line TX86A8072 was consistently cooler than the drought-sensitive line TX86A5606. The smaller genotypic variation for CTD from 0300 to 0700 h in 2001 may be due to higher precipitation (Table 1), as suggested by smaller genotypic CTD variation under irrigated conditions (Fig. 1). To our knowledge, there are no other reports in the literature of consistent genotypic differences for CTD during predawn hours. It has been established, however, that nighttime transpiration occurs in wheat (Rawson and Clarke, 1988; Richards et al., 2002) and other C_3 species (Snyder et al., 2003) in low-humidity environments, and that even nontranspiring leaves can be cooler than the air above because they radiate to the atmosphere (Leuning, 1988, 1989).

Genotypic CTD variation was least under irrigated conditions. Differences among genotypes were significant only from 1100 to 1800 h in 2001 and at 1800 to 1900 h in 2002 (Fig. 1). The largest mean CTD variation among genotypes ($P < 0.0001$) under this environment occurred between 1100 and 1500 h in 2001. At this time, the drought-sensitive line TX86A5606 was warmer than TX86A8072 and TX88A6880, with mean CTD values of 0.4, 0.9, and 0.7°C, respectively (Fig. 1). Blum et al. (1982) also found that canopy temperature differences among various wheat and triticale (×*Triticosecale* spp.) cultivars were least when plants had favorable water and greatest under water stress.

Grain Yield

Under dryland conditions, genotype and year had significant effects on grain yield, with no significant genotype

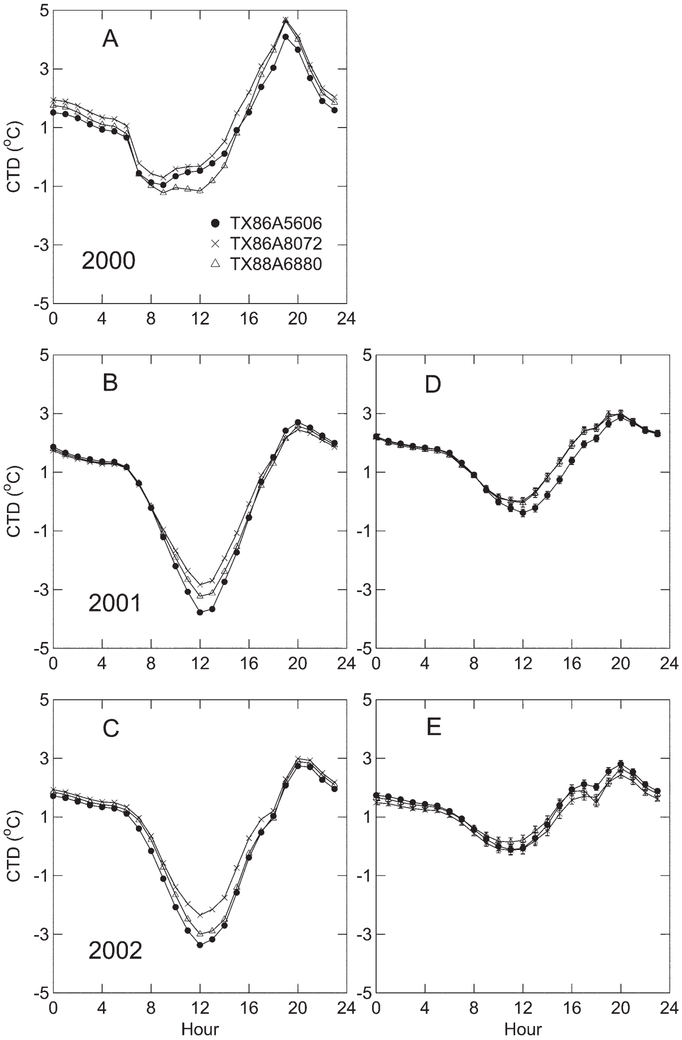

Figure 1. Diurnal canopy temperature depression (CTD) trends for three closely related wheat (*Triticum aestivum* L.) lines grown under (A–C) dryland and (D–E) irrigated conditions during 3 yr at Bushland, TX. Points represent hourly means during the entire measurement period, which was from heading to −20 d after anthesis in 2000 and from heading to −40 d after anthesis in 2001 and 2002. See Fig. 3 for error bars for graphs A to C. Vertical bars in graphs D and E represent ± 1 SD. Genotype TX86A5606 was the most drought sensitive and TX86A8072 was the most drought tolerant (Lazar et al., 1995).

× year interaction (Table 2). The drought-tolerant line TX86A8072 had a mean grain yield of 335 g m^{-2} in 2000, 585 g m^{-2} in 2001, and 307 g m^{-2} in 2002; the drought-susceptible line TX86A5606 produced 309 g m^{-2} in 2000, 548 g m^{-2} in 2001, and 255 g m^{-2} in 2002; the intermediate line TX88A6880 produced 286 g m^{-2} in 2000, 555 g m^{-2} in 2001, and 260 g m^{-2} in 2002. Our dryland yield data for combined years (Table 3), along with published data from Lazar et al. (1996), indicated that TX86A8072 performs better under drought conditions than its sister lines. Under irrigated conditions, we measured no significant differences for grain yield among genotypes (Table 3), in contrast to both published (Lazar et al., 1996, 1995) and unpublished data (Lazar, personal communication, 2002), suggesting that the drought-tolerant line, TX86A8072, has a smaller grain yield than its sister lines under irrigated conditions.

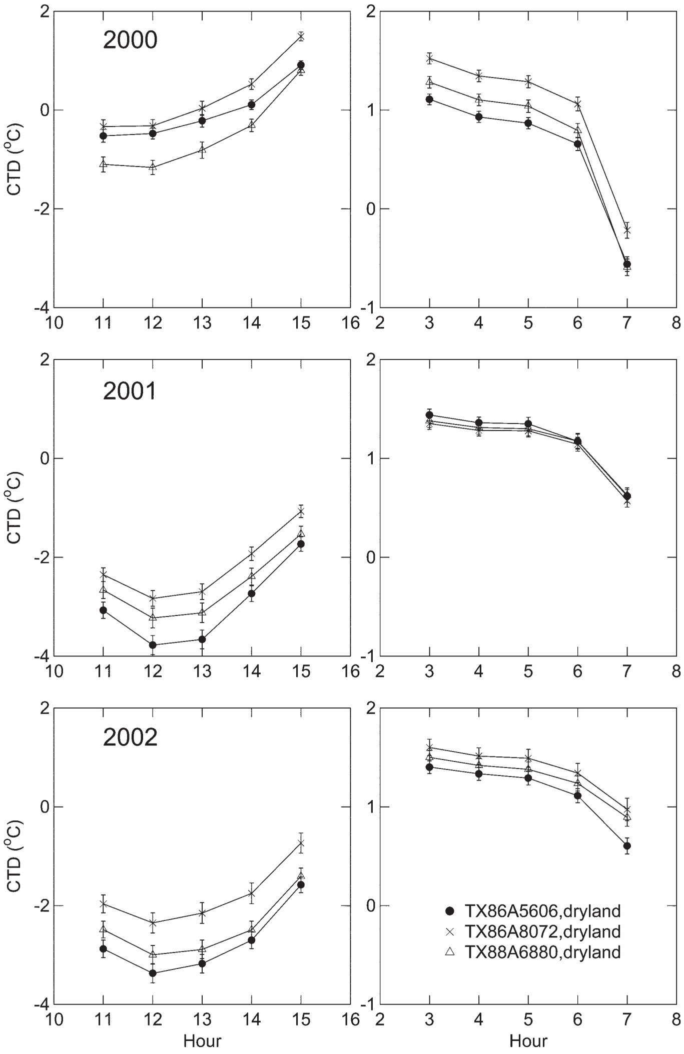

Figure 2. Genotypic effect on canopy temperature depression (CTD) at midday and at predawn for winter wheat (*Triticum aestivum* L.) under dryland conditions. Points represent mean values for the entire measurement period. Vertical bars represent ±1 SD. Genotype TX86A5606 was most drought sensitive and TX86A8072 was most drought tolerant (Lazar et al., 1995).

Grain Yield–Canopy Temperature Depression Relations

Under dryland conditions, grain yield and mean CTD at 1200 h for the entire measurement period were correlated (Fig. 3a) among the three lines ($r^2 = 0.56$) in 2000 and 2001, similar to other studies (Blum et al., 1989; Royo et al., 2002). Even though the range of mean CTD values was different (approximately −0.9 to 1.2°C in 2000, and −3.0 to −1°C in 2001), slope values in both years suggested an approximate 45 g m^{-2} increase in grain yield °C^{-1} increase in CTD (Fig. 3a). Yield and mean CTD at 1200 h were not significantly correlated for any genotype in 2002, which had the driest and hottest conditions (Table 1), the smallest mean yield, and only three replicates in larger plots. The CTD appeared to be inversely related to yield for TX86A5606 (Fig. 3a), the line that Lazar et al. (1996) found to be well adapted to irrigated conditions but poorly adapted to dryland conditions. Under irrigated conditions in 2001, yield and mean CTD at 1200 h for the entire measurement period were inversely correlated (Fig. 3b) among the three lines ($r^2 = 0.41$). The inverse relation between yield and CTD was apparent in 2001 for all growth stages and all hours. Furthermore, yield and mean CTD were uncorrelated under irrigated conditions in 2002 when pooled across cultivars (Fig. 3b), and indeed appeared to be inversely related for the cultivar TX86A5606. When dryland and irrigation data were combined, seasonal mean CTD at 1200 h was positively correlated with yield, with r^2 values of 0.45 in 2001 and 0.85 in 2002.

Table 2. Effect of genotype and year on winter wheat (*Triticum aestivum* L.) grain yield under irrigated and dryland conditions in Bushland, TX (2000–2002).

Source of variation	Dryland			Irrigation		
	df	Mean square	*P*	df	Mean square	*P*
Genotype	2	5758	0.007	2	207	0.929
Year	2	274991	0.0001	1	133024	0.0001
Replication	3	1731	0.163	3	1311	0.707
Genotype × year	4	365	0.808	2	1569	0.582
Error	21	917		12	2773	

Table 3. Average grain yield of three closely related wheat (*Triticum aestivum* L.) lines under dryland and irrigated conditions at Bushland, TX, in 2000 to 2002.

Line	Yield	
	Dryland	Irrigated
	g m^{-2}	
TX86A8072	406.8 a[†]	544.7 a
TX88A6880	365.2 b	551.1 a
TX86A5606	367.1 b	555.6 a

[†] Within columns, means with the same letter are not significantly different at $P = 0.05$.

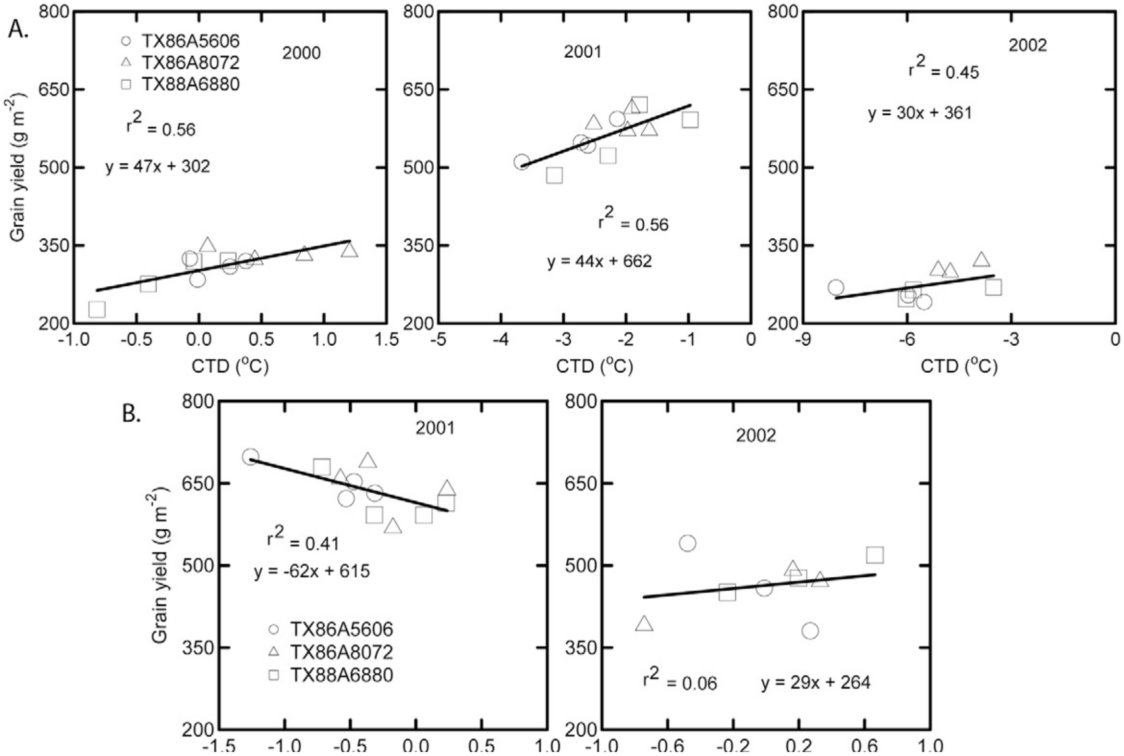

Figure 3. The relations between seasonal mean canopy temperature depression (CTD) at 1200 h and winter wheat (*Triticum aestivum* L.) grain yield for individual plots under (A) dryland conditions in 2000, 2001, and 2002 at Bushland, TX ($P < 0.01$, 0.01, and 0.20, respectively), and (B) irrigated conditions in 2001 and 2002 at Bushland, TX (in 2001, $P < 0.025$; in 2002, correlation was not significant; without TX86A5606 in 2002, $P < 0.0001$).

Table 4. Linear regression statistics for canopy temperature depression (CTD) and wheat (*Triticum aestivum* L.) grain yield under dryland conditions for individual days with contrasting air temperature, wind speed, 1200 h and daylight average (0700–1900 h) solar irradiance, vapor pressure deficit (VPD), and precipitation; CTD and weather parameters were measured at 1200 h except for days of the year (DOY) 123 and 124 in 2001, when they were measured at 0700 h, and daylight average solar irradiance for all other days.

DOY	r^2	SEE†	Air temperature	Wind speed at 2 m	Solar radiation at 1200 h	Average solar radiation	VPD	Precipitation
2000			°C	m s^{-1}	W m^{-2}	W m^{-2}	kPa	mm
131	0.51	24.2	32	9.5	970	645	4.2	0
132	0.44	26.0	34	10.2	1010	670	4.6	0
133	0.26	30.0	17	7.0	740	455	1.7	0
134	0.61	21.8	21	4.0	1010	670	2.2	0
135	0.50	24.5	24	9.0	980	620	2.7	0
2001								
123 at 0700 h	0.66	26.3	8	0.5			0	0
124 at 0700 h	0.05	44.0	9	0.4			0	6
132	0.04	43.0	18	3.9	230	230	0.2	0.2
133	0.36	35.0	18	5.0	850	590	1.1	0
134	0.35	35.4	20	7.0	950	620	1.4	0
135	0.51	30.7	22	4.3	960	650	1.9	0
136	0.60	27.7	24	3.5	960	650	3.3	0
137	0.67	25.3	22	4.3	950	610	1.8	0.3
138	0.56	29.3	19	1.1	960	630	0.9	0.02
2002								
105	0.57	15.5	29	3.8	980	560	3.4	0
106	0.64	14.3	26	9.0	990	560	2.8	0
107	0.52	16.5	27	7.8	800	520	3.0	0
108	0.58	15.3	29	9.3	1020	600	3.5	0
109	0.57	15.6	12	5.7	960	580	0.7	0

†Standard error of the estimate.

Our results from irrigated plots contrast with those from other hot, irrigated environments (e.g., Reynolds et al., 1994), and underscore that the suitability of CTD must be determined for individual environments. Some have suggested that CTD should be measured under water-stress conditions to identify cooler canopies because higher associated transpiration rates indicate greater growth and yield (Blum et al., 1982; Gardner et al., 1986; Mtui et al., 1981; Sojka et al., 1981). Others have suggested measuring CTD under well-watered conditions to identify warmer canopies because smaller associated transpiration rates indicate greater water conservation and therefore more water for growth and reproduction later in the season (Chaudhuri et al., 1986; Kirkham et al., 1984; Pinter et al., 1990).

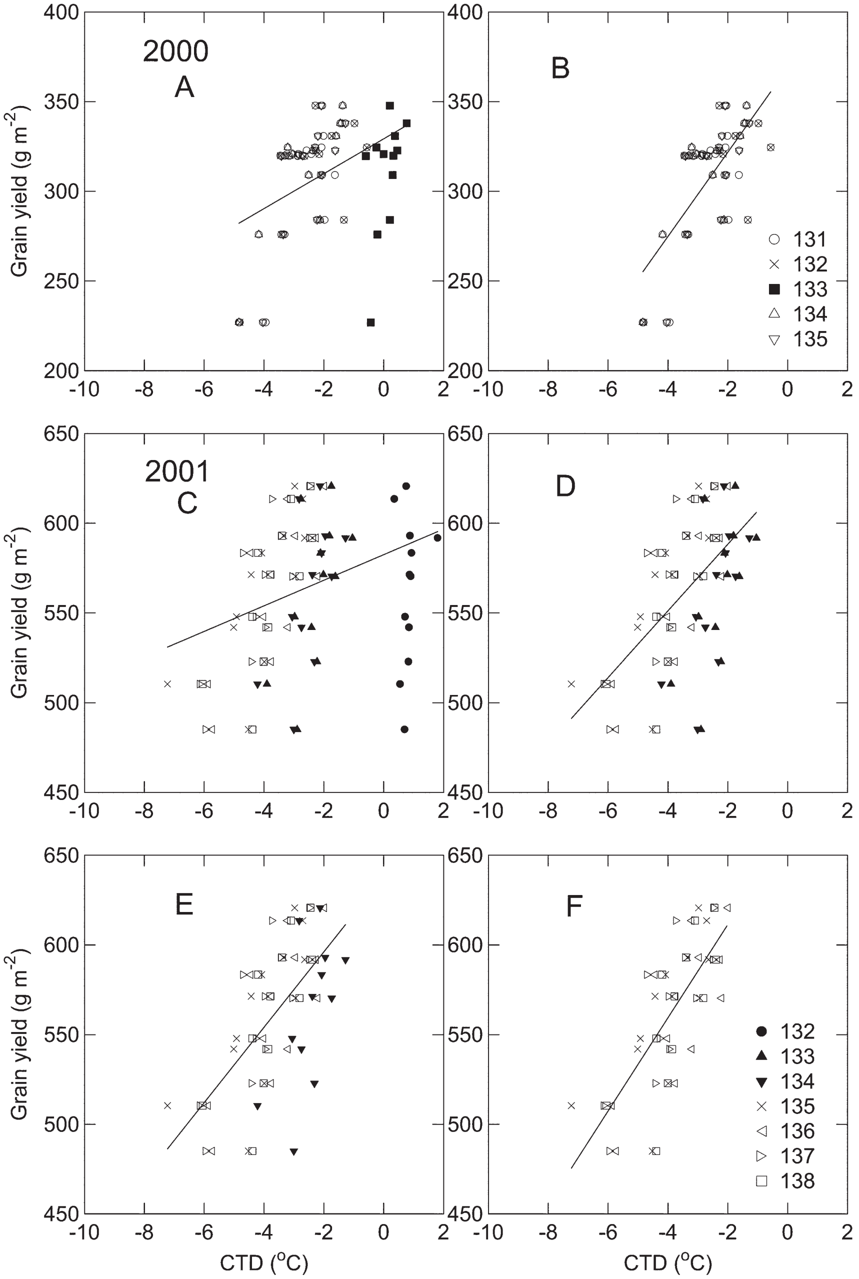

Figure 4. Correlation of wheat (*Triticum aestivum* L.) grain yield with canopy temperature depression (CTD) at 1200 h at ~2 wk after anthesis in (A–B) 2000 and (C–F) 2001, using days of the year (DOY) with contrasting solar irradiance, vapor pressure deficit, and wind speed (Table 4). In 2000, DOY 131 was 11 May; on DOY 133, solar irradiance at 1200 h was 750 W m^{-2} and daylight average between 0700 and 1900 h was 450 W m^{-2}: (A) including CTD data from DOY 133 gave a linear model with $r^2 = 0.17$ and standard error of the estimate (SEE) = 29; (B) excluding CTD data from DOY 133 gave a linear model with $r^2 = 0.48$ and SEE = 23. In 2001, DOY 132 was 12 May: (C) using data from all 7 d, the model $r^2 = 0.04$ and SEE = 38; (D) without DOY 132, when solar irradiance at 1200 h was 230 W m^{-2} (Table 4), $r^2 = 0.34$ and SEE = 33; (E) without DOY 132 and DOY 133, when wind speed at 1200 h was 5 m s^{-1}, $r^2 = 0.41$ and SEE = 31; and (F) without DOY 132, 133, and 134, $r^2 = 0.57$ and SEE = 27. On DOY 134, wind speed at 1200 h was 7 m s^{-1}.

To examine the effect of individual weather parameters on grain yield estimation, simple linear regression models of CTD readings at 1200 h and yield were evaluated for several individual days using data from dryland plots (Table 4). These days were chosen from all years to cover different growth stages from preheading to 3 wk after anthesis and to represent consecutive days with contrasting weather patterns. Pearson correlations (r^2) ranged from 0 to 0.71. Values of r^2 were consistently <0.5 on days of low solar irradiance, high wind speed, and rain events (see examples in Fig. 4–6). Without exception, CTD was not correlated with yield on days for which average solar radiation between 0700 and 1900 h was <500 W m^{-2}, and irradiance at 1200 h was <800 W m^{-2}. Data from these days were discarded in analyses.

The influence of wind speed on the CTD–yield correlation was less clear. Based on r^2 values, during a relatively calm year such as 2001, CTD readings taken on days with average wind speed >5 m s^{-1} reduced the correlation between yield and CTD, whereas in relatively windy years (2000 and 2002) this did not appear to be the case (Fig. 4 and 6).

Because hourly CTD is related to short-term transpiration rates that respond to changing ambient weather conditions, whereas mean seasonal CTD represents a long-term, integrated measurement value, one can expect the relation of daily CTD readings to yield to be much more variable than the relation of long-term mean CTD readings to yield. This is illustrated in Fig. 6 using data from days with a range of weather conditions, as shown in Table 4. Within any given day, apparent linear relations existed between CTD and yield, but when daily data were pooled, there was no relation. A practical implication of this is that cultivars that were not measured during the same time period should not be compared with one another because of large genotype × environment interaction. Long-term CTD measurements to obtain mean values are preferable for quantitatively relating yield to CTD using linear regression, but this is seldom practical in a breeding program. Data in Fig. 6 do suggest that short-term measurements can be used to rank cultivars.

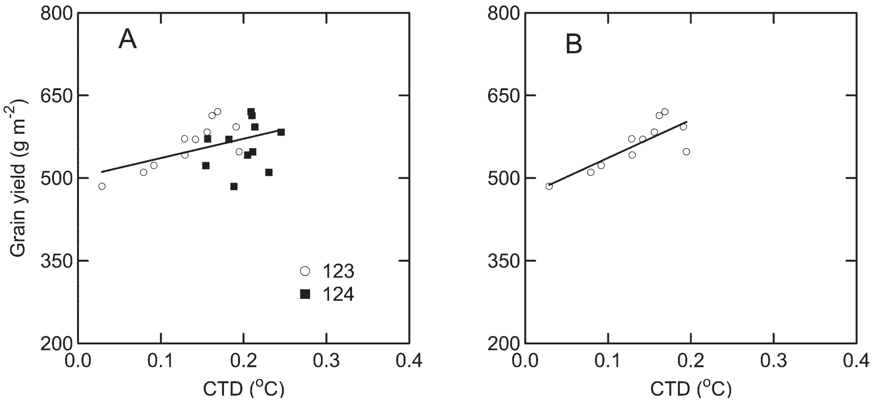

Figure 5. Correlation of canopy temperature depression (CTD) measured at 0700 h and wheat (*Triticum aestivum* L.) grain yield under dryland conditions in 2001. Day of the year (DOY) 123 was 3 May; on DOY 124 at 0700 h, a rain event of 6 mm occurred: (A) using data from both days, $r^2 = 0.19$; (B) without data from DOY 124, $r^2 = 0.66$.

The conservative nature of CTD diurnal trends that we (Fig. 1–2) and others (Ehrler et al., 1978; Peters and Evett, 2004) observed suggests that CTD data from successive hours should be similar to one another. With a view toward identifying the best time of day to measure dryland and irrigated CTD to assess grain yield, we used hierarchical clustering to identify natural groupings of hourly CTD data. Euclidian distances were used to compute dissimilarities between hours of sampling CTD and to identify three clusters, as shown in Fig. 7. Based on the fairly consistent clustering of 0 to 0800, 0900 to 1800, and 1900 to 2300 h, we labeled these time periods as Clusters 1, 2, and 3. Forward stepwise regression was then used to select a model for yield when CTD was sampled during these three time intervals. The results of forward stepwise regression for individual years, environments, and growth stages are presented in Table 5. In all years, Cluster 2 (0900–1800 h) was the first and most important indicator, and alone explained from 29 to 69% of the yield variability. With few exceptions, models were considerably improved when the other clusters, mainly Cluster 3, were included in the model. Canopy temperature depression sampled between 0900 and 1800 h was always positively related to yield, whereas negative relationships were observed for CTD from Cluster 1 (0–0800 h) and Cluster 3 (1900–2300 h). The best linear correlations between yield and CTD were obtained when CTD was sampled at anthesis ($r^2 = 0.79$ in 2001 and 0.69 in 2002). Good estimates were also obtained however, from one to three weeks from anthesis (Table 5).

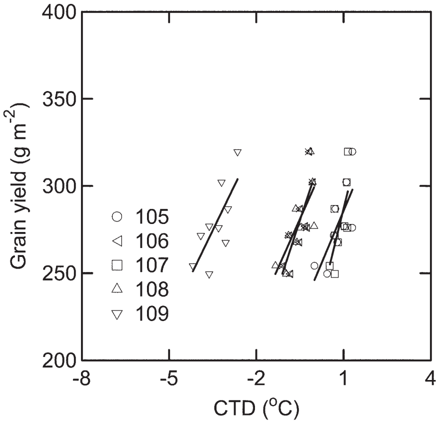

Figure 6. Correlations of canopy temperature depression (CTD) at 1200 h measured at preheading and wheat (*Triticum aestivum* L.) grain yield under dryland conditions in 2002. Day of the year (DOY) 105 was 15 April. Data were taken on days with contrasting weather in terms of solar irradiance, vapor pressure deficit, and wind speed (*Table 4*). For individual days, $r^2 = 0.57$ on DOY 105, 0.64 on DOY 106, 0.52 on DOY 107, 0.58 on DOY 108 and 0.57 on DOY 109. When all data are combined, $r^2 = 0.03$.

Genotype Effects on Canopy Temperature Depression

Other studies comparing genotypes measured CTD anywhere from 1000 to 1600 h, but mostly from 1200 to 1600 h (e.g., Amani et al., 1996; Hofmann et al., 1984; Pinter et al., 1990; Reynolds et al., 1994). In contrast, we found that main and some interactive effects of genotype on CTD were detectable at any time of day during all 3 yr, as shown for 4-h periods in Table 6. Measurement day and time of day also had large effects (based on sums of squares) on CTD. With few exceptions, the genotype × hour interaction was significant during 4-h intervals during the day, but insignificant at night. This suggests that CTD measurements must be taken during relatively short intervals during the day to differentiate genotypes, effectively reducing the number of entries that can be compared. Nighttime measurements may provide more stable conditions for CTD comparison among genotypes.

The regression tree method splits the response variable (i.e., yield) into two subsets based on the indicator variable (i.e., CTD) and values of that variable that result in the greatest increase in explained variance of the response variable (Breiman et al., 1984). Each subset, or daughter node, is then analyzed independently using the same binary partitioning procedure. The resulting statistic is a proportion of reduction in error, which is equivalent to the multiple R^2. The regression tree models for yield and CTD

Table 5. Stepwise linear regression results with hours of canopy temperature depression (CTD) measurements (clusters) included between brackets and listed in order of selection by stepwise forward procedure. Clusters from 0 to 0800 h (1), 0900 to 1800 h (2), and 1900 to 2300 h (3) were retained in the model when their regression coefficients were different from 0 at $P = 0.05$; CTD was measured in wheat (*Triticum aestivum* L.) under dryland in 2000 and under dryland and irrigation in 2001 and 2002, at preheading, anthesis, and 1st, 2nd, 3rd, 4th, and 5th wk after anthesis.

Year	Statistic	Preheading	Anthesis	1st wk	2nd wk	3rd wk	4th wk	5th wk
2000	r^2[†]	–	–	0.37	0.35	0.59	–	–
	SEE[‡]	–	–	26.0	26.2	21.1	–	–
	RC[§]	–	–	(2, 1)	(2, 3)	(2, 1)	–	–
2001	r^2	0.62	0.79	0.31	0.49	0.56	0.38	0.49
	SEE	34.8	29.7	50.2	41.0	37.4	43.9	40.0
	RC	(2, 3)	(2, 3)	(2)	(2, 3)	(2, 3)	(2, 3)	(2, 1)
2002	r^2	0.40	0.69	0.67	0.71	0.50	0.59	0.29
	SEE	79.0	57.4	58.6	55.8	71.6	64.9	63.9
	RC	(2, 3)	(2)	(2, 1, 3)	(2, 1, 3)	(2, 3)	(2)	(2)

[†] Cumulative r^2.

[‡] Standard error of the estimate.

[§] Retained cluster.

Table 6. Probability levels from ANOVA for the effect of sampling time on canopy temperature depression in dryland wheat (*Triticum aestivum* L.) for three growing seasons.

Source of variation	0–0300 h	0400–0700 h	0800–1100 h	1200–1500 h	1600–1900 h	2000–2300 h
2000						
Genotype (G)	***	***	***	***	***	***
Hour (H)	***	***	***	***	***	***
Day (D)	***	***	***	***	***	***
G × H	NS	***	***	***	***	NS
G × D	NS	NS	***	***	NS	***
H × D	***	***	***	***	***	***
G × H × D	NS	NS	NS	NS	NS	NS
2001						
Genotype	***	***	***	***	***	***
Hour	***	***	***	***	***	***
Day	***	***	***	***	***	***
G × H	NS	NS	***	NS	***	NS
G × D	***	NS	**	***	NS	***
H × D	***	***	***	***	***	***
G × H × D	NS	NS	NS	NS	NS	NS
2002						
Genotype	***	***	***	***	***	***
Hour	***	***	***	***	***	***
Day	***	***	***	***	***	***
G × H	NS	NS	*	NS	*	NS
G × D	***	***	***	***	***	***
H × D	***	***	***	***	***	***
G × H × D	NS	NS	NS	NS	NS	NS

*Significant at $P < 0.5$; NS = not significant at $P < 0.5$.

**Significant at $P < 0.01$.

***Significant at $P < 0.001$.

at anthesis in 2001 and 2002, the years in which both irrigated and dryland conditions were present, are presented in Fig. 8 and 9. In 2001 CTD sampled at 1300 h was most highly related with yield. The fact that no additional splits were performed on the left side of the tree indicates that CTD at 1300 h was sufficient to model low yields (i.e., dryland yields) at anthesis. The model also shows that values of CTD at 1300 h <0.4°C were associated with low yields. The CTD at 1800 h was second most highly related to yield, because it bisected high (i.e., irrigated) yield data. According to the model, CTD at 1800 h <4.5°C was associated with higher yields. In 2002 CTD sampled at 0900 h was the most highly related to yield (Fig. 9). The model shows that yields >278 g m^{-2} were obtained when CTD at 0900 h was >1.7°C. These models explained roughly 64% of yield variability in 2001 and 91% in 2002. They also assessed genotypic variation well, that is, TX86A8072 had larger yield under dryland and smaller yield under irrigation than TX86A5606 (Fig. 8 and 9).

Results of the regression tree models for all years and stages of vegetation are presented in Table 7. In 2000 and 2001, the hours of best CTD measurement selected by the models to split data were, with few exceptions, between 1100 and 1400 h, when CTD was least, and between 1800 and 2200 h, when CTD was greatest (Fig. 1–2). In 2000, when measurements were only taken under dryland conditions, positive relationships between yield and CTD were observed at all hours of CTD sampling. In 2001, when CTD data were taken from dryland and irrigated plots, CTD was positively correlated with yield from 1100 to 1400 h, and negatively correlated with yield from 1800 to 2200 h. In 2002 the first hour of CTD measurement selected to split data ranged from 0800 to 1600 h, depending on phenological stage, but CTD near 0900 h was selected often. When data from all years were combined, 0900 h was always selected to split data, and in most cases was the main splitting variable, explaining up to 78% of yield variation (Table 7).

In general, tree regression appeared to calculate yield from short-term CTD measurements better than linear regression (compare Fig. 4–6 to Fig. 8 and 9). The best times to measure CTD to assess yield and genotype performance varied with year and growth stage, but based on results in Table 7 appear to be near 0900, 1300, and 1800 h.

CONCLUSIONS

Based on the results shown in Fig. 3a, we conclude that long-term mean CTD data can be used to estimate yield among wheat genotypes under High Plains growing conditions. A linear relationship between yield and long-term mean CTD is to be expected since long-term CTD is related

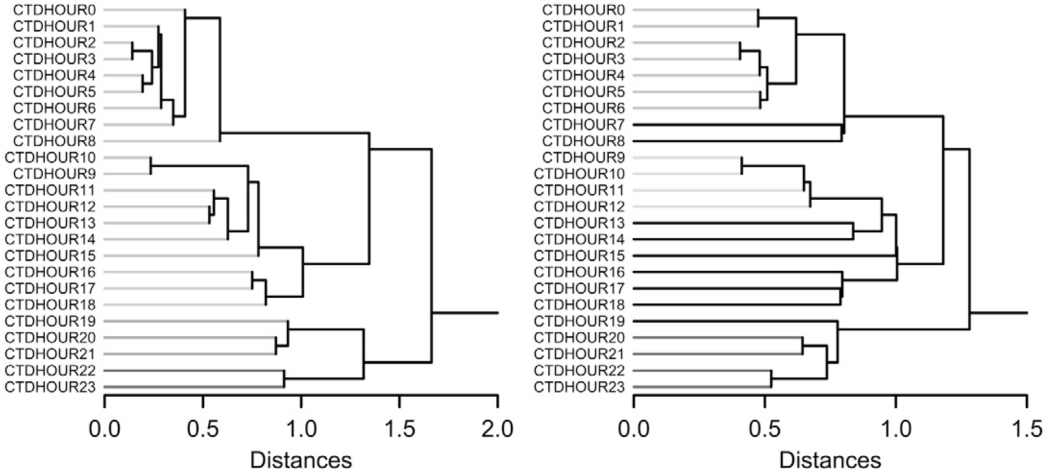

Figure 7. An example of cluster analysis for canopy temperature depression (CTD) sampling in wheat (*Triticum aestivum* L.). Data represent hourly mean CTD during anthesis (left) and 2 wk from anthesis (right) from all years combined. Clusters are hours from 0 to 0800, 0900 to 1800, and 1900 to 2300 h. Similar clusters were obtained when individual years and stages were used.

to cumulative transpiration, which in turn is linearly related to yield (de Wit, 1958).

Estimating yield from a small number of short-term CTD measurements seems much more dubious, however, since short-term CTD and transpiration rate are related to temporally variable environmental properties including irradiance, air temperature, wind speed, and vapor pressure deficit. If suitable days are used for CTD measurement in terms of sufficiently high irradiance, sufficiently low wind speed, no rainfall, and sufficient vapor pressure deficit to permit transpiration, fairly consistent rankings for genotypes can be obtained; however, measurements should be made in as short a time as possible (<<4 h, based on genotype × hour interaction terms in Table 6). Unless one has high confidence in weather stability, it is doubtful whether readings from different days can be combined without introducing a large error from genotype × environment interaction.

Based on empirical comparisons under our conditions, CTD data from days in which mean solar irradiance was <500 W m^{-2} or mean wind speed was >4 m s^{-1} were unsuitable for estimating yield or ranking genotypes. The possibility of measuring nighttime CTD to rank genotypes (but not to estimate yield) should be further explored because it appeared to have less genotype × environment error (Table 6).

Our results suggest that tree regression offers advantages compared with linear regression for estimating yield from short-term CTD data. In addition to providing

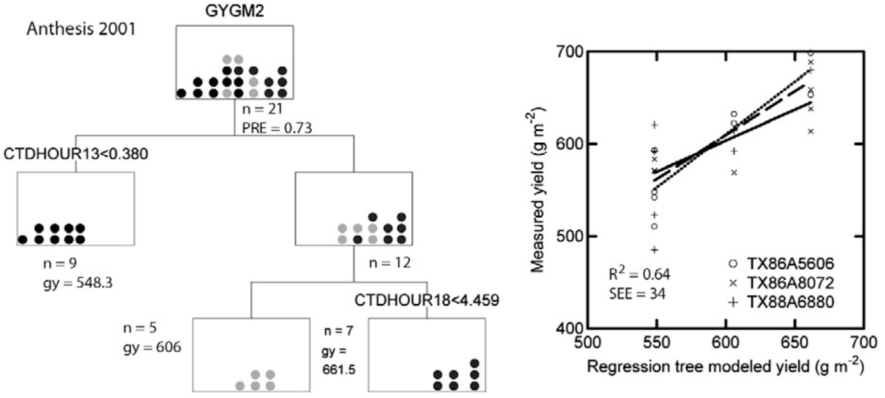

Figure 8. Regression tree model for wheat (*Triticum aestivum* L.) yield using canopy temperature depression (CTD) data at anthesis as the independent variable in 2001 (left) and comparison of measured yields with regression tree models (right). The solid line represents the regression line for TX86A8072 (slope = 0.67, standard error of the slope [SES] = 0.2); the dotted line for TX86A5606 (slope = 1.15, SES = 0.2); and the dashed line for TX88A6880 (slope = 0.95, SES = 0.4); gy = grain yield (g m^{-2}), SEE = standard error of the estimate, and PRE = proportion of reduction in error.

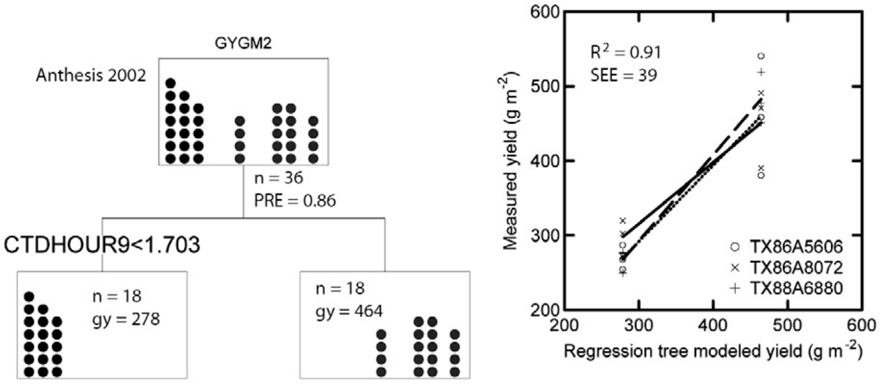

Figure 9. Regression tree model of wheat (*Triticum aestivum* L.) yield with canopy temperature depression (CTD) data measured at anthesis as the independent variable in 2002 (left) and comparison of measured yield with regression tree models (right). The solid line represents the regression line for TX86A8072 (slope = 0.82, standard error of the slope [SES] = 0.12); the dotted line for TX86A5606 (slope = 1.02, SES = 0.16); and the short dashed line for TX88A6880 (slope = 1.16, SES = 0.16) ; gy = grain yield (g m^{-2}), SEE = standard error of the estimate, and PRE = proportion of reduction in error.

Table 7. Regression tree statistic, with hours in order of selection. Proportional reduction in error (PRE), which is equivalent to R^2, with only the 1st h in the model is included in parentheses. Hours with a minimum improvement in PRE of 0.05 were retained in the model.

Hour	Preheading	Anthesis	1st wk	2nd wk	3rd wk	4th wk	5th wk
2000							
PRE			0.47 (0.3)	0.55 (0.48)	0.76 (0.62)		
1st h			14	12	13		
2nd h			17	6	18		
3rd h			15	18	14		
2001							
PRE	0.68 (0.64)	0.76 (0.73)		0.69 (0.60)	0.73 (0.65)	0.59 (0.46)	0.59 (0.59)
1st h	13	13		12	13	13	11
2nd h	16	18		16	22	12	10
3rd h	20			10	11	22	18
2002							
PRE	0.57 (0.49)	0.86	0.81 (0.76)	0.85	0.76 (0.70)	0.77 (0.76)	0.79 (0.79)
1st h	14	9	12	11	16	8	15
2nd h	20		20		4	18	7
3rd h	12		2		21		17
All years							
PRE	0.45	0.78	0.83 (0.54)	0.54 (0.28)	0.76 (0.53)	0.74 (0.59)	0.57
1st h	14	9	9	9	9	9	7
2nd h	2		19	0	5	18	22
3rd h	9		20	23	4	19	9

better agreement with empirical data, tree regression pointed to three measurement times (0900, 1300, and 1800 h) that are at least heuristically related to crop water status under different scenarios of soil water availability. The CTD at 1300 h is related to the ability of the plant to avoid diurnal wilt and meet atmospheric evaporative demand, which is typically largest at this time; CTD at 1800 h reflects the degree to which the crop recovered from diurnal wilt; CTD at 0900 h reflects the degree to which the crop rehydrated overnight because stomata are nearly fully opened (Henzell et al., 1975).

Finally, our data suggest that it is important that measurements are made in as little time as possible to reduce potentially large errors from a changing environment. In our experience, the traditional handheld IRT is not well suited to this requirement. Currently, we are experimenting with radiometric thermal imagers. Alternatively, development of wireless IRTs in a meshed network environment would reduce the complexity of wiring and datalogging IRTs, and could be less expensive than a thermal imager approach.

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