Leaf and Canopy Temperatures of Pearl Millet Genotypes under Irrigated and Nonirrigated Conditions[1]

Piara Singh and E. T. Kanemasu[2]

ABSTRACT

It has been reported from previous research that leaf and canopy temperatures correlate with the level of water stress in a plant. If genotypes of a given species differ in their response to water stress, then leaf and canopy temperatures could serve as indices of their drought resistance. To test this hypothesis, 10 pearl millet (*Pennisetum americanum* (L.) Leeke) genotypes differing in plant morphology were grown on a Eudora silt loam soil (fine silty, mixed, mesic, Pachic Haplustoll) under both irrigated and nonirrigated conditions. Leaf temperature (T_l), canopy temperature (T_c), canopy minus air temperature ($T_c - T_a$), leaf-water potential (Ψ_l), leaf-diffusion resistance (LDR), water use (WU), and crop yields were observed in both irrigated and nonirrigated treatments. Significant differences ($P<0.05$) were found in the grain yield, T_c, and $T_c - T_a$ of genotypes, only in the irrigated treatment. Grain yield was negatively and significantly correlated with average afternoon T_c($r = -0.81$) and average afternoon $T_c - T_a$($r = -0.78$). Grain yield ratio (nonirrigated grain yield/irrigated grain yield) was positively and significantly correlated with average afternoon T_l($r = 0.64$), average afternoon T_c($r = 0.64$), and average afternoon $T_c - T_a$($r = 0.75$). In the nonirrigated treatment, however, correlations of grain yield and grain yield ratio with various stress indices were nonsignificant. Average afternoon T_c and $T_c - T_a$ was significantly correlated with average afternoon LDR only in the irrigated treatment. This study suggests that average afternoon T_c and $T_c - T_a$ as observed in a nonstressed environment with an infrared thermometer could effectively be used as a technique to screen millet genotypes for their grain yield and grain-yield stability (nonirrigated grain yield/irrigated grain yield).

Additional index words: **Canopy minus air temperature, Water stress, *Pennisetum americanum* (L.) Leeke, Drought screening.**

ENERGY exchange by radiation, convection, and transpiration determines leaf and canopy temperatures of crop plants. Leaf temperature of a given plant type is influenced by many environmental variables, including windspeed, solar radiation, soil moisture availability, and ambient air temperatures.

It has been shown that transpiration reduces leaf temperature considerably (Gates, 1964; Tanner, 1963; Pallas et al., 1967; Van Bavel and Ehrler, 1968; Slatyer and Bierhuizen, 1964). When water deficits develop in the leaves, stomates close progressively, and hence leaf temperature rises. Leaf temperature (T_l) and canopy temperatures (T_c) are related to plant-water stress level (Millard et al., 1978). Other temperature-based indices of water stress in plants are leaf minus air temperature ($T_l - T_a$) and canopy minus air temperature ($T_c - T_a$), both reportedly correlated to plant-water stress (Ehrler and Van Bavel, 1967; Idso and Ehrler, 1976; and Blad and Rosenberg, 1976). Ehrler et al. (1978) reported that maximum value of $T_l - T_a$ or $T_c - T_a$ is obtained in the afternoon at 1400 and that those measurements represent the whole day of plant-water stress. In durum wheat (*Triticum durum* Desf.), Ehrler et al. (1978) revealed that ($T_c - T_a$) and plant-water potential were significantly correlated, whereas, for barley (*Hordeum vulgare* L.) and soybeans (*Glycine max* (L.) Merr.) Millar et al. (1971) and Carlson et al. (1972) respectively showed that leaf temperature and water saturation deficit of leaves were significantly correlated. Similarly, Wiegand and Namken (1966) reported that a decrease in relative turgidity of cotton (*Gossypium hirsutum* L.) leaves from 83 to 59% resulted in a 3.6 C increase in leaf temperature and a 2.7 to 3.7 C increase in $T_l - T_a$ when air temperature and solar radiation were approximately constant.

Blum (1974a, 1974b) observed significant genotypic differences in maintenance of leaf-water potentials of sorghum (*Sorghum bicolor* L.) under water stress. Similar results were obtained by Quarrie and Jones (1979) in spring wheat (*Triticum aestivum* L. em. Thell.) and O'Toole and Moya (1978) in rice (*Oryza sativa* L.). In view of the information that a significant correlation exists between level of water stress in a plant and its leaf or canopy temperatures, it was speculated that leaf or canopy temperatures could be used as criteria to screen genotypes of a species for their crop yields or susceptibility to drought. Because leaf thermocouples and infrared thermometers could easily be used to determine such temperatures, genotypes thereby could be screened for drought resistance faster than by the methods currently used. We tested these hypotheses on pearl millet (*Pennisetum americanum* (L.) Leeke) under both irrigated and nonirrigated conditions: (1) to determine differences in leaf and canopy temperature of pearl millet genotypes under both irrigated and nonirrigated conditions; (2) to correlate leaf and canopy temperatures with leaf-water potential, leaf diffusion resistance, water use, and crop yields of genotypes in both environments.

MATERIALS AND METHODS

This experiment was conducted in the 1980 summer season at the Ashland Agronomy Research Farm, Evapotranspiration Site, 14 km southwest of Manhattan, Kans. The soil is Eudora silt loam (fine silty, mixed, mesic, Pachic Haplustoll) that holds about 250 mm of available water in the top 180-cm of soil profile. Daily maximum and minimum temperatures observed during the crop growth period were above normal in the summer of 1980 (Fig. 1). Total rainfall received during that period was only 15.6 cm. Very high air saturation deficits, high day temperatures, and more rain-free days than normal were observed from the middle of July to the end of August.

Six cultivars (HMP 600, HMP 1700, Serere-3A, HMP 550, Senegal Bulk, and HMP 559) and four hybrids (2221 × 7024, 2221 × 4104, 2094 × 4104, and 2094 × 7024) were planted on 22 May 1980 in an experiment having randomized complete block design in a split-plot layout and replicated three times. Two main treatments consisted of irrigation and no irrigation. Each main treatment area was divided into 10 subplots to which 10 genotypes (subtreatments) were randomly assigned. Each plot of size 7 × 10 m had eight rows 76 cm apart. Plants were kept 10 cm apart within a row. Prior to planting, 68 kg N/ha was applied. Starting 1 July, irrigated plots received 37.9 cm (total) of irrigation water, split in six irrigations of approximately same amount and applied weekly.

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[1] Contribution No. 82-325-j; Dep. of Agronomy, Evapotranspiration Laboratory, Kansas Agric. Exp. Stn., Manhattan, KS 66506. Received 14 Apr. 1982.

[2] Soil scientist with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru P.O., A.P. 502 324, India (formerly graduate research assistant, Kansas State Univ.) and research microclimatologist, Evapotranspiration Lab., Kansas State Univ., Manhattan, KS 66506.

To determine leaf temperature (T_l), one thin wire copper-constantan thermocouple (gauge SWG 42 obtained from Dural Plastics and Eng. Pvt. Ltd.[3], Dural, N.S.W. Australia, 2158) per plot was woven into a fully expanded top leaf such that the thermocouple junction touched the lower side of the leaf away from direct solar radiation. Thermocouples were moved up on the newly expanded leaves as the crop grew. To monitor air temperatures, teflon-coated copper constantan thermocouples of size 24 (obtained from Omega Engineering, Inc. P.O. 4047, Stanford, CT 06907) were placed midway between two parallel sheets of 6 mm-thick plywood spaced 5 cm apart. The upper plate (20 × 25 cm) was centered over the lower plate (15 × 20 cm). The plates (radiation shields) painted white to reflect solar radiation, were used to shade the thermocouples during sunshine and to provide natural air flow. Four such shields containing thermocouples were randomly placed in the field 1 m above the crop canopy and moved up as the plants grew. Air-temperature data were averaged before they were used for any purpose. Differences between wet-bulb and dry-bulb temperature were recorded continuously throughout the season with a psychrometer (Delta T-Devices, Cambridge, England). Electrical output from leaf thermocouples, air temperature thermocouples, and a psychrometer was recorded hourly with a data-acquisition system (Campbell CR5).

Canopy temperature (T_c) and canopy minus air temperature ($T_c - T_a$) were observed between 1300 and 1500 with an infrared thermometer (Teletemp Model 44) having a bandpass filter (10.5 to 12.5 μ). The infrared thermometer used to record temperatures was pointed at the sunlit leaves from the top of canopy, care being taken to avoid interference by the exposed ground surface. Two or three observations per plot were taken on T_c and $T_c - T_a$ on 43, 46, 52, 58, and 64 days after the plant had emerged (DAE).

Leaf-water potentials (Ψ_l) were estimated with a pressure chamber apparatus (Scholander et al., 1965). Two fully expanded top leaves per plot were sampled and then enclosed in a polyethylene bag containing a small piece of damp paper towel and transported to a nearby air-conditioned room where potential measurements were made. Leaf-water potential determinations were made in all replications.

To determine leaf-diffusion resistance (LDR), resistances of both adaxial and abaxial surfaces of fully expanded top leaves were measured with a steady state porometer (Model LI 1600, LI-COR, Inc., Lincoln, NE). These measurements were taken on two leaves per plot in all replications. Leaf-diffusion resistance for a leaf was calculated from the following relationship:

Table 1. Period of observation, time of observation, and number of observations averaged over days to calculate various stress indices for pearl millet.

Stress index	Period of observation (Days after emergence)	Time of observation (hours)	No. of observations averaged over days
Average afternoon leaf temperature (T_l)	37 to 77	1300 to 1500	34
Average afternoon canopy temperature (T_c)	43 to 64	1300 to 1500	5
Average afternoon canopy minus air temperature ($T_c - T_a$)	43 to 64	1300 to 1500	5
Average afternoon leaf water potential (ψ_l)	42 to 73	1200 to 1700	14
Average afternoon leaf diffusion resistance (LDR)	51 to 73	1200 to 1700	10

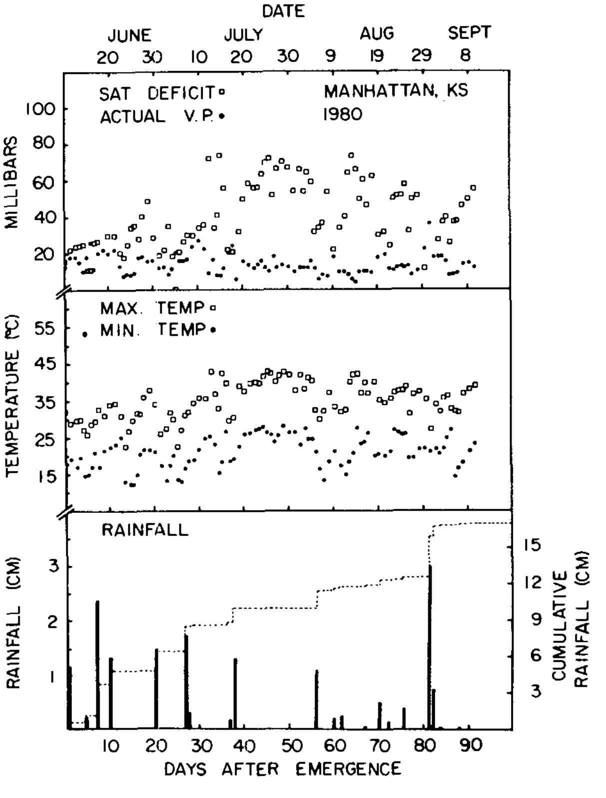

Fig. 1. Air-saturation deficit and actual vapor pressure, maximum and minimum temperature, and rainfall during the 1980 growing season.

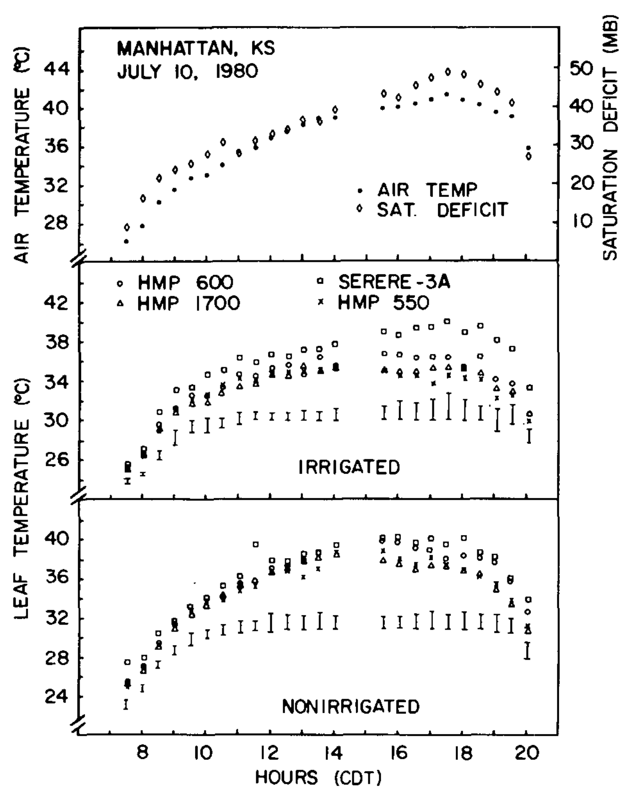

Fig. 2. Air temperature, air-saturation deficit, and leaf temperature of pearl millet genotypes in irrigated and nonirrigated treatments on 10 July 1980. Vertical bars represent the average of standard deviations observed in data points just above the bar.

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[3] Mention of a trademark or proprietory product does not imply approval by the Kansas Agric. Exp. Stn. to the exclusion of other products that may also be suitable.

$$\frac{1}{LDR} = \frac{1}{LDR_{ab}} + \frac{1}{LDR_{ad}},$$

where LDR_{ab} and LDR_{ad} are abaxial and adaxial resistance of a leaf, respectively.

Water use by genotypes was determined by recording soil-moisture changes in each plot. Neutron probe access tubes were installed within a row in the middle of each plot and probe observations (Troxler Model 380) were taken every week from 15 to 165 cm soil profile at every 15 cm depth increments. Soil moisture in the top 15 cm soil layer was determined gravimetrically. Water use was computed by the water balance method. No surface runoff occurred during the season.

The observations on T_l, T_c, $T_c - T_a$, Ψ_l, and LDR were averaged over days for each plot to arrive at various stress indices as given in Table 1. For example, average afternoon leaf temperature is the leaf temperature observed between 1300 and 1500 hours and averaged over 34 days. Mean yields and yield ratios (nonirrigated yield/irrigated yield) were correlated with mean values of stress indices (as given in Table 1) and correlation coefficients determined.

RESULTS AND DISCUSSION

Leaf and Canopy Temperatures

Diurnal variations in leaf temperature (T_l) of genotypes as measured on 10 July 1980 are presented in Fig. 2, 3, and 4. In the irrigated treatment, a 4.5 to 5.0 C difference in afternoon leaf temperature of genotypes was observed. In the nonirrigated treatment, differences in afternoon leaf temperatures of genotypes were relatively less. In the irrigated treatment, Serere-3A and HMP 550 had the warmest and the lowest afternoon leaf temperatures, respectively (Fig. 2). In the nonirrigated treatment, Serere-3A maintained the highest afternoon leaf temperature, which was 3.0 C greater than that of HMP 1700. For relatively late-maturing varieties in the irrigated treatment, HMP 559 was 3.5 C warmer than Senegal Bulk (Fig. 3). But in the nonirrigated treatment, Senegal Bulk was 1.0 to 2.0 C warmer than HMP 559 in the afternoon. Differences in the afternoon leaf temperatures among hybrids were relatively less (Fig. 4), presumably because genetic variability was less in them. Hybrid 2221 × 7024 had the warmest afternoon leaf temperature in both irrigated and nonirrigated treatments. Differences in the afternoon leaf temperature among genotypes could be attributed to differences in the genetic make up of the plants that influence the gain and loss of energy from plant surfaces such as the leaf conductance to water loss. The literature contains little information on leaf temperature of genotypes of a single specie. Carlson et al. (1972) reported that two soybean cultivars had different leaf temperatures under water stress. Ehrler (1973) observed a 2.0 C difference in the afternoon leaf temperature of two cotton genotypes.

Data on average afternoon T_l, T_c, and $T_c - T_a$ are in Table 2. Differences among most genotypes in their average afternoon T_l were statistically nonsignificant in both irrigated and nonirrigated treatments, presumably because T_l (as observed with leaf thermocouples) does not adequately represent all the leaves on the canopy space. Statistically significant differences among some genotypes were observed in their T_c and $T_c - T_a$ in the irrigated treatment. But in the nonirrigated treatment, gen-

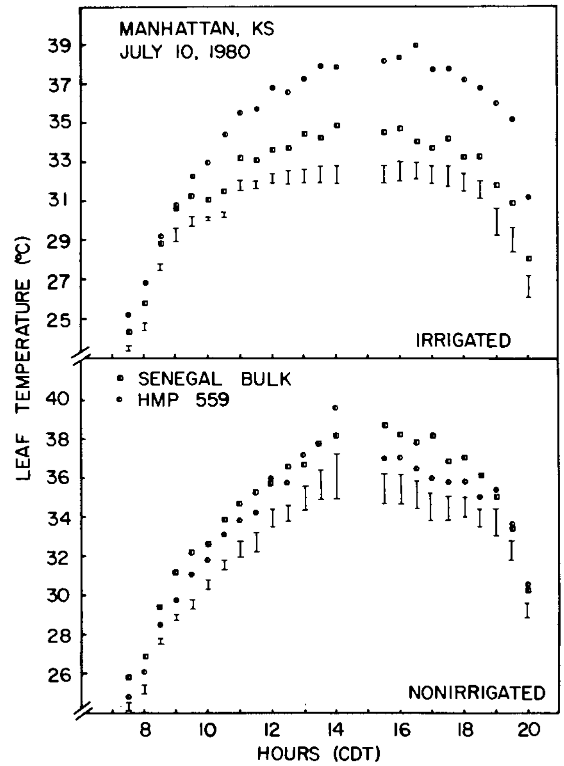

Fig. 3. Leaf temperature of genotypes in irrigated and nonirrigated treatments on 10 July 1980. Vertical bars represent the average of standard deviations observed in data points just above the bar.

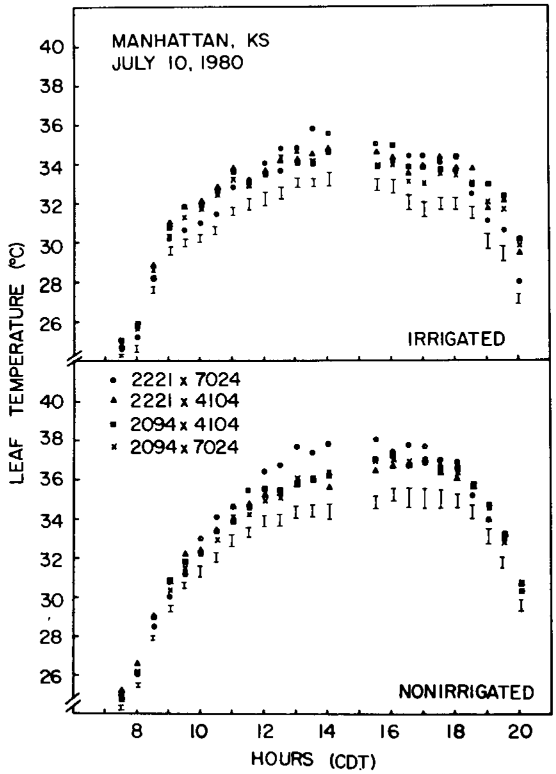

Fig. 4. Leaf temperature of hybrids in irrigated and nonirrigated treatments on 10 July 1980. Vertical bars represent the average of standard deviations observed in data points just above the bar.

Table 2. Average afternoon T_l, T_c, and $T_c - T_a$ of genotypes in the irrigated and nonirrigated treatments.

Pearl millet genotypes	Average afternoon T_l (C)		Average afternoon T_c (C)		Average afternoon $T_c - T_a$ (C)	
	Irrig.	Nonirrig.	Irrig.	Nonirrig.	Irrig.	Nonirrig.
HMP 600	35.3 a	36.4 a	34.4 abc	36.0 bc	−2.5 bc	−1.2 ab
HMP 1700	33.3 a	36.2 ab	33.6 cd	36.6 ab	−2.9 abc	−0.7 b
Serere-3A	34.0 a	36.5 a	35.1 a	37.2 a	−2.4 bc	−0.3 b
HMP 550	34.6 a	35.8 ab	34.0 bcd	36.2 bc	−2.9 abc	−0.7 b
Senegal Bulk	33.7 a	35.5 ab	33.3 d	36.2 bc	−4.0 a	−1.4 ab
HMP 559	34.4 a	35.4 ab	34.8 ab	36.1 bc	−1.9 c	−1.3 ab
2221 × 7024	33.4 a	35.6 ab	33.8 cd	35.4 c	−3.3 ab	−2.0 a
2221 × 4104	33.2 a	35.9 ab	33.5 cd	36.0 bc	−4.0 a	−1.5 ab
2094 × 4104	33.8 a	34.1 b	33.6 cd	36.0 bc	−3.6 ab	−1.0 ab
2094 × 7024	33.3 a	35.3 ab	33.1 d	36.8 ab	−3.9 a	−1.1 ab
PR > F for irrigation × genotype interaction	0.635		0.003		0.092	

• Means within a column followed by the same letter are not significantly different at 5% level of probability based on Duncan's Multiple Range Test.

otypic differences in T_c and $T_c - T_a$ were less and most genotypes did not differ statistically. Tall genotypes tended to have higher (more positive) T_l, T_c, and $T_c - T_a$ than did shorter genotypes. For example, HMP 559, Serere-3A, and HMP 600 had higher (more positive) T_l, T_c, and $T_c - T_a$ than did other cultivars, particularly in the irrigated treatment, though most differences could not be proved significant statistically (Table 2). Hybrids had low plant temperatures, compared with other genotypes, as indicated by their relatively lower values of T_c, and $T_c - T_a$. Irrigation by genotype interaction for T_c was significant ($PR > F = 0.003$), indicating that genotypes with high T_c, under nonstressed conditions would not necessarily have high T_c under stressed conditions. Genotypic differences in T_c and $T_c - T_a$ reflected the differential transpirational cooling of genotypes in an environment, which in turn would be determined by the soil and plant resistance to flow of water.

Table 3. Simple correlation of crop yields and yield ratios with average afternoon T_l, T_c, and $T_c - T_a$ in both the irrigated and nonirrigated treatments ($N = 10$).

	Average afternoon T_l	Average afternoon T_c	Average afternoon $T_c - T_a$
		Irrigated treatment	
Total yield	−0.54	−0.37	−0.47
Total yield ratio	0.58	0.63	0.70*
Grain yield	−0.62	−0.81**	−0.78**
Grain yield ratio	0.64*	0.64*	0.75*
		Nonirrigated treatment	
Total yield	−0.33	0.11	0.16
Total yield ratio	0.09	−0.10	0.20
Grain yield	0.39	−0.27	−0.04
Grain yield ratio	0.32	−0.19	0.02

*,** Significant at 0.05 and 0.01 levels of probability, respectively.

Correlations Across Genotypes of Crop Yields with Stress Indices

Data on correlation of yields with stress indices are given in Table 3 and Fig. 5. In the irrigated treatment, grain yields of genotypes were negatively and significantly correlated with average afternoon T_c ($r = -0.81$) and average afternoon $T_c - T_a$ ($r = -0.78$); whereas, grain yield ratio (nonirrigated grain yield/irrigated grain yield) was positively and significantly correlated with average afternoon T_l ($r = 0.64$), T_c ($r = 0.64$), and $T_c - T_a$ ($r = 0.75$). Similarly, total yield ratio (nonirrigated total yield/irrigated total yield) was significantly correlated with average $T_c - T_a$ ($r = 0.70$). These results were consistent with the hypothesis that cooler genotypes yield more under irrigation (nonstressed condition) and warmer genotypes are more drought resistant.

In the nonirrigated treatment, the correlation of crop yields and yield ratios with average afternoon T_l, T_c, and $T_c - T_a$ were low and statistically nonsignificant, attributable to low and statistically nonsignificant differences in grain yields of genotypes and genotypic differ-

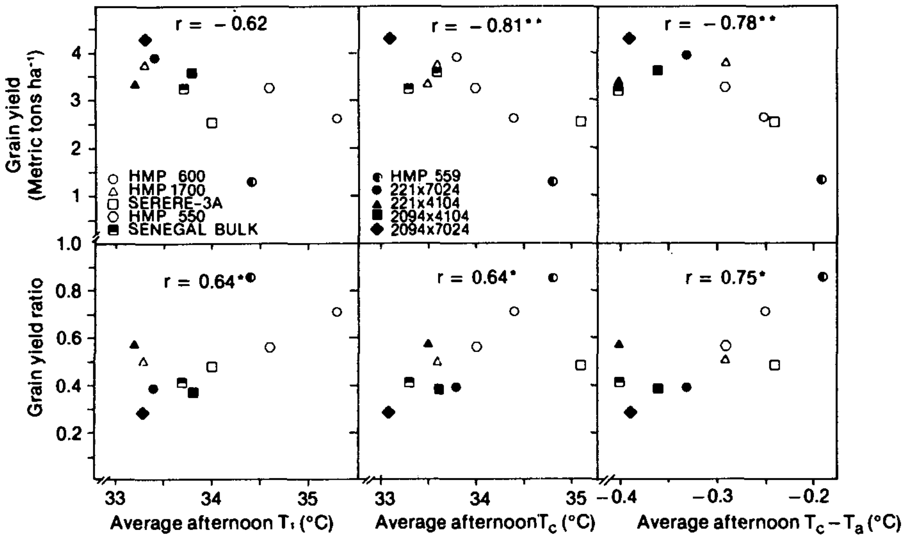

Fig. 5. Plot of the grain yield and grain yield ratio against average afternoon T_l, average afternoon T_c, and average afternoon $T_c - T_a$ as observed in the irrigated treatment. Each point on the graph is average of three observations.

Table 4. Simple correlations of average afternoon T_l, T_c, and $T_c - T_a$ with average afternoon ψ_l, LDR, and water use in irrigated and nonirrigated treatments (N = 10).

	Average afternoon ψ_l (MPa)	Average afternoon LDR (sm^{-1})	Water use (mm)
		Irrigated treatment	
Average afternoon T_l	−0.39	0.57	0.47
Average afternoon T_c	−0.33	0.87**	0.09
Average afternoon $T_c - T_a$	−0.22	0.85**	0.24
		Nonirrigated treatment	
Average afternoon T_l	−0.20	0.22	−0.26
Average afternoon T_c	−0.02	0.28	−0.42
Average afternoon $T_c - T_a$	−0.04	0.22	−0.36

*,** Significant at 0.05 and 0.01 levels of probability, respectively.

ences in various temperature-based stress indices. This leads to the conclusion that as the differences in plant temperature are narrowed with increasing water stress, it is increasingly difficult to screen genotypes for their yield and yield stability, based on plant temperature.

Correlations Across Genotypes Among Various Stress Indices

Average afternoon T_l, T_c, and $T_c - T_a$ were poorly correlated with average afternoon Ψ_l and water use in both irrigated and nonirrigated treatments (Table 4). Average afternoon LDR was positively and significantly correlated with average afternoon T_c ($r = 0.87$) and average afternoon $T_c - T_a$ ($r = 0.85$), but not with average afternoon T_l. Also, these correlations were nonsignificant in the nonirrigated treatment. Similar results on the relationship between transpiration and plant temperature have been reported by various workers (Gates, 1964; Tanner, 1963; Pallas et al., 1967; Van Bavel and Ehrler, 1968; Slatyer and Bierhuizen, 1964). In the nonirrigated treatment, poor correlations of plant temperature with average LDR presumably were due to the small differences in afternoon plant temperature of genotypes and also to greater errors involved in assessing these temperatures with the available techniques, particularly under stressed conditions.

Our study shows that genotypes differ in their canopy temperature and canopy minus air temperatures, as observed with a portable infrared thermometer. Plant temperatures were significantly correlated with average LDR, grain yields, and grain yield ratio of genotypes, especially in the nonstressed environment. We can conclude that canopy temperature and canopy minus air temperature, as observed in a nonstressed environment, could be successfully used as criteria for screening millet genotypes for their grain yields and yield stability.

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