Selection Criteria for Drought-resistance Breeding in Turfgrass

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Abstract. Cumulative evapotranspiration (ET_{cum}) patterns of 10 commercially available cool-season turfgrass species and cultivars were evaluated under progressive water stress in the semi-field conditions using a gravimetric mass balance method in three studies. At the end of water stress, the cultivars were visually scored for green appearance on a 0 (no green) to 10 (100% green) scale. A Gompertz nonlinear model gave a best fit to ET_{cum} vs. days adjusted for pan evaporation variation. Two of the ET_{cum} attributes (t_i , the time during which the rate change in ET is zero, and ET_{max} , the maximum ET rate) estimated from the Gompertz model appeared to reflect efficient water-use attributes in the turfgrass. Among the physiological screening techniques studied, electrolyte leakage, relative water content, and the difference between canopy and air temperature appeared to separate cultivars by drought resistance and water use efficiency (WUE). These physiological attributes were also relatively easy to measure and had high correlations with color score and WUE. Biplot display is a graphical technique in which the interrelationships between the cultivars and water-use attributes can be displayed together. Based on t_i , ET_{max} , color score, and physiological attributes, 'Wabash' and 'Bristol' Kentucky bluegrass (*Poa pratensis* L.), 'Aurora' hard fescue (*Festuca ovina* var. *duriuscula* L. Koch.), and 'FRT-30149' fine fescue (*F. rubra* L.) were identified as cultivars with higher WUE.

Interest in water conservation by the turfgrass industry establishes the need for breeding drought-resistant species and cultivars (Salaiz et al., 1991). The results of many studies on evapotranspiration (ET) rates, between and within turfgrass species under nonlimiting moisture conditions, are summarized by Beard (1985, 1990) and reviewed by Kneebone et al. (1992). These studies only measure the initial phase of the turf water-use curve. Fernandez and Love (1993) suggested that water-use measurements under nonlimiting conditions are not good predictors of low water-use patterns under restricted water use, which may be appropriate to conserve water. These authors found that, under greenhouse conditions, a significant cultivar $\times$ day interaction occurred under progressive water stress, and a nonlinear Gompertz model was used to describe the cumulative ET (ET_{cum}) pattern for the turfgrasses. Two ET_{cum} attributes (t_i , the time during which the rate change in ET is zero, and ET_{max} , the maximum ET rate) estimated from the Gompertz model were highly correlated with color score. Based on final ET_{cum} (FET_{cum} , accumulated ET over the experimental period), ET_{max} , t_i , and color score, cultivars with low water use were identified. However, ET_{cum} patterns of the cultivars under progressive water stress in the field may differ from those in the greenhouse.

Several physiological techniques have been suggested for drought-resistance screening, including leaf water potential (ψ) (Fisher and Sanchez, 1979; Sojka et al., 1981), relative water content (RWC) (Matin et al., 1989), canopy temperature (T_c) (Blum et al., 1982; Sullivan and Ross, 1979), and electrolyte leakage (EL) (Levitt, 1980; Sullivan, 1972). These and other potential screening techniques are discussed in several reviews

(Blum, 1988; Hanson and Nelson, 1980). Hanson and Nelson (1980) examined agronomic, physiological, and biochemical approaches that might be used in a breeding program for assessing cultivar sensitivity to drought. They suggested that an ideal screening test should be 1) highly correlated with drought resistance under field conditions under which drought stress occurred at the growth stage or stages at which the component is expressed; 2) rapid, accurate, and able to handle many samples during the season; and 3) nondestructive.

The objectives of this study are to 1) determine the comparative ET rates of turfgrass grown in pots subjected to progressive water stress under semi-field conditions; 2) test for a significant cultivar $\times$ day interaction under progressive water stress; 3) identify cultivars with efficient water-use potentials; 4) compare the effectiveness of several physiological screening techniques; and 5) study the interrelationships among ET_{cum} (t_i , ET_{max}) and the physiological screening components.

Materials and Methods

Experiment I. In February 1991, 10 turfgrass cultivars (Table 1) were selected based on their ET_{cum} pattern under greenhouse conditions (Fernandez and Love, 1993) and established in plastic pots. The pots were 30 cm in diameter $\times$ 22 cm high with a separate water reservoir (26 cm in diameter $\times$ 5 cm high) at the bottom of the container. The pots were filled with Dialoam (Eagle-Pitcher Minerals, Reno, Nev.), chosen for its water-retention properties (Van Bavel et al., 1978). After germination, the turf was established for 6 months. During this period, the turf was irrigated with half-strength Hoagland's solution (Hoagland and Arnon, 1950) and mowed to a height of 5 cm. On 9 Aug. 1991, pots were moved into prepositioned plastic sleeves located within a turfgrass field at the Univ. of Nevada–Reno Valley Road Farm. The sleeves were 31 cm in diameter and 28 cm deep and arranged in 5 blocks of 10 units.

On 19 Aug. after the turf had adjusted for 10 days to the field conditions, the pots were watered thoroughly with nutrient solution to fill the reservoir. Pots were not watered until 10 Sept. 1991 to impose progressive water stress. Water loss by the turfgrass was measured daily by the gravimetric mass-balance method (Bow-

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Table 1. Species, cultivars, and their seeding rates and water-use efficiency (WUE) in Expts. I, II, and III.

Species	Seeding rate (g·m ⁻²)	Cultivar	WUE ^z
<i>Expt. I</i>			
Kentucky bluegrass (<i>Poa pratensis</i> L.)	16 ^y	Abbey Bristol Wabash	Unknown High High
Perennial ryegrass (<i>Lolium perenne</i> L.)	50	Caravelle Citation Omega	Unknown Low Low
Tall fescue (<i>Festuca arundinacea</i> Schreb.)	100	Apache Bonanza	Low Low
Sheep fescue (<i>F. ovina</i> L.)	50	MX86	High
Creeping fescue (<i>F. rubra</i> L.)	50	Shademaster	High
<i>Expts. II and III</i>			
Kentucky bluegrass (<i>P. pratensis</i> L.)	8	Abbey Bristol Challenger Wabash	Unknown High High High
Tall fescue (<i>F. arundinacea</i> Schreb.)	50	Arid Bonanza	Low Low
Sheep fescue (<i>F. ovina</i> L.)	25	Meck MX86	Unknown High
Fine fescue (<i>F. rubra</i> L.)	25	FRT-30149	High
Hard fescue (<i>F. ovina</i> var. <i>duriuscula</i> L. Koch.)	25	Aurora	High

^zClassified based on a study by Fernandez and Love (1993).

^ySeeding rates for turfgrasses in Expt. I were doubled to compensate for low germination rates.

man and Macaulay, 1991). On days 0 and 20, the turfgrass cultivars were scored visually for green retention on a 0 to 10 scale, where 9 = 90% of the leaf tissue green and 1 = 90% of the leaf tissue scorched (Fernandez and Love, 1993). Final color score was adjusted using the initial color score (on day 0) as a covariate to eliminate any preexisting difference among cultivars. Adjusted final color score was estimated from the least square means. Water-use efficiency (WUE) was calculated by dividing the adjusted final color score by FET_{cum}. The turf was mowed once on day 14 of the dry-down period. Weather conditions during this and subsequent experimental periods are presented in Table 2.

The experimental design for water-stress treatment in Expt. I was a randomized complete-block design with three replications. Well-watered pots (watered at the time of each weighing with half-strength Hoagland's solution to fill the reservoir) were set between the treatments with two replications. Cultivar mean of ET_{cum} of the well-watered turf was used to correct day-to-day variation by estimating adjusted days in two steps.

Step I: Daily average ET of well-watered turf = cultivar mean of FET_{cum}/total number of days under progressive water stress.

Table 2. Weather conditions during the experiments.^z

Temp (°C)		Solar radiation	Wind speed	Relative humidity	Pan evapotranspiration
Min	Max	(Ly)	(miles/h)	(%)	(mm·day ⁻¹)
<i>Expt. I (19 Aug. to 10 Sept. 1991)</i>					
8.3	27.7	516.22	2.11	44.9	7.21
<i>Expt. II (10 to 25 July 1992)</i>					
10.9	31.6	590.34	3.12	38.3	8.33
<i>Expt. III (1 to 17 Sept. 1992)</i>					
5.6	28.6	402.73	1.60	33.8	6.51

^zMean value over the experiments.

Step II: Adjusted days = cultivar mean of ET_{cum} at ith day/daily average ET.

Experiment II. In March 1992, the experiment was repeated with 10 turfgrass cultivars (Table 1). Perennial ryegrass cultivars used in Expt. I were not included because of their high water-use rates and poor color scores. The pots and growth medium were the same except that the reservoir at the bottom of the pot was not used for water storage; also, four drainage holes were bored at the bottom of each reservoir to prevent flooding. After germination, the turf was established in the greenhouse for 4 months. On 25 June 1992, the pots were moved into the prepositioned sleeves located in the turfgrass field. The sleeves were the same as in Expt. I, except the bottom of the sleeves was constructed with a 10-cm layer of gravel to facilitate drainage. The sleeves were arranged in 5 rows of 10 units each, west to east. On 10 July 1992, pots were watered thoroughly with half-strength Hoagland's solution until run-through. The pots were not watered until 25 July 1992. Pots were weighed on days 0, 2, 4, 7, 10, 12, and 14. On days 0 and 14, the turfgrass cultivars were scored for green retention, and adjusted color score and WUE were estimated as in Expt. I.

The experimental design for water-stress treatment in Expt. II was a randomized complete-block design with four replications. Well-watered turf pots were set in between treatments with one replication. Pots were rotated every 2 days within each block to warrant good randomization. ET_{cum} of the well-watered turf pots was used to calculate adjusted days as in Expt. I.

Experiment III. Experiment II was repeated, using the same cultivars, the same experimental design with three replications, and under the same field conditions. Thirty-seven days were allowed between the two experiments to let the stressed turfgrass cultivars recover from water stress. During the recovery period, the pots were irrigated using half strength Hoagland's solution every 2 days. At the start of Expt. III, color scores had reached at least 7.

Progressive water stress was imposed on these cultivars by withholding water for 16 days, starting 1 Sept. Turfgrass ET was measured on days 0, 2, 4, 6, 8, 10, 12, 14, and 16 thereafter. On days 0 and 16, the turfgrasses were scored visually as before and an adjusted final green color score and WUE were calculated.

Physiological measurements on WUE. In Expts. II and III, the following physiological screening techniques were used and evaluated: 1) ψ ; 2) RWC; 3) T_c and ΔT ; and 4) EL.

The ψ was measured by a thermocouple psychrometer (series 74; J.R.D. Merrill Specialty Equipment, Logan, Utah) and a nanovoltmeter (model NT-3; Decagon Devices, Pullman, Wash.). About 0.5 g of progressively stressed (2 days before the end of the stress treatment) turfgrass leaves were excised between 8 and 10 AM, put into the psychrometer chamber, and immediately sealed with the thermocouple assembly. The assembly was allowed to

equilibrate in a water bath at 25°C for 4 h. Psychrometer measurements were taken by first measuring the zero offset, cooling for 30 sec, then measuring the peak voltage. The ψ was calculated with a computer program (Brown and Bartos, 1982). All psychrometer were individually calibrated with standard NaCl solutions.

RWC was determined gravimetrically. About 0.6 g progressively stressed (3 days before the end of the stress treatment) leaves was excised between 8 and 10 AM, put into scintillation vials, sealed immediately, and transported to the lab. Fresh weight was measured and the leaves were then floated on distilled water under continuous fluorescent light (photosynthetic photon flux density was $100 \pm 15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) for 24 h at room temperature. Leaves were then blotted dry and turgid weight was determined. Next the leaves were dried at 70°C for 48 h and dry weight was taken. RWC was calculated according to equation (Barrs, 1968): $\text{RWC} (\%) = 100 (\text{fresh weight} - \text{dry weight}) / (\text{turgid weight} - \text{dry weight})$

T_c was determined with a hand-held infrared thermometer (Telatemp Corp., Fullerton, Calif.) between 11 AM and 2 PM on progressively stressed turf (3 days before the end of the stress treatment). The thermometer was held 1 m above the turf at a 45-degree angle from horizontal. ΔT was determined at the same time.

EL was determined by the procedure of Sullivan (1972). About 0.3 g of progressively stressed (4 days before the end of the stress treatment) turfgrass leaf segments was cut and placed in scintillation vials between 3 and 5 PM, washed with distilled water three

times, and drained. Then, 15 ml of distilled water was added to the vials, followed by vacuum infiltration for 15 min. After 24 h of incubation on a shaker, the first electrical conductivity reading was measured with a conductance meter (model 32; Yellow Springs Instrument Co., Yellow Springs, Ohio) after vigorously mixing the vial contents. Upon completion of the first measurement, the samples were autoclaved for 15 min to disrupt the cell membrane, then incubated on a shaker for 24 h. Then the second electrical conductivity reading was taken. EL was calculated as $\text{EL} (\%) = 100 \times \text{first reading} / \text{second reading}$.

Statistical analyses. A repeated-measure analysis (Fernandez, 1991) with profile contrast was performed on the ET_{cum} at adjusted days for all three experiments. For each cultivar, the ET_{cum} mean was fitted with a Gompertz sigmoidal-nonlinear model. The Gompertz model gave the best fit to the ET_{cum} patterns based on smaller MSE compared with logistic and monomolecular nonlinear models (data not shown).

$$\text{Gompertz model: } Y = a \exp [-b \exp (-kt)]$$

where, Y = predicted ET_{cum} ; t = adjusted days (ET_{cum} at i^{th} day / mean ET); a = the asymptote, theoretical maximum value for Y ; b and k = model parameters with different values for different cultivars.

The ET_{cum} components are then estimated from the Gompertz model parameters, a , b , and k . The ET rate is $kY \log_e(aY^{-1})$. The ET_{max} in the Gompertz model occurs when the rate of change in ET

Fig. 1. Gompertz nonlinear model curves for cumulative evapotranspiration (ET_{cum}) and ET rate vs. adjusted days for turfgrass cultivars evaluated under field Expt. I. KB = Kentucky bluegrass; PR = perennial ryegrass. The cubic spline option was used to connect the points in these plots.

is zero at the time of inflection (t_i) of the curve: $ET_{max} = (ka)e^{-1}$ and $t_i = (\log_e b)k^{-1}$ (Fernandez and Love, 1993; Tipton, 1984).

From the Gompertz model, t_i and ET_{max} were calculated. For Expt. I, group contrast was performed for color score and FET_{cum} . In the absence of a significant cultivar $\times$ experiment interaction (verified by Tukey's test for nonadditivity, Tukey, 1949), combined analysis of variance and group contrast comparisons (cultivar means over Expts. II and III) were performed for t_i , ET_{max} , FET_{cum} , color score, and WUE and all physiological attributes using cultivar $\times$ experiment as the error term for Expts. II and III. The correlations between FET_{cum} , t_i , and ET_{max} with color score and WUE were determined. The correlations of t_i , ET_{max} , and color score between experiments of this study and a previous greenhouse study (Fernandez and Love, 1993) were also determined using the eight turf cultivars common to both studies.

Biplot display of principal component analysis (Gabriel, 1971) was used to identify cultivars with high WUE. A two-dimensional approximation to a two-way table (rows $\times$ columns) can be obtained from the first two principal components. The biplot shows the cultivars (row points) and WUE-related attributes (including t_i , ET_{max} , RWC, ΔT , EL, and color score, vector coordinates) in a single plot by projecting them onto the plane (thus biplot) in the transformed variable space that accounts for the most variance. Thus, biplot display allows visual appraisal of the structure of a large two-way data matrix, and provides a graphical representation of interaction perns that allows the responses of

each cultivar in each WUE-related attribute predicted by the principal component model to be directly identified. The relative angles and the directions between the variable vectors illustrate the strength and negative or positive correlations between variables. The ranking of cultivars based on a given attribute is achieved by ordering the projected points. The PC-SAS (1988) procedures PRINQUAL, FACTOR and GPLOT were used in developing the SAS codes to display the biplot.

Results and Discussion

Cumulative Evap Transpiration (CET) attributes. Cultivar effects were statistically significant in Expts. I and II ($P = 0.01$ and 0.02 , respectively) but not in Expt. III ($P = 0.19$). In repeated-measure analysis, day effects were significant in Expts. I, II, and III ($P = 0.0001$). The cultivar $\times$ day interaction was significant at $\alpha = 0.05$ by the G-G adjusted univariate test. Profile contrasts (differences between two adjacent time periods) were used to investigate the cultivar $\times$ day interaction pattern. The results of profile contrasts showed that the cultivar $\times$ day interactions existed prominently between days 2 and 4, 9 and 12, and 16 and 19 in Expt. I (Fig. 1). In Expt. II, the interactions existed prominently between days 10 and 14 (Fig. 2). In Expt. III, the interactions existed between days 4 and 6 and 10 and 12 (Fig. 3).

Cultivar effects for color score and FET_{cum} were significant ($P = 0.04$ and 0.01 , respectively) for Expt. I. Cultivar effects were

Fig. 2. Gompertz nonlinear model curves for cumulative evapotranspiration (ET_{cum}) and ET rate vs. adjusted days for turfgrass cultivars evaluated under field Expt. II. KB = Kentucky bluegrass; TF = Tall fescues; Other F = other fescues. The cubic spline option was used to connect the points in these plots.

significant for color score ($P = 0.0001$) and WUE ($P = 0.0001$) but not significant for FET_{cum} ($P = 0.48$) in the combined analysis of Expts. II and III. Group contrasts for Expt. I and for the combined analysis of Expts. II and III are presented in Tables 3 and 4. Color score and WUE can be used to differentiate an efficient from an inefficient water-use group between and within the same species (Tables 3 and 4). However, FET_{cum} could not distinguish cultivars within the same species. Group contrasts for t_i and ET_{max} were not performed for Expt. I due to lack of replications. Group contrasts in the combined analysis of Expts. II and III (Table 5) showed that t_i and ET_{max} could differentiate an efficient water-use group from an inefficient water-use group but failed to distinguish cultivars within the same species.

The relationship between ET_{cum} , ET rate, and adjusted day is shown in Figs. 1–3. Tall fescue and perennial ryegrass had higher ET rate and ET_{cum} throughout Expt. I (Fig. 1). In Expts. II and III, tall fescue had higher ET rate during the initial phase of the experiments, followed by lower ET in the later phase. As a result, tall fescue had a FET_{cum} similar to that of Kentucky bluegrass and the fine-leaved fescues (Figs. 2 and 3).

The mean t_i , ET_{max} , FET_{cum} , color score, and WUE for Expt. I and the combined analysis of Expts. II and III are presented in Tables 3 and 4. Longer t_i , lower ET_{max} and FET_{cum} , and higher color scores are desirable attributes that can be used to identify efficient water-use turfgrass cultivars (Fernandez and Love, 1993).

In general, tall fescue ('Arid', 'Apache', and 'Bonanza') had shorter t_i (7.2 to 7.6 days in Expt. I equal to 43.5 to 45.9 mm in ET_{cum}

of well-watered turf; 4.0 to 4.3 days in Expts. II and III equal to 27.1 to 29.1 mm in ET_{cum} of well-watered turf) and larger ET_{max} (5.9 to 6.1 mm·day⁻¹ in Expt. I; 7.7 to 8.0 mm·day⁻¹ in Expts. II and III). Even though tall fescue had similar FET_{cum} to Kentucky bluegrass and the fine-leaved fescues in Expts. II and III (Figs. 2 and 3), they had poor color scores, perhaps due to severe dehydration in the later phase of the experiments. Therefore, they are classified in a lower WUE category.

Perennial ryegrasses had a longer t_i (7.4 to 8.2 days equal to 44.7 to 49.5 mm in ET_{cum} of well-watered turf) and medium ET_{max} (5.2 to 5.6 mm·day⁻¹) but a large FET_{cum} , probably due to a slower adjustment to the stressful environment. As a result, they had poor color scores and WUEs. Therefore, they are assigned to a low ('Citation' and 'Omega') or medium WUE (cultivar 'Caravelle') category.

'Bristol' and 'Wabash' Kentucky bluegrass, 'FRT-30149' fine fescue, 'Shademaster' creeping fescue, and 'Aurora' hard fescue expressed the more efficient water-use attributes of lower ET_{max} (4.4 to 5.3 mm·day⁻¹ in Expts. I; 6.4 to 7.1 mm·day⁻¹ in Expts. II and III), delayed t_i (7.5 to 8.5 days in Expt. I equal to 45.4 to 51.5 mm in ET_{cum} of well-watered turf; 4.8 to 5.3 days in Expts. II and III equal to 32.4 to 35.4 mm in ET_{cum} of well-watered turf) and higher color scores and WUE. They are therefore assigned to a higher WUE category.

'Challenger' was identified as a water-use efficient cultivar in a greenhouse study (Fernandez and Love, 1993). However, it was not as efficient as 'Abbey', 'Bristol', and 'Wabash' in Expts. II and

Fig. 3. Gompertz nonlinear model curves for cumulative evapotranspiration (ET_{cum}) and ET rate vs. adjusted days for turfgrass cultivars evaluated under field Expt. III. KB = Kentucky bluegrass; TF = Tall fescues; Other F = other fescues. The cubic spline option was used to connect the points in these plots.

Table 3. Mean inflection time (t_i), maximum evapotranspiration (ET_{max}) estimated from the Gompertz model², final cumulative ET (FET_{cum}), adjusted color score, and water-use efficiency (WUE) under progressive water stress in Expt. I.

Cultivar (species ³)	t_i	ET_{max}	FET_{cum}	Color score	WUE
Abbey (KB)	7.45	5.24	85	3.0	0.035
Apache (TF)	7.58	5.89	97	4.3	0.045
Bonanza (TF)	7.28	6.12	102	4.0	0.039
Bristol (KB)	7.49	4.44	74	6.1	0.082
Caravelle (PR)	8.00	5.22	89	5.3	0.059
Citation (PR)	8.20	5.60	95	3.7	0.039
MX86 (SF)	7.50	5.00	87	4.8	0.055
Omega (PR)	7.38	5.53	94	3.7	0.039
Shademaster (CF)	7.61	4.04	72	4.3	0.061
Wabash (KB)	8.54	5.25	91	6.6	0.072

P values for contrast comparisons

	FET_{cum}	Color score
High vs. low WUE	0.0002	0.0086
KB vs. TF	0.0013	NS
KB vs. PR	0.0297	NS
KB vs. SF	NS	NS
KB vs. CF	NS	NS
Wabash and Bristol vs. Abbey	NS	0.0024
PR vs. TF	NS	NS
PR vs. SF	NS	NS
PR vs. CF	0.0036	NS
TF vs. SF	0.0342	NS
TF vs. CF	0.0005	NS
SF vs. CF	0.0489	NS

²Gompertz model: $ET_{cum} = a \exp[-b \exp(-kt)]$.

³KB = Kentucky bluegrass, TF = tall fescue, SF = sheep fescue, CF = creeping fescue, PR = perennial ryegrass.

^{*}Classified based on a study by Fernandez and Love (1993) (see Table 1).

^{NS}Nonsignificant.

III of this study. 'Abbey' was water-use efficient in the combined analysis but not in Expt. I, probably due to the cultural conditions in Expt. I. In Expt. I, the pots were sealed and potentially anaerobic, which may have been harmful to 'Abbey'. 'Meck' and 'MX86' sheep fescue were significantly different from Kentucky bluegrass, fine fescue, hard fescue, and creeping fescue. Based on these results, 'Challenger', 'Abbey', 'Meck', and 'MX86' were placed in the medium WUE category.

The correlations between FET_{cum} , t_i , and ET_{max} with color score and WUE for 10 cultivars are shown in Table 5. FET_{cum} and ET_{max} negatively correlated with color score and WUE, whereas t_i positively correlated with color score and WUE. None of the correlations were statistically significant except ET_{max} with WUE ($P = 0.04$) in Expt. I. However, ET_{max} and t_i significantly correlated with color score and WUE, while FET_{cum} did not correlate significantly in Expts. II and III. It appears that WUE is a superior parameter to color score in that WUE increased the sensitivity of the group contrast test (smaller P values, Table 5) over color score.

The rank correlations of t_i , ET_{max} , and color score between field studies and a previous greenhouse study (Fernandez and Love, 1993) were estimated. In general, ET_{max} and color score significantly correlated ($r > 0.65$) between the two studies, while t_i was marginally insignificant.

Under water-limiting conditions, turfgrass appearance is complicated by many factors. First, it is possible that cultivars with high water-use rates could maintain a high color score due to high drought

Table 4. Mean inflection time (t_i), maximum evapotranspiration (ET_{max}) estimated from the Gompertz model, final cumulative ET (FET_{cum}), adjusted color score, and water-use efficiency (WUE) under progressive water stress in Expts. II and III.

Cultivar (species ³)	t_i	ET_{max}	FET_{cum}	Color score	WUE
Abbey (KB)	4.59	6.93	78	6.6	0.084
Arid (TF)	3.96	7.97	78	2.4	0.031
Aurora (HF)	4.83	6.38	75	6.2	0.083
Bonanza (TF)	4.29	7.66	81	2.3	0.028
Bristol (KB)	5.27	6.38	77	7.1	0.092
Challenger (KB)	4.60	7.25	76	4.3	0.056
FRT-30149 (FF)	5.03	6.63	78	6.3	0.081
Meck (SF)	5.03	6.44	80	4.4	0.056
MX86 (SF)	4.44	6.94	80	4.3	0.054
Wabash (KB)	4.90	7.07	80	5.8	0.073

P values for contrast comparisons³

High vs. low WUE ^x	0.0011	0.0103	NS	0.0001	0.0001
KB vs. TF	0.0017	0.0262	NS	0.0001	0.0001
KB vs. HF	NS	NS	NS	NS	NS
KB vs. SF	NS	NS	NS	0.0029	0.0015
KB vs. FF	NS	NS	NS	NS	NS
Wabash, Bristol, and Abbey vs. Challenger	NS	NS	NS	0.0019	0.0018
SF vs. TF	0.0099	0.0191	NS	0.0014	0.0011
SF vs. FF	NS	NS	NS	0.0062	0.0036
SF vs. HF	NS	NS	NS	0.0082	0.0024
TF vs. FF	0.0033	0.0360	NS	0.0001	0.0001
TF vs. HF	0.0130	0.0157	NS	0.0001	0.0001
FF vs. HF	NS	NS	NS	NS	NS

²KB = Kentucky bluegrass, TF = tall fescue, SF = sheep fescue, FF = fine fescue, HF = hard fescue.

³In absence of a significant cultivar $\times$ experiment interaction, a combined contrast comparison (genotypic means over Expts. II and III) was performed using cultivar $\times$ experiment as the error term. The significance of cultivar $\times$ experiment was determined by Tukey's test for nonadditivity.

^xClassified based on a study by Fernandez and Love (1993) (see Table 1).

^{NS}Nonsignificant.

Table 5. Pearson correlation coefficient (r) of mean inflection time (t_i), maximum evapotranspiration (ET_{max}), and final cumulative ET (FET_{cum}) with color score and water-use efficiency (WUE).

Expt.	Variable	Color score		WUE	
		r	P	r	P
I	t_i	0.51	NS	0.34	NS
	ET_{max}	-0.35	NS	-0.66	0.04
	FET_{cum}	-0.27	NS	---	---
II	t_i	0.71	0.02	0.74	0.01
	ET_{max}	-0.74	0.02	-0.76	0.01
	FET_{cum}	-0.28	NS	---	---
III	t_i	0.73	0.02	0.72	0.02
	ET_{max}	-0.72	0.02	-0.75	0.01
	FET_{cum}	-0.08	NS	---	---

^{NS}Nonsignificant.

tolerance. However, cultivars with high water-use rate are not the goal for breeding water-conserving plants (Beard, 1990). Secondly, in the present study, the roots were grown in a confined space. Caution should be taken when interpreting these results because the plants' ability to extract water from deep layers of soil was excluded.

Table 6. Mean electrolyte leakage (EL), relative water content (RWC), leaf water potential (ψ), canopy temperature (T_c), and canopy–air temperature difference (ΔT) for combined analysis of Expts. II and III.

Cultivar (species ^a)	EL (%)	RWC (%)	ψ (MPa)	T_c (°C)	ΔT (°C)
Abbey (KB)	6.4	52.9	−4.46	40.0	7.4
Arid (TF)	59.8	15.7	−2.33	43.7	12.2
Aurora (HF)	12.6	52.5	−4.04	40.2	7.7
Bonanza (TF)	53.0	14.8	−2.93	45.9	14.2
Bristol (KB)	10.5	62.7	−2.89	39.0	6.8
Challenger (KB)	47.8	16.5	−1.88	44.6	12.5
FRT-300149 (FF)	11.3	44.3	−2.37	37.0	4.9
Meck (SF)	23.2	50.6	−4.69	40.2	7.9
MX86 (SF)	18.6	47.9	−2.29	39.4	7.2
Wabash (KB)	6.2	47.5	−1.51	40.8	8.6

P values for contrast comparisons

High vs. low WUE ^y	0.0001	0.004	--- ^x	0.0008	0.006
KB vs. TF	0.0001	0.005	---	0.03	0.02
KB vs. HF	NS	NS	---	NS	NS
KB vs. SF	NS	NS	---	NS	NS
KB vs. FF	NS	NS	---	NS	NS
Wabash, Bristol, and Abbey vs. Challenger	0.0001	0.007	---	0.04	0.04
SF vs. TF	0.0001	0.006	---	0.02	0.01
SF vs. FF	NS	NS	---	NS	NS
SF vs. HF	NS	NS	---	NS	NS
TF vs. FF	0.0001	0.03	---	0.004	0.004
TF vs. HF	0.0001	0.01	---	0.05	0.03
FF vs. HF	NS	NS	---	NS	NS

^aKB = Kentucky bluegrass, TF = tall fescue, HF = hard fescue, FF = fine fescue, SF = sheep fescue.

^yWUE = water-use efficiency.

^xThe contrast was not performed on ψ due to significant cultivar $\times$ experiment interactions.

^{NS}Nonsignificant.

Table 7. Pearson correlation coefficient (*r*) of electrolyte leakage (EL), relative water content (RWC), leaf water potential (ψ), canopy temperature (T_c), and canopy–air temperature difference (ΔT) with color score and water-use efficiency (WUE) for combined analysis of Expts. II and III.

Variable	Color score		WUE	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
EL	−0.87	0.0001	−0.86	0.0001
RWC	0.62	0.003	0.66	0.002
ψ	−0.14	NS	−0.11	NS
T_c	−0.69	0.0007	−0.66	0.002
ΔT	−0.73	0.0003	−0.70	0.0006

^{NS}Nonsignificant.

Physiological attributes. Cultivar effects of the combined analysis were statistically significant for RWC ($P = 0.04$) and EL ($P = 0.0001$) but not significant for ψ , T_c , and ΔT . Group contrasts for the combined analysis (Table 6) showed that RWC, EL, T_c , and ΔT can differentiate the water-use efficient group from the inefficient group and also cultivars between and within species; ψ failed to differentiate the water-use efficient group from the inefficient group.

The correlations between ψ , RWC, T_c , ΔT , and EL with color

score and WUE for 10 cultivars are shown in Table 7. EL, T_c , and ΔT were significantly and negatively correlated with the color score and WUE, whereas RWC had a significant positive correlation with color score and WUE; ψ was not significantly correlated with color score and WUE.

Based on their ability to separate cultivars and correlations with color score and WUE, EL and RWC are promising screening techniques. Furthermore, these two techniques are fairly easy and require simple equipment. T_c and ΔT can separate cultivar differences to some extent but not as well as EL and RWC. Ranking the cultivar effects using T_c and ΔT correlates well with color score and WUE. Kneebone and Pepper (1979) found that, at equivalent soil moisture, differentials in transpiration levels could be distinguished between turfgrass species by using a hand-held infrared thermometer. Measuring temperature is nondestructive, easy, and large numbers of readings may be taken rapidly. The ψ seems to be a poor selection criterion because it did not detect cultivar differences, required expensive equipment, and was time consuming.

Interrelationships between CET and physiological attributes are shown in a biplot display of t_1 , ΔT , EL, and color score (Fig. 4). Parameters that are either not significantly correlated with color score and WUE or have poor separation for cultivars were not included in the biplot to improve clarity. T_c and WUE were not included in the biplot because they were dependent with either ΔT or color score. The first dimension, which explains $\approx 90\%$ of the variation, can be considered as the overall WUE index, since it is a weighted difference between ET_{max} , RWC, color score, ΔT , and EL. Thus, the first dimension effectively separated the cultivars into groups with relatively high and low WUE. The angles and the directions between the variable vectors illustrate the strength and the negative–positive correlations between variables. The second dimension, which explained $\approx 10\%$ of the total variation, mainly accounted for differences in t_1 . The cultivars with relatively high WUE were ‘Abbey’, ‘Aurora’, ‘Bristol’, ‘FRT-30149’, ‘Meck’, ‘MX86’, and ‘Wabash’. ‘Arid’ and ‘Bonanza’ tall fescue and ‘Challenger’ Kentucky bluegrass had relatively low WUE.

In conclusion, there was a significant interaction between cultivar and day for ET_{cum} . Two of the ET_{cum} attributes, t_1 and ET_{max} , appeared to reflect efficient water-use attributes in the turfgrass cultivars. Based on t_1 , ET_{max} , and color score, ‘Wabash’, ‘Bristol’, ‘Aurora’, ‘Shademaster’, and ‘FRT-30149’ were identified as cultivars with relatively high WUE, whereas ‘Apache’, ‘Bonanza’, ‘Arid’, ‘Citation’, and ‘Omega’ were identified as cultivars with relatively low WUE. The ranking of the turfgrass cultivars in a previous greenhouse study generally correlates well with the present field study.

EL, RWC, and ΔT are promising screening techniques for drought resistance in turfgrass. EL, T_c , and ΔT were significantly and negatively correlated with the color score and WUE, whereas RWC had a significant positive correlation with color score and WUE; ψ was not significantly correlated with color score and WUE. Based on biplot display of six screening techniques, ‘Abbey’, ‘Aurora’, ‘Bristol’, ‘FRT-30149’, ‘Meck’, ‘MX86’, and ‘Wabash’ were identified as cultivars with relatively high WUE.

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Cultivars: 0=Abbey 1=Arid 2=Aurora 3=Bonanza 4=Bristol
5=Challenger 6=FRT30149 7=Meck 8=MX86 9=Wabash

Fig. 4. Biplot display of drought resistance selection criteria and turfgrass cultivars. The first dimension, which accounts for $\approx 90\%$ of the variation, can be considered as the overall water use efficiency index, since it is a weighted difference between maximum evapotranspiration (ET_{max}), relative water content (RWC), color score, canopy-air temperature difference (ΔT), and electrolyte leakage (EL). The second dimension, which explained $\approx 10\%$ of the total variation, mainly accounted for the differences in mean inflection time (t_i).

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