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Advanced Turf-type Bermudagrass Experimental Genotypes Show Marked Variation in Drought Response

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Abstract. **Bermudagrass (*Cynodon* sp.) is one of the most commonly used warm-season turfgrasses in the southern areas and transition zone of the United States. Due to the increasing demand for water resources and periodic drought, it is important to improve the drought resistance of bermudagrass for water savings and persistence under drought stress. This study was conducted to determine whether experimental bermudagrass genotypes have improved drought resistance compared with the standard cultivars Tifway and Riley's Super Sport (Celebration®) at Stillwater, OK. The trials were designed as randomized complete blocks with four replications in Expt. I and three replications in Expt. II. In each experiment, genotypes were subjected to progressive acute drought conditions using polyethylene waterproof tarps to exclude precipitation over a period of at least 72 d. Bermudagrass entries were evaluated for turfgrass quality, leaf firing, normalized difference vegetation index, and live green cover at least once each week during the dry-down. Substantial drought response variations were found in this study, and all parameters were positively and highly correlated. A turf performance index (TPI) was assembled based on the number of times an entry ranked in the top statistical group across all testing parameters on each date. 'DT-1' (TifTuf®) and OSU1221 had the top TPI in both experiments. Most of bermudagrass experimental genotypes had equal or greater TPI than the standard Tifway, showing improved drought resistance through breeding effects. The identification of superior drought resistance experimental genotypes provided useful information to breeders on cultivar release.**

There are more than 31 million acres of irrigated turfgrass, making it the largest irrigated crop in the United States (Milesi et al. 2005). Bermudagrass (*Cynodon* spp.) is widely used on athletic fields, golf courses, lawns, and roadsides in the southern regions and the transition zone of the United States. Water scarcity is one of the major issues for turf management worldwide (Fuentealba et al. 2015). Selecting drought-resistance turfgrass species and cultivars is one of the primary strategies in water conservation to meet the needs of the growing human population (Carrow et al. 2002).

Sufficient soil moisture is required to sustain turfgrass growth and maintain both shoot density and acceptable turf quality (TQ; Taliaferro 2003). When the soil moisture in the root zone is not sufficient for the growth and development of turfgrass, several changes in physiological and biochemical processes take place (Youngner 1985). When drought stress occurs; grass leaves may wilt; undergo osmotic adjustment; and produce abscisic acid, heat shock proteins, or dehydrins (Huang 2008). When drought continues from several days to weeks, depending on the soil types, leaf firing (LF) may occur, and grass will eventually go dormant (Passioura 1996). Leaf firing refers to the browning of leaves due to the destruction of chromatophores in the leaf, which starts from the leaf tips and margins and gradually progress down to the leaf blade base (Carrow 1996).

Several studies have evaluated the response of various bermudagrass cultivars under drought stress, and substantial variations were observed. A study conducted in San Antonio, TX, reported that 'Premier' bermudagrass showed the lowest TQ and most severe LF at the end of the 60-day drought period, whereas 'Tex Turf' bermudagrass had minimal leaf firing (Chalmers et al. 2008). Steinke et al. (2011) reported that the live green cover (LGC) of 'Riley's Super Sport' (Celebration®) bermudagrass did not drop to 50% until 50 d under drought. Richardson et al. (2010) found that it took more than 60 d without water before 'Tifway' bermudagrass lost 50% LGC. Tifway was ranked in the top statistical group regarding the number of days that it took LGC to drop to 75%, 50%, and 25%. A greenhouse study conducted by Baldwin et al. (2006) found that after 4 weeks of different irrigation intervals, there were no statistical differences on TQ among the Celebration, 'Arizona Common', Tift No. 3, 'TifSport', 'Aussie Green', and SWI-1012 at 5- and 15-d watering intervals. However, 'Arizona Common' had lower TQ after 4 weeks of treatment at 10-day watering intervals.

Increased demands on water resources, as well as periodic and persistent drought, have been driving forces in developing drought-resistant turfgrass cultivars. In recent years, turfgrass breeding programs at Oklahoma State University (OSU) and the University of Georgia (UGA) have focused on improving bermudagrass drought resistance. This study was conducted as part of a project involving testing elite bermudagrass experimental genotypes developed by OSU and UGA in different locations throughout the United States. The objective of this study was to evaluate the drought response of bermudagrass under acute drought stress conditions at Stillwater, OK.

Materials and Methods

Field experiments and plant materials. Two experiments were conducted at the OSU Turfgrass Research Center in Stillwater, OK (lat. 36°07′27.4″ N, long. 97°06′07.1″ W). The soil types present were an Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic haplustolls) (Soil Survey Staff 2016) with 40% sand, 41.2% silt, and 18.8% clay in Expt. I and an Easpur loam with 56.2% sand, 30% silt, and 13.8% clay in Expt. II. Before planting, trials were sprayed with glyphosate to kill existing vegetation then tilled, leveled, and raked before planting. Soil testing was conducted using the OSU Soil, Water, and Forage Analytical Laboratory, which used the Mehlich III method (Mehlich 1984). Testing revealed a soil pH of 7.1 with optimal phosphorus and potassium levels for both trials. The experiment design was a randomized complete block design with four replications for Expt. I and three replications for Expt. II. Plot size was 1.2 × 1.2 m and 1.6 × 1.6 m for Expts. I and II, respectively, with 23-cm-wide alleys between each plot.

A total of 13 bermudagrass entries were evaluated in Expt. I. Ten of 13 were experimental genotypes (Table 1) along with commercial cultivars Tifway, Celebration, and DT-1 (TifTuf®). The 10 bermudagrass experimental genotypes included five entries from the OSU turfgrass breeding program (designated

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Table 1. Bermudagrass entries list for Expts. I and II that were dried down in the field condition in Stillwater, OK.

Entry	Species	Status	Expt.
Astro	*Cynodon* dactylon × *C. transvaalensis*	Local standard	II
Celebration®	*C. dactylon* × *C. transvaalensis*	Drought resistance standard	I, II
OSU1220	*C. dactylon* × *C. transvaalensis*	OSU experimental	I, II
OSU1221	*C. dactylon* × *C. transvaalensis*	OSU experimental	I, II
OSU1225	*C. dactylon* × *C. transvaalensis*	OSU experimental	I, II
OSU1257	*C. dactylon* × *C. transvaalensis*	OSU experimental	I, II
OSU1273	*C. dactylon* × *C. transvaalensis*	OSU experimental	I, II
U-3	*C. dactylon*	Local standard	II
TifTuf® (DT-1)	*C. dactylon* × *C. transvaalensis*	Drought resistance standard	I, II
Tifway	*C. dactylon* × *C. transvaalensis*	Industry standard	I, II
UGB103	Not disclosed	UGA experimental	I, II
UGB117	Not disclosed	UGA experimental	I, II
UGB118	Not disclosed	UGA experimental	I, II
UGB120	Not disclosed	UGA experimental	I, II
UGB136	Not disclosed	UGA experimental	I, II

OSU = Oklahoma State University; UGA = University of Georgia.

OSU genotypes) and the other five were from the UGA turfgrass breeding program (designated UGB genotypes). There were 15 bermudagrass entries evaluated in Expt. II (Table 1). Cultivars U-3 and Astro were added in addition to the entry listed in Expt. I. Expt. I was planted in July 2014 with 18 3.8-cm by 3.8-cm plugs in each plot, and Expt. II was planted in July 2014 with 24 3.8-cm by 3.8-cm plugs in each plot.

After transplanting, Ronstar 2G herbicide (oxadiazon; Bayer Environment Science, Montvale, NJ, USA) was applied at 2.2 kg·ha^{-1} a.i. for preemergence weed control and applied again in spring and fall each year to prevent summer and winter annual weeds. In 2014, 107 kg·ha^{-1} urea (46–0–0, N–P–K) was applied after transplanting, the first week of August, and the first week of September, respectively. In 2015, 107 kg·ha^{-1} urea was applied at the first week of June, July, August, and September, respectively. In 2016, 107 kg·ha^{-1} urea was only applied one week before initiating dry-down. Optimal irrigation was applied to avoid drought stress during establishment. In 2014 and 2015, plots were mowed at 3.8 cm with a rotary mower twice per week. In 2016, plots were mowed with a reel mower at 3.8 cm. Alleys were sprayed with glyphosate (Roundup Pro; Monsanto, St. Louis, MO, USA) at 2.24 kg·ha^{-1} a.i. and 0.25% (v/v) nonionic surfactant using a custom bordering machine to prevent overgrowth among neighboring plots.

In 2016, once plots were fully greened up and had reached ~100% visually assessed green cover, drought conditions were implemented. One week before starting dry-down, 24 mm of irrigation was applied daily, and three 24 mm of irrigation events with 30-min intervals were applied the day before dry-down to soak the plot to field capacity. The volumetric soil water content (VSWC) of each plot was measured with a Stevens POGO HydraProbe (Stevens Water Monitoring Systems Inc., Portland, OR, USA) to ensure saturated soil conditions with the VSWC of 37% or higher at a 6.4-cm soil profile. Hand watering was applied when ununiform VSWC was detected only before dry-down. Irrigation was held off for 72 d for Expt. I (16 Jun–28 Aug) and 90 d (17 Jul–15 Oct) for Expt. II. A 600 m^2 (30 × 20 m) high-density woven polyethylene waterproof tarp (Tarp Supply, Inc., Lombard, IL, USA) was used as a rain cover during the study to prevent natural precipitation from entering the plots for each trial. Tarps were put over plots before rainfalls and removed timely to avoid any high-temperature stress on grasses from contacting traps that were exposed to direct sunlight for too long. Tarps were secured with ground stakes through metal grommets along the margins of the tarp. Mowing was stopped once drought stress presented to avoid additional traffic stresses on the wilting grass canopy.

Data collection and analysis. Both experiments were evaluated twice a week for Expt. I and weekly for Expt. II during the drought period to evaluate the performance of bermudagrass. TQ was evaluated based on the National Turfgrass Evaluation Program protocol (1–9 scale, 1 = completely dead or dormant turf, 9 = outstanding turf, and 6 = acceptable-quality turf; Morris and Shearman 2000). LF was rated on a 1 to 9 scale; 1 represented completely straw-colored leaves and 9 represented completely green leaves. Normalized difference vegetation index (NDVI) was measured using a GreenSeeker Handheld Crop Sensor (Trimble Navigation Limited, Sunnyvale, CA, USA). Digital images were taken using a Canon Powershot G15 (Canon USA, Inc., Melville, NY, USA) digital camera mounted on a custom-built light box, and the LGC was analyzed using SigmaScan Pro software (v. 5.0; SPSS, Inc., Chicago, IL, USA) (Richardson et al. 2001). The VSWC of each plot was measured at 0, 7, 12, 23, 29, 36, 43, and 50 d of study (DOS) for Expt. I and at 0, 8, 15, 22, and 29 DOS for Expt. II with a Stevens POGO HydraProbe at 6.4 cm and stopped when the soil became so hard and inserting the probe became infeasible.

Analysis of variance (ANOVA) for Expts. I and II was conducted separately for TQ, LF, NDVI, and LGC using the MIXED procedure in SAS 9.4 (SAS Institute Inc., Cary, NC, USA) with a repeated-measures model. Variance components of each source variation for TQ, LF, NDVI, and LGC were estimated using TYPE III method of moments estimation (Chang et al. 2016). Similar to broad-sense heritability, reliability (i^2) estimates the proportion of genetic variance contributing to total observed phenotypic variation with testing materials from different breeding backgrounds compared with the broad-sense heritability estimates that only apply to a reference population (Bernardo 2002). The reliability estimates for TQ, LF, NDVI, and LGC were calculated using the equation: $i^2 = \sigma_G^2/(\sigma_G^2 + \sigma_{GR}^2/R + \sigma_{GD}^2/D + \sigma_E^2/RD)$, in which σ_G^2, σ_{GR}^2, σ_{GD}^2, σ_E^2, R, and D represent the variance of genotype, the variance of genotype-by-replication, the variance of genotype-by-date, the error variance, the number of replications, and the number of rating dates (Bernardo, 2002). When the genotype-by-date interaction was significant ($P < 0.05$), means of entries were separated within sampling dates using Fisher's protected least significant difference test (LSD) at the $P = 0.05$ significance level. Pearson correlation coefficients among TQ, LF, NDVI, LGC, VSWC, and DOS were calculated using SAS/

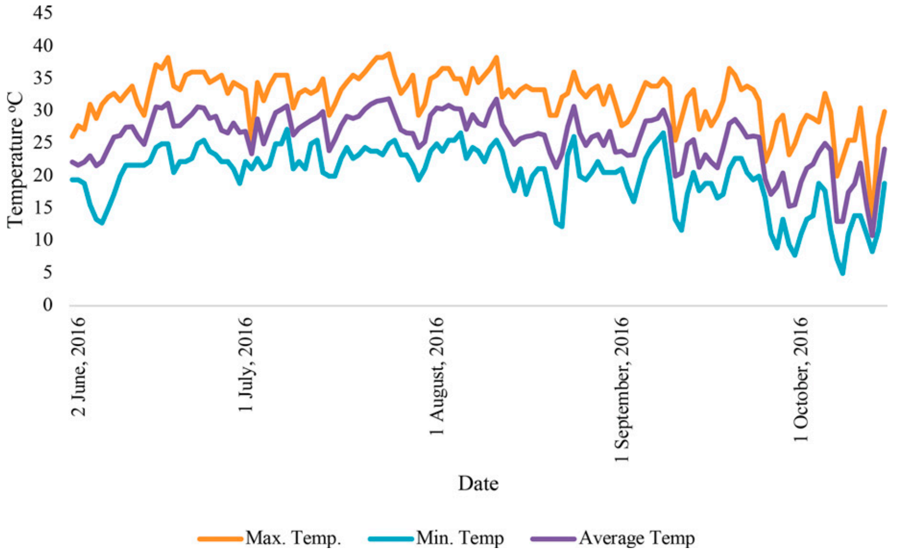

Fig. 1. Daily maximum, minimum, and average air temperatures during the dry-down of Expts. I and II (12 Jun 2016–15 Oct 2016).

CORR procedure. Turf performance index (TPI) was summarized, representing the number of times each entry ranked in the top statistical grouping as determined by LSD across all parameters and all sampling dates for both experiments (Wherley et al. 2011).

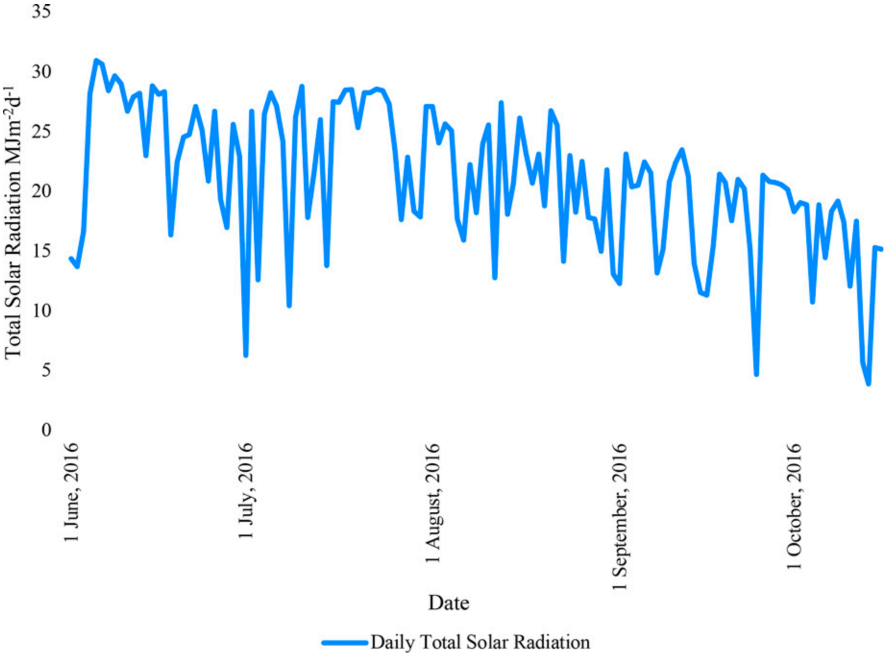

Fig. 2. Total daily solar radiations (MJ·m^{-2}·d^{-1}) from 1 Jun through 15 Oct 2016 measured by the Stillwater Mesonet station.

Results

Environmental conditions and VSWC. The maximum and minimum temperatures were 39 and 12 °C for Expt. I, respectively, and 39 and 5 °C for Expt. II (Fig. 1). The average total solar radiation during Expt. I was 22.1 MJ·m^{-2}·d^{-1}, with the highest of 28.8 and the lowest of 6.4 MJ·m^{-2}·d^{-1} (Fig. 2). The average daily total solar radiation of Expt. II was 20.1 MJ·m^{-2}·d^{-1}, while the highest and lowest were 27.9 and 3.5 MJ·m^{-2}·d^{-1}, respectively (Fig. 2). The accumulated warm-season turfgrass evapotranspiration (ET) estimated by the local Mesonet stationwas 300.0 mm and 303.3 mm using the Standardized Reference Evapotranspiration Equation multiplied by the warm-season grass crop coefficient for Expts. I and II, respectively (Fig. 3). However, on 9 Aug, Expt. I was exposed to 5.1 mm of rain, whereas Expt. II received 5.1 mm of rain on 9 Aug and 4.1 mm on 27 Aug. The total water deficits for Expts. I and II were 294.9 and 294.1 mm, respectively. The VSWC measurements for Expts. I and II during dry-down are reported in Figs. 4 and 5. Measurements stopped when VSWC values reached ∼11%.

ANOVA and reliability. The ANOVA and variance components for each measurement are given in Table 2. Highly significant ($P < 0.0001$) date and entry effects were detected for TQ, LF, NDVI, and LGC in both experiments. Interactions of entry-by-date and entry-by-block were highly significant ($P < 0.0001$) for TQ, LF, NDVI, and LGC in both experiments. Although entry, entry-by-date, and entry-by-block effects were all highly significant, the variance components of entry remained the largest for all drought response measurements. The reliability of each measurement in Expts. I and II was high, ranging from 0.88 to 0.93 (Table 2). Measurements with the highest reliability were LF in Expt. I and TQ in Expt. II, respectively.

Turf 1uality. In Expt. I, at the beginning of the study, each bermudagrass entry had a mean TQ ranging from 7 to 8 (Table 3). At 23 DOS, the TQ of all bermudagrass entries remained acceptable (acceptable >6) with means ranging from 6 to 7. At 37 DOS, 'TifTuf' had a significantly higher TQ than all other entries except for OSU1221, OSU1273, and UGB136. At 54 DOS, TQ ranged from 3.3 to 5.8. 'TifTuf' and OSU1221 were ranked in the top statistical group, while 'Tifway' and UGB117 were ranked in the bottom group. At the end of the study, TQ ranged from 2.8 to 5.5; 'TifTuf', OSU1221, OSU1225, OSU1257, and UGB103 ranked in the top statistical group while 'Tifway' and UGB117 ranked at the bottom statistical group.

In Expt. II, all bermudagrass entries had TQ means ranging from 5.7 to 7.7 before initiating the dry-down (Table 3). At 22 DOS, 'Celebration', UGB120, UGB136, 'Astro', and 'U-3' had statistically lower TQ compared with other entries. At 44 DOS, TQ ranged from 3.7 to 6.0. 'TifTuf', OSU1221, OSU1225, OSU1257 as well as UGB103, and UGB136 were ranked in the top statistical group. At 90 DOS, the TQ means ranged from 2.0 ('Astro') to 5.3 ('TifTuf'). OSU1221 performed statistically better than each other entry except 'TifTuf'.

Leaf firing. In Expt. I, at 27 ODS, UGB117 was the first entry to show LF symptoms with a mean LF rating of 8.8 (Table 4). At 37 DOS, all entries had LF ranging from 7 to 8.8. At the end of this study, mean LF ratings ranged from 3.3 to 8.5, with 'Celebration', OSU1221, OSU1225, 'TifTuf', and UGB120 ranked in the top statistical group. Meanwhile, 'Tifway' and UGB117 were ranked in the bottom statistical group. Besides UGB117, all OSU and UGA experimental genotypes demonstrated better resistance to LF under drought than 'Tifway'.

In Expt. II, Astro had a mean LF value of 7.3, which statistically differed from all other

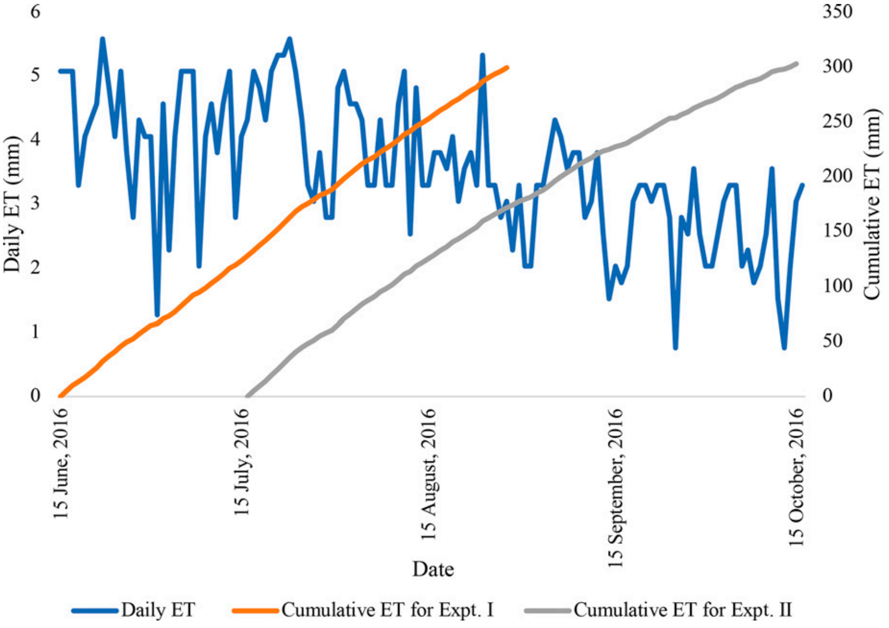

Fig. 3. Daily evapotranspiration (ET) rate and cumulative ET rate estimated by the Stillwater Mesonet station during the dry-down of Expts. I (16 Jun 2016–28 Aug 2016) and II (17 Jul 2016–15 Oct 2016).

entries at 22 DOS (Table 4). At 44 DOS, LF ranged from 6.7 to 9. ‘TifTuf’ did not show LF symptoms, statistically better than ‘Celebration’, OSU1273, ‘Tifway’, ‘Astro’, and ‘U-3’. At 68 DOS, ‘TifTuf’, together with ‘Celebration’, OSU1221, OSU1225, OSU1257, UGB103, UGB118, and UGB136, ranked in the top statistical group. At the end of this study, mean LF ranged from 2.3 to 8.0, and ‘TifTuf’ and OSU1221 ranked in the top statistical group while ‘Astro’ and ‘Tifway’ ranked in the bottom statistical group. The remaining entries of OSU and UGA experimental genotypes did not differ on LF ratings from ‘Celebration’ at 90 DOS.

Normalized difference vegetation index. At the beginning of Expt. I, NDVI means ranged from 0.76 to 0.81 (Table 5). Experimental genotypes OSU1220, OSU1221, and all experimental entries from UGA were ranked in the top statistical group, significantly better than ‘Tifway’ and ‘TifTuf’. At 23 DOS, ‘TifTuf’ performed better than ‘Celebration’ and ‘Tifway’. At 37 DOS, ‘TifTuf’ as well as eight other entries, ranked in the top statistical group, better than OSU1273, ‘Tifway’, UGB117, and UGB120. At the end of the study, UGB103, OSU1221, OSU1225, UGB136, UGB118, UGB120, and ‘TifTuf’ ranked in the top statistical group with NDVI values from 0.55 to 0.65, whereas ‘Tifway’ and UGB117 were in the bottom statistical group with NDVI of 0.32 and 0.41, respectively.

In Expt. II, at the beginning of the study, NDVI mean ranged from 0.65 to 0.80 (Table 5). At 22 DOS, ‘Tifway’ and ‘Astro’ ranked in the bottom statistical group and continued ranking at the bottom statistical group until the end of the study. At 44 DOS, there was a slight increase in the NDVI due to the inability to tarp the trial in time to prevent exposure to an unexpected 4.1 mm rain event at 42 DOS. At 90 DOS, the mean NDVI ranged from 0.28 to 0.68. ‘TifTuf’ and OSU1221 ranked in the top statistical group, performing better than ‘Celebration’. Besides ‘TifTuf’ and OSU1221, experimental genotypes OSU1257 and OSU1273 had higher NDVI values compared with ‘Celebration’.

Live green cover. In Expt. I, at 23 DOS, all entries maintained LGC above 90% (Table 6). At 37 DOS, LGC ranged from 63.0% to 89.1%. OSU1221, OSU1225, ‘TifTuf’, and UGB136 ranked in the top statistical group, whereas UGB117 ranked in the bottom group. At 57 DOS, only ‘Celebration’, OSU1221, OSU1225, and ‘TifTuf’ maintained more than 80% of LGC. At the end of the study, few entries had slight increases in LGC due to the rainfall. However, the LGC of ‘Tifway’ showed a substantial decrease in LGC compared with other entries. ‘Celebration’, ‘TifTuf’, OSU1221, OSU1225, UGB103, UGB118, UGB120, and UGB136 ranked in the top statistical group at the end of the study, whereas ‘Tifway’ and UGB117 ranked in the bottom statistical group.

In Expt. II, OSU1257, OSU1273, ‘Tifway’, UGB120, and ‘Astro’ ranked in the bottom statistical group at the beginning of the study. At 22 DOS, substantial decreases in LGC were observed. LGC means ranged from 62.7% to 90.2% (Table 6). At 44 DOS, only ‘TifTuf’ and OSU1221 had more than 90% of green cover, statistically better than other entries except for OSU1257 and UGB136. Similar to NDVI, there were slight increases in LGC on a few entries at 44 DOS due to an unexpected 4.1-mm rainfall on 27 Aug. However, this rainfall was not able to compensate water deficit for those entries with more severe drought symptoms. At 68 DOS, ‘Astro’, ‘Tifway’, and UGB120 had LGC below 50%, whereas ‘TifTuf’ maintained more than 90% green cover, better than all entries except for

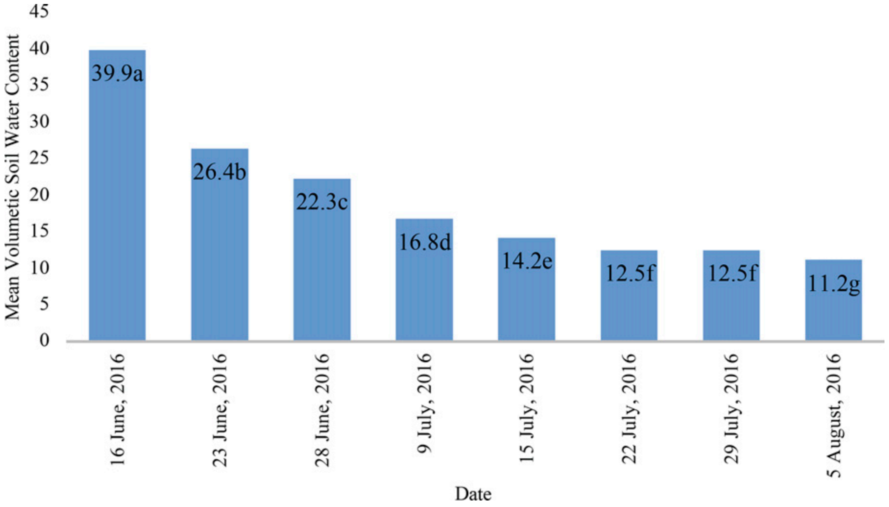

Fig. 4. Mean volumetric soil water content was measured by a 6.4 cm-long time domain-reflectometer probe during the dry-down of Expts. I. Soil moisture was measured on eight dates. Mean volumetric soil water content with different letters are significantly different at the $P = 0.05$ level using Fisher’s protected least significant difference test.

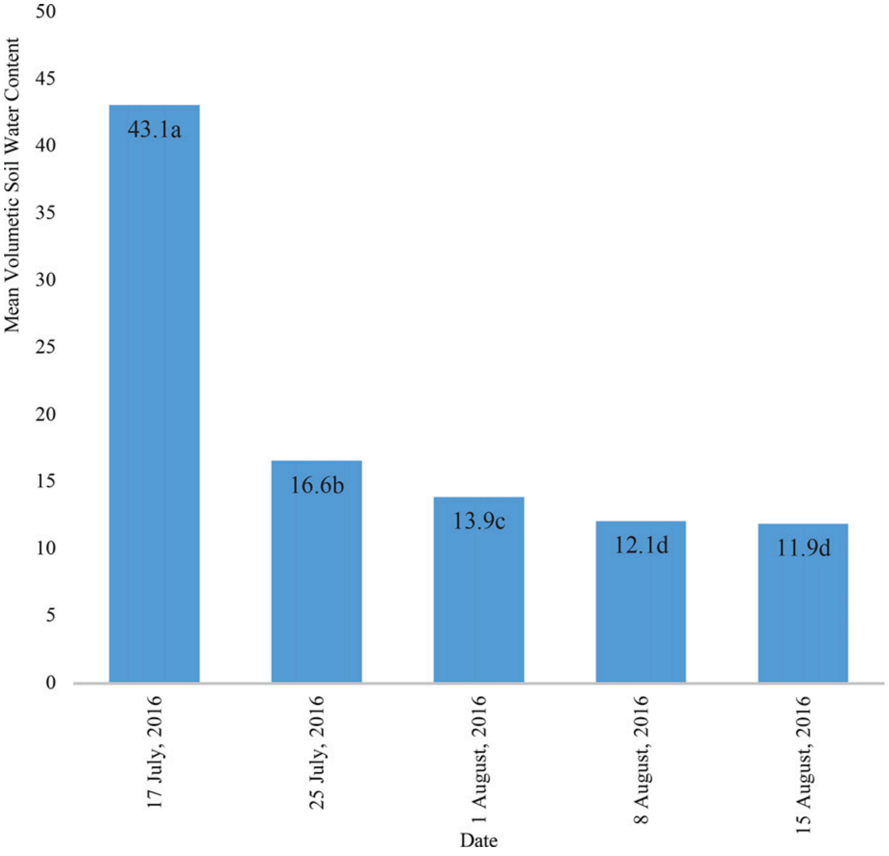

Fig. 5. Mean volumetric soil water content was measured by a 6.4 cm-long time domain-reflectometer probe during the dry-down of Expt. II. Soil moisture was measured on five dates. Mean volumetric soil water content with different letters are significantly different at the $P = 0.05$ level using Fisher’s protected least significant difference test.

Table 2. Analysis of variance for the effects of entry, date, block, and their interactions on turf quality (TQ), leaf firing (LF), normalized difference vegetation index (NDVI), live green cover (LGC) response, and volumetric soil water content (VSWC) during the dry-down cycles for Expts. I and II.

Source of variation	Expt. I								Expt. II							
	TQ[i]		LF[ii]		NDVI[iii]		LGC[iv]		TQ		LF		NDVI		LGC	
	$P > F$	VC	$P > F$	VC	$P > F$	VC	$P > F$	VC	$P > F$	VC	$P > F$	VC	$P > F$	VC	$P > F$	VC
Date	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
Block	0.1212		0.0578		0.0128		0.0373		0.9193		0.5325		0.4558		0.5514	
Date × Block	0.0009		<0.0001		<0.0001		<0.0001		0.0883		0.6169		0.3728		0.3628	
Entry	<0.0001	0.153	<0.0001	0.551	<0.0001	0.0024	<0.0001	56.267	<0.0001	0.342	<0.0001	0.679	<0.0001	0.004	<0.0001	105.770
Entry × Block	<0.0001	0.049	<0.0001	0.095	<0.0001	0.0007	<0.0001	23.916	<0.0001	0.067	<0.0001	0.112	<0.0001	0.001	<0.0001	34.828
Entry × Date	<0.0001	0.130	<0.0001	0.370	<0.0001	0.0010	<0.0001	33.254	<0.0001	0.132	<0.0001	0.456	<0.0001	0.001	<0.0001	35.179
Residual		0.139		0.181		0.0008		27.920		0.148		0.194		0.001		22.304
Reliability (i^2)		0.89		0.93		0.91		0.88		0.91		0.90		0.90		0.88

[i] TQ was rated on a scale of 1–9 during dry-down, where 1 = lowest quality and 9 = excellent quality.

[ii] LF was rated on a scale of 1–9 during dry-down, where 1 = all leaves fired and 9 = no leaf firing.

[iii] NDVI measured by Trimble GreenSeeker handheld sensor on a scale of 0–1, where 0 = no green cover and 1 = complete green cover.

[iv] LGC measured by digital image analysis calculating the percent live cover on a scale of 0–100 where 0 = no green cover and 100 = all the leaves are green.

VC = variance component.

Table 3. Comparison of mean turfgrass quality (TQ) among bermudagrass entries at five selected rating dates during the dry-down of Expts. I and II.

	Expt. I TQ[i]						Expt. II TQ				
Entry	0 DOS[ii]	23 DOS	37 DOS	54 DOS	72 DOS	Entry	0 DOS	22 DOS	44 DOS	68 DOS	90 DOS
Celebration	8.0 a[iii]	6.3 cd	5.0 cd	5.0 bc	4.5 b	Celebration	6.0 ef	5.0 c	5.0 bc	4.0 bc	3.0 bc
OSU1220	7.8 ab	7.0 a	5.0 cd	4.5 c	4.0 b	OSU1220	7.0 bc	6.0 a	5.0 bc	4.3 b	3.7 b
OSU1221	7.5 abc	7.0 a	5.8 ab	5.5 ab	4.8 ab	OSU1221	7.0 bc	6.0 a	6.0 a	5.3 a	5.0 a
OSU1225	7.0 c	7.0 a	5.5 bc	5.0 bc	4.8 ab	OSU1225	7.0 bc	6.0 a	5.3 abc	4.0 bc	3.3 b
OSU1257	8.0 a	6.8 ab	5.5 bc	5.0 bc	4.8 ab	OSU1257	7.0 bc	5.7 ab	5.3 abc	4.3 b	3.7 b
OSU1273	7.3 bc	7.0 a	5.8 ab	5.0 bc	4.0 b	OSU1273	6.3 de	5.3 bc	4.7 cd	3.3 cd	3.0 bc
TifTuf	8.0 a	7.0 a	6.3 a	5.8 a	5.5 a	TifTuf	7.0 bc	6.0 a	5.7 ab	5.7 a	5.3 a
Tifway	7.8 ab	7.0 a	4.8 d	3.3 d	2.8 c	Tifway	7.0 bc	5.7 ab	3.7 e	2.3 ef	2.3 cd
UGB103	7.5 abc	7.0 a	5.5 bc	5.0 bc	4.8 ab	UGB103	7.3 ab	6.0 a	5.3 abc	4.0 bc	3.3 b
UGB117	8.0 a	7.0 a	4.8 d	3.8 d	3.0 c	UGB117	7.7 a	6.0 a	4.7 cd	3.3 cd	3.0 bc
UGB118	7.5 abc	6.0 d	5.3 bcd	4.5 c	4.5 b	UGB118	6.7 cd	5.7 ab	4.7 cd	3.7 bcd	3.3 b
UGB120	7.5 abc	6.8 ab	5.0 cd	4.8 c	4.0 b	UGB120	7.3 ab	5.0 c	4.7 cd	3.3 cd	3.0 bc
UGB136	7.0 c	6.5 bc	5.8 ab	4.8 c	4.3 b	UGB136	7.0 bc	5.0 c	5.3 abc	4.0 bc	3.3 b
						Astro	5.7 f	5.0 c	3.7 e	2.0 f	2.0 d
						U-3	6.3 de	5.0 c	4.0 e	3.0 de	3.0 bc

[i] TQ was rated on a scale of 1–9 during dry-down, where 1 = lowest quality and 9 = excellent quality.

[ii] DOS = days of study. In Expt. I, the dry-down started on 16 Jun and ended on 28 Aug. In Expt. II, the dry-down started on 17 Jul and ended on 15 Oct. Before the initiation of dry-down, plots were saturated with excessive amounts of irrigation and verified with a soil moisture probe. Then irrigation was turned off, and woven polyethylene waterproof tarps were used to cover plots to avoid precipitation reaching plots for both experiments.

[iii] Means within the same column followed by the same letter are not significantly different at the $P = 0.05$ level using Fisher's protected least significant difference test.

Table 4. Comparison of mean leaf firing (LF) among bermudagrass entries at five selected rating dates during the dry-down of Expts. I and II.

	Expt. I LF[i]						Expt. II LF				
Entry	0 DOS[ii]	27 DOS	37 DOS	57 DOS	72 DOS	Entry	0 DOS	22 DOS	44 DOS	68 DOS	90 DOS
Celebration	9.0 a[iii]	9.0 a	8.0 b	7.8 abc	7.5 ab	Celebration	9.0 a	8.0 c	7.7 bc	7.0 ab	5.3 bc
OSU1220	9.0 a	9.0 a	7.3 c	6.8 d	6.5 b	OSU1220	9.0 a	8.7 ab	8.0 ab	6.3 bc	6.0 bc
OSU1221	9.0 a	9.0 a	8.0 b	7.5 bcd	7.5 ab	OSU1221	9.0 a	9.0 a	8.7 ab	8.0 a	8.0 a
OSU1225	9.0 a	9.0 a	8.0 b	7.8 abc	7.5 ab	OSU1225	9.0 a	8.3 bc	8.0 ab	6.7 ab	6.3 b
OSU1257	9.0 a	9.0 a	8.0 b	7.8 abc	7.3 b	OSU1257	9.0 a	9.0 a	8.0 ab	7.3 ab	6.3 b
OSU1273	9.0 a	9.0 a	7.5 bc	7.0 cd	6.5 b	OSU1273	9.0 a	8.3 bc	7.7 bc	5.0 cd	4.7 c
TifTuf	9.0 a	9.0 a	8.8 a	8.5 a	8.5 a	TifTuf	9.0 a	9.0 a	9.0 a	8.0 a	8.0 a
Tifway	9.0 a	9.0 a	6.5 d	3.8 f	3.3 c	Tifway	9.0 a	8.0 c	6.7 c	2.3 ef	2.3 d
UGB103	9.0 a	9.0 a	7.5 bc	7.3 bcd	7.3 b	UGB103	9.0 a	9.0 a	8.0 ab	6.7 ab	5.0 bc
UGB117	9.0 a	8.8 b	7.0 cd	5.0 e	4.3 c	UGB117	9.0 a	9.0 a	8.0 ab	5.0 cd	4.7 c
UGB118	9.0 a	9.0 a	8.0 b	7.0 cd	7.0 b	UGB118	9.0 a	8.0 c	8.0 ab	6.7 ab	5.7 bc
UGB120	9.0 a	9.0 a	8.0 b	8.0 ab	7.5 ab	UGB120	9.0 a	8.3 bc	8.0 ab	6.0 bc	5.0 bc
UGB136	9.0 a	9.0 a	8.0 b	7.3 bcd	7.0 b	UGB136	9.0 a	9.0 a	8.0 ab	6.7 ab	5.7 bc
						Astro	9.0 a	7.3 d	6.7 c	3.7 de	2.3 d
						U-3	9.0 a	8.0 c	7.7 bc	5.0 cd	4.7 c

[i] LF was rated on a scale of 1–9 during dry-down, where 1 = all leaves fired and 9 = no leaf firing.

[ii] DOS = days of study. In Expt. I, the dry-down started on 16 June and ended on 28 Aug. In Expt. II, the dry-down started on 17 Jul and ended on 15 Oct. Before the initiation of dry-down, plots were saturated with excessive amounts of irrigation and verified with a soil moisture probe. Then irrigation was turned off and woven polyethylene waterproof tarps were used to cover plots to avoid precipitation reaching plots for both experiments.

[iii] Means within the same column followed by the same letter are not significantly different at the $P = 0.05$ level using Fisher's protected least significant difference test.

Table 5. Comparison of mean normalized difference vegetation index (NDVI) among bermudagrass entries at five selected rating dates during the dry-down of Expts. I and II.

	Expt. I NDVI[i]						Expt. II NDVI				
Entry	0 DOS[ii]	23 DOS	37 DOS	57 DOS	72 DOS	Entry	0 DOS	22 DOS	44 DOS	68 DOS	90 DOS
Celebration	0.78 bcd[iii]	0.74 de	0.63 abc	0.63 a	0.52 bc	Celebration	0.65 b	0.64 ab	0.58 bcd	0.47 c–f	0.43 c
OSU1220	0.81 a	0.78 ab	0.63 abc	0.53 b	0.50 cd	OSU1220	0.76 a	0.57 d–g	0.58 bcd	0.49 cde	0.50 bc
OSU1221	0.79 ab	0.78 a	0.65 ab	0.62 a	0.61 ab	OSU1221	0.78 a	0.57 c–g	0.70 a	0.62 ab	0.66 a
OSU1225	0.78 bcd	0.77 ab	0.63 abc	0.62 a	0.61 ab	OSU1225	0.74 ab	0.59 b–e	0.57 bcd	0.51 cd	0.50 bc
OSU1257	0.76 de	0.78 a	0.63 abc	0.59 ab	0.55 bc	OSU1257	0.74 ab	0.61 a–d	0.63 b	0.55 bc	0.54 b
OSU1273	0.77 cde	0.75 cd	0.61 c	0.57 ab	0.52 bc	OSU1273	0.78 a	0.53 f–i	0.55 cd	0.46 def	0.45 b
TifTuf	0.76 e	0.76 abc	0.66 a	0.63 a	0.65 a	TifTuf	0.76 a	0.64 a	0.70 a	0.66 a	0.68 a
Tifway	0.76 de	0.72 e	0.52 d	0.40 c	0.32 e	Tifway	0.75 ab	0.5 i	0.44 e	0.31 g	0.31 d
UGB103	0.80 ab	0.77 ab	0.63 abc	0.57 ab	0.55 abc	UGB103	0.78 a	0.58 c–f	0.56 bcd	0.47 c–f	0.45 bc
UGB117	0.79 abc	0.73 de	0.53 d	0.43 c	0.41 de	UGB117	0.78 a	0.53 ghi	0.53 d	0.41 f	0.42 c
UGB118	0.80 ab	0.77 abc	0.64 abc	0.63 a	0.62 ab	UGB118	0.80 a	0.62 abc	0.60 bc	0.49 c–f	0.50 bc
UGB120	0.79 ab	0.76 bc	0.61 bc	0.58 ab	0.58 abc	UGB120	0.74 ab	0.53 ghi	0.53 d	0.42 ef	0.45 c
UGB136	0.80 ab	0.77 ab	0.65 a	0.61 a	0.58 abc	UGB136	0.80 a	0.55 e–h	0.61 bc	0.45 def	0.50 bc
						Astro	0.76 a	0.51 hi	0.38 e	0.26 g	0.28 d
						U-3	0.78 a	0.61 a–d	0.55 cd	0.45 def	0.42 c

[i] NDVI was measured by the Trimble GreenSeeker handheld sensor on a scale of 0–1, where 0 = no green cover and 1 = complete green cover.

[ii] DOS = days of study. In Expt. I, the dry-down started on 16 Jun and ended on 28 Aug. In Expt. II, the dry-down started on 17 Jul and ended on 15 Oct. Before the initiation of dry-down, plots were saturated with excessive amounts of irrigation and verified with a soil moisture probe. Then irrigation was turned off and woven polyethylene waterproof tarps were used to cover plots to avoid precipitation reaching plots for both experiments.

[iii] Means within the same column followed by the same letter are not significantly different at the $P = 0.05$ level using Fisher's protected least significant difference test. A dash appearing between two letters means all the letters between those two letters are included.

OSU1221. At the end of the study, LGC means ranged from 28.5% to 91.9%. 'TifTuf' and OSU1221 ranked in the top statistical group, whereas 'Tifway' and 'Astro' were in the bottom statistical group.

Correlation analysis. Highly significant and positive correlations were observed (from 0.83 to 0.94) among the assessed parameters, including TQ, LF, LGC, and NDVI in Expts. I and II (Table 7). Correlations between quantitative parameters of LGC and NDVI were 0.93 in Expt. I and 0.94 in Expt. II, the highest among all correlations in each experiment. Correlations between VSWC and the canopy-related parameters were positively significant, ranging from moderate ($r = 0.41$) between VSWC and LF in Expt. I to high ($r = 0.81$) between VSWC and NDVI in Expt. II. Generally, lower correlation coefficients were observed between VSWC and the canopy-related measurements in contrast to the higher correlation coefficients amongst canopy-related measurements. The correlation between DOS and other parameters was statistically significant and negative, ranging from –0.65 (between DOS and LF and TQ) to −0.88 (between DOS and VSWC) in Expt. I and from −0.58 (between DOS and LGC) to –0.85 (between DOS and VSWC) in Expt. II.

Turf performance index. In Expt. I, the order of the drought responses of entries from the best to the worst was as follows: 'TifTuf', OSU1221, OSU1225, OSU1257, UGB136, 'Celebration', UGB118, UGB120, OSU1220, OSU1273, UGB117, and 'Tifway' based on the TPI for TQ, LF, NDVI, and LGC (Table 8). Because the TPI presented the numbers, each genotype ranked at the top statistical group and should not analyze statistically. Therefore, the ranking of genotypes does not indicate that they were statistically different.

In Expt. II, the order of the drought responses of entries from the best to the worst was as follows: 'TifTuf', OSU1221, OSU1257, OSU1220, UGB136, UGB103, UGB118, UGB117, 'Celebration', 'U-3', OSU1225, 'Tifway', UGB120, OSU1273, and 'Astro' based on the TPI for TQ, LF, NDVI, and LGC (Table 8). The experimental genotype OSU1221 was the best performer among all experimental genotypes. OSU1257 and UGB136 consistently showed improved drought response compared with 'Celebration' in both experiments. OSU1225 performed better than 'Celebration' in Expt. I but not Expt. II.

Table 6. Comparison of mean live green cover (LGC) amongst bermudagrass entries at five selected rating dates during the dry-down of Expts. I and II.

	Expt. I LGC[i]						Expt. II LGC				
Entry	0 DOS[ii]	23 DOS	37 DOS	57 DOS	72 DOS	Entry	0 DOS	22 DOS	44 DOS	68 DOS	90 DOS
Celebration	99.4 bcd[iii]	94.2 ef	80.1 cd	86.5 abc	84.2 a–d	Celebration	98.2 abc	90.2 a	78.1 bcd	66.2 cd	54.9 bc
OSU1220	99.8 a	96.9 abc	81.1 cd	69.4 e	68.3 de	OSU1220	97.6 a-d	74.5 bcd	77.3 bcd	65.4 cd	59.2 bc
OSU1221	99.5 abcd	99.0 a	88.2 ab	87.2 ab	88.1 ab	OSU1221	97.4 a-d	78 bcd	93.7 a	86.9 ab	88.0 a
OSU1225	99.5 bcd	97.9 ab	85.0 abc	84.6 a–d	85.3 abc	OSU1225	98.0 abc	76 bcd	77.1 bcd	67.8 cd	60.9 bc
OSU1257	99.7 ab	99.0 a	81.8 bcd	79.5 a–d	74.0 bcd	OSU1257	97.1 cde	82 abc	85.4 ab	75.1 bc	67.9 b
OSU1273	99.5 bcd	96.5 bcd	76.3 de	76.5 b–e	69.9 cd	OSU1273	96.9 cde	70.1 de	71.9 cde	59.1 cde	53.7 bc
TifTuf	99.3 de	97.9 ab	89.1 a	89.0 a	91.4 a	TifTuf	98.2 abc	89.4 a	94.1 a	92.2 a	91.9 a
Tifway	99.2 e	95.4 c–f	69.8 f	50.9 f	34.0 f	Tifway	97.2 b-e	70.2 de	60.2 e	39.6 fg	35.8 de
UGB103	99.5 abcd	97.9 ab	79.4 cde	74.2 de	77.2 a–d	UGB103	98.1 abc	72.6 cde	68.9 de	60.0 cde	54.1 bc
UGB117	99.7 abc	96.0 bcde	63.0 g	53.5 f	53.6 e	UGB117	99.0 ab	69.2 de	67.7 de	47.6 ef	45.5 cd
UGB118	99.4 de	93.7 f	76.3 de	75.5 cde	84.0 a–d	UGB118	98.4 abc	77.7 bcd	70.9 de	55.7 def	57.1 bc
UGB120	99.7 ab	94.5 def	73.2 ef	69.3 cde	79.3 a–d	UGB120	95.5 e	62.7 e	63.3 e	45.6 ef	49.8 cd
UGB136	99.4 cde	97.6 abc	84.6 abc	79.5 a–e	80.8 a–d	UGB136	99.2 a	71.3 de	83.6 abc	60.7 cde	57.4 bc
						Astro	96.1 de	64.2 e	43.5 f	28.5 g	28.5 e
						U-3	98.4 abc	83.1 ab	75.8 bcd	64.6 cd	57.1 bc

[i] LGC = measured by digital image analysis calculating the percent live cover on a scale of 0–100, where 0 = no green cover and 100 = all the leaves are green.

[ii] DOS = days of study. In Expt. I, the dry-down started on 16 June and ended on 28 Aug. In Expt. II, the dry-down started on 17 Jul and ended on 15 Oct. Before the initiation of dry-down, plots were saturated with excessive amounts of irrigation and verified with a soil moisture probe. Then irrigation was turned off and woven polyethylene waterproof tarps were used to cover plots to avoid precipitation reaching plots for both experiments.

[iii] Means within the same column followed by the same letter are not significantly different at the $P = 0.05$ level using Fisher's protected least significant difference test. A dash appearing between two letters means all the letters between those two letters are included.

Table 7. Pearson's correlation analysis amongst leaf firing (LF), turf quality (TQ), live green cover (LGC), normalized difference vegetation index (NDVI), volumetric soil water content (VSWC), and days of study (DOS) in Expts. I and II.

	Expt. I					Expt. II				
Parameter	TQ[i]	NDVI[ii]	LGC[iii]	VSWC[iv]	DOS[v]	TQ	NDVI	LGC	VSWC	DOS
LF[vi]	0.84***	0.89***	0.89***	0.48***	−0.65***	0.89***	0.83***	0.82***	0.41***	−0.73***
TQ		0.90***	0.83***	0.69***	−0.86***		0.87***	0.84***	0.67***	−0.78***
NDVI			0.93***	0.62***	−0.79***			0.94***	0.81***	−0.61***
LGC				0.56***	−0.65***				0.77***	−0.58***
VSWC					−0.88***					−0.85***

[i] TQ was rated on a scale of 1–9 during dry-down, where 1 = lowest quality and 9 = excellent quality.

[ii] NDVI was measured by the Trimble GreenSeeker handheld sensor on a scale of 0–1, where 0 = no green cover and 1 = complete green cover.

[iii] LGC was measured by digital image analysis calculating the percent live cover on a scale of 0–100 where 0 = no green cover and 100 = all the leaves are green.

[iv] VSWC was measured with a Stevens POGO HydraProbe.

[v] DOS = days of study.

[vi] LF was rated on a scale of 1–9 during dry-down, where 1 = all leaves fired and 9 = no leaf fired.

***Significant at $P < 0.001$.

Discussion

Due to different plant materials and experimental designs, Expts. I and II were analyzed separately. Thus, we were not able to detect the location and entry-by-location interaction. By analyzing Expts. I and II separately, highly significant ($P < 0.0001$) entry, entry-by-block, and entry-by-date interactions were identified. However, variances of entry remained greatest among other sources of variation for all measurements. High reliability was observed for all measurements in both experiments, indicating the genetic component played a significant role in the drought response. Similarly, Yu et al. (2022) reported LF had a high broad-sense heritability ($H^2 = 0.80$) in African bermudagrass (*Cynodon transvaalensis* Burtt-Davy). Although with diverse genetic backgrounds from different breeding programs, plant materials used in this study had been carefully selected for drought resistance in prior research. Major genes associated with drought resistance could be similar for experimental lines from the same breeding program and they were consistently expressed in Stillwater, OK. Although the experimental design did not include variation to test the entry-by-location interaction, weekly data collection provided enough statistical power to detect the variance caused by environments in both experiments. The high reliability gives breeders confidence to select improved drought resistance entries in the current study.

Table 8. Turf performance index (TPI) of bermudagrass entries in Expts. I and II using four assessment parameters. The maximum number of TPI for Expts. I and II were 88 and 56, respectively.

Expt. I		Expt. II	
Entry	TPI[i]	Entry	TPI
TifTuf	66	TifTuf	55
OSU1221	58	OSU1221	49
OSU1225	51	OSU1257	21
OSU1257	43	OSU1220	18
UGB136	38	UGB136	17
Celebration	36	UGB103	16
UGB103	35	UGB118	16
UGB118	33	UGB117	14
UGB120	32	Celebration	13
OSU1220	26	U-3	12
OSU1273	21	OSU1225	11
UGB117	18	Tifway	8
Tifway	10	UGB120	7
		OSU1273	6
		Astro	2

[i] TPI represents the total number of times that the entry's mean ranked in the top statistical ranking group (according to Fisher's protected least significant difference at the $P = 0.05$ level) for each measurement over 22 dates in Expt. I and 14 dates in Expt. II. Measures of drought response included leaf firing, turf quality, normalized difference vegetation index, and live green cover.

On the basis of the differences between ET estimation by the Mesonet station in Stillwater, OK, and the precipitation from the rain events, the total water deficits for Expts. I and II were 294.9 and 294.1 mm, respectively. The results of Expts. I and II indicated that the LGC of 'TifTuf', OSU1221, and 'Tifway' were similar by the end of each study. Due to the different soil textures, the average VSWC in Expt. II dropped faster than in Expt. I, which could partially interpret why 'Celebration', OSU1225, UGB118, UGB120, and UGB136 lost more than 30% of LGC at the end of the study in Expt. II compared with Expt. I. Another factor that may contribute to the result is the air temperature. To have a good separation of drought response, we pushed the length of Expt. II to 90 d. The minimal temperature near the end of the study was 5 °C which may cause chilling injury to bermudagrass and result in loss of chlorophyll (White and Schmidt 1989). The reduction of LGC on 'Celebration', OSU1225, UGB118, UGB120, and UGB136 in Expt. II could result from being less susceptible to either chilling stress or the combination of chilling and drought stress than other entries.

Similar to Chalmers et al. (2008), who reported that 'Celebration' can maintain 50% green cover after 50 d or longer without water. 'Celebration' had LGC ranked in the top statistical group but TQ and NDVI were not in the top statistical at the end of the Expt. I. This could be partially due to Celebration's color changing drastically from bluish-green to gray-green under drought stress. Experimental selection OSU1221 was the best performer except for 'TifTuf' in terms of TPI, and it was the only experimental genotype with excellent performance in both experiments. Industry-standard Tifway did not perform as well compared with other bermudagrass entries in this study, and results were consistent with Kim et al. (1988). 'Tifway' has been widely used in the southern United States for more than 50 years. Compared with 'Tifway', all experimental bermudagrass genotypes performed better in Expt. I, and 'Tifway' was only better than UGB120 and OSU1273 in Expt. II. However, 'Tifway' performed better during the early stage of the study according to TPI, when soil volumetric water content was above 12% in both experiments. When a severe drought was imposed, Tifway's performance declined rapidly. All experimental genotypes outperformed 'Tifway' under drought, demonstrating genetic improvement in drought resistance in both breeding programs. Overall, our results suggested that 'TifTuf' and OSU1221 could adapt well to prolonged acute drought stress at Stillwater, OK.

Amgain et al. (2018) reported that 'TifTuf' had a higher ET rate than 'Tifway'. Similarly, Yurisic (2016) reported 'TifTuf' used more water than 'Tifway' by calculating soil moisture content. Subsequently, Yurisic (2016) found that the root length of 'TifTuf' did not statistically differ from 'Tifway' in 45-cm-long lysimeters. However, 'TifTuf' produced more total root biomass compared with 'Tifway'. Similarly, Kaur (2021) found that 'TifTuf' has a higher root diameter, a higher root-to-shoot ratio, and a higher total root dry weight than 'Tifway' in 120-cm tubes. These suggest 'Tiftuf' is superior in producing more root biomass to accommodate the prolonged period without irrigation or precipitation. It is assumed that with a nonrestricted rooting depth, 'TifTuf' draws more water from deeper soil than shallow soil. In this study, the correlations between VSWC and DOS were consistently the highest in both experiments. Although the VSWC showed substantial decreases in the first week of both experiments (Figs. 4 and 5), bermudagrass can use moisture from a deeper soil profile, thus no water deficit stresses were observed in the first few weeks of both experiments. Since the VSWC was measured at 6.4-cm-deep soil profile, VSWC collected from a deeper soil profile could provide insight information in future drought-related research. From a breeding perspective, although different entries may have different drought tolerance and avoidance mechanisms to survive during the prolonged water deficit period, developing genotypes with a more extensive root system and higher root-to-shoot ratio could be an effective strategy to improve the drought performance of bermudagrass.

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