Physiological Response to Water Deficit Stress with Restricted Rooting in Tall Fescue and Zoysiagrass[1]

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Abstract

Urban soils may restrict turfgrass rooting depth with shallow soil layers in high sand content soils, which may influence water conservation. A greenhouse study sought to quantify water usage and determine the physiological response of turfgrasses at four irrigation levels. 'ATF-1434′ tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort. nom. cons.; syn. *Festuca arundinacea* Schreb.), 'Jamur' Japanese lawngrass (*Zoysia japonica* Steud.), and 'Zeon' Manilagrass [*Zoysia matrella* (L.) Merr.] were established in 10 cm (4 in) diameter by 17.8 cm (7 in) tall containers. Each species was irrigated with 16.5, 21.9, 27.3, or 32.7 mm·wk^{-1} (0.65, 0.86, 1.1, or 1.3 in·wk^{-1}). Gravimetric water loss was determined by pre- and post-irrigation pot weights. Turf quality, leaf discoloration, percent green cover, and gross photosynthesis were evaluated weekly and root parameters were measured at the conclusion of each trial. Although root mass was similar among species, water deficit stress and leaf discoloration occurred sooner in tall fescue than the two *Zoysia* species, reducing turf quality and green cover. Japanese lawngrass and Manilagrass had greater stomatal conductance, resulting in 109 and 89% higher gross photosynthesis relative to tall fescue. Both zoysiagrasses maintained acceptable turf quality with 27.3 mm water·wk^{-1}. However, tall fescue quality was not acceptable at any irrigation level.

Index words: Photosynthesis, gravimetric water loss, tall fescue, Japanese lawngrass, Manilagrass.

Species used in this study: Tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort. nom. cons.; syn. *Festuca arundinacea* Schreb.); Japanese lawngrass (*Zoysia japonica* Steud.); Manilagrass [*Zoysia matrella* (L.) Merr.].

Significance to the Horticulture Industry

Reducing water consumption in urban landscapes continues to be a high priority, and the majority of irrigation is applied to turfgrasses within these landscapes. Numerous factors should be considered when selecting a turfgrass species for a residential lawn to ensure aesthetic and functional quality with reduced water inputs. Adaptation to environmental conditions or microclimates in the landscape should be a primary consideration. Additionally, turfgrass species or cultivars capable of producing deep roots would be advantageous in water conservation efforts. However, compacted soils from home construction practices or rocky parent soil may restrict rooting of turfgrasses following establishment. This study compared water usage, physiological fitness, and visual appeal of 'ATF-1434′ tall fescue, 'Jamur' Japanese lawngrass, and 'Zeon' Manilagrass managed under different levels of water deficit stress. Under these stated conditions, this greenhouse research demonstrated the benefit of physiological adaptations to drought stress in zoysiagrass species over tall fescue. Japanese lawngrass and Manilagrass were able to maintain transpiration and sustain greater photosynthetic capacity under deficit-irrigated conditions with increased green cover and quality when grown in high sand content soil. High temperatures and vapor pressure deficits likely affected physiological parameters of tall fescue to a greater extent than either zoysiagrass species. For regions that experience hot summer temperatures, limited rainfall, and high water demand, data suggest Japanese lawngrass and Manilagrass may be better adapted than tall fescue, especially where shallow soils limit root development.

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Introduction

The transition zone covers the central portion of the United States and provides environmental conditions between subtropical and tropical (Fu et al. 2004). Combining these two climates often provide warm summer temperatures and freezing winter temperatures. Rainfall amounts and patterns generally shift from wet to dry conditions moving westward through the central portion of the United States (Burke et al. 1989). Limited precipitation farther west in this region increases supplemental irrigation requirements for adequate plant growth in semiarid to arid climates.

Turfgrass dominates plant selection in most residential lawns throughout the United States (Milesi et al. 2005). However, landscape designers and homeowners are drawn to landscapes that include trees (Kaplan 1985, Schroeder and Cannon 1987, St. Hilaire et al. 2008). Many landscape plant selection decisions are aesthetically or economically driven, but inclusion of larger trees in urban landscapes have been cited for their functional benefits. Surveyed homeowners in Las Cruces, NM equally identified beneficial aesthetic and functional value from shade producing trees in desert landscape designs (Spinti et al. 2004). Shade trees can provide a cooler temperature for landscape enjoyment and reduce energy cost in hot summer months. However, reductions in light quantity and quality reaching the soil surface may negatively affect growth of turfgrasses planted under trees.

Bermudagrass (*Cynodon* spp.) and buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] are common turfgrasses selected for landscapes throughout the Southwestern

United States because of their increased heat and drought tolerance compared to other adapted turfgrasses (Fu et al. 2004, Qian and Fry 1997, Wherley et al. 2015). However, these turfgrass species have limited shade tolerance (Amundsen et al. 2017, Baldwin et al. 2009). Furthermore, colder climates may injure some bermudagrass cultivars with extended freezing temperatures during winter months (Anderson et al. 2002, Munshaw et al. 2006, Richardson 2002). Newer zoysiagrass (*Zoysia* spp.) and tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort. nom. cons.; syn. *Festuca arundinacea* Schreb.) cultivars are more adapted to shade and high or low temperatures consistent with landscapes in semiarid climates of the transition zone (Patton 2009, Patton and Reicher 2007, Wu et al. 1985).

Tall fescue has been identified as one of the most drought-resistant cool-season turfgrass species (Fry and Huang 2004). Previous research demonstrated more proficient and deeper root production as a drought avoidance mechanism for tall fescue when comparing to other cool-season turfgrasses (Huang and Gao 2000, Karcher et al. 2008, Sun et al. 2013). In contrast, zoysiagrass species generally produce shallower roots that may lead to greater drought symptom development as soil moisture near surface is depleted (Carrow 1996, Fu et al. 2004, Huang et al. 1997, Qian et al. 1997). Osmotic adjustment is an additional drought tolerance mechanism some plants use to maintain physiological function by retaining greater internal leaf moisture as soil moisture is reduced. However, cool-season turfgrasses (i.e. tall fescue) have reduced capabilities to osmotically adjust when compared to warm-season turfgrasses (i.e. zoysiagrass) (Barker et al. 1993, Qian and Fry 1997, White et al. 1992).

Turfgrass landscapes provide numerous ecosystem services to urban landscapes (Beard and Green 1994, Monteiro 2017). However, anthropogenic manipulation or shallow top soil from natural soil formation can restrict rooting potential of turfgrasses (Pouyat et al. 2007). Restricted root zones have been evaluated in a 60-day acute drought assessment (Steinke et al. 2011) or through studies to determine effective substrate or turfgrass selections for green roof development (Ntoulas et al. 2013, Ntoulas et al. 2017). However, limited research is available comparing water use characteristics and photosynthetic production of zoysiagrasses and tall fescue under water deficit stress. Therefore, objectives of this greenhouse research were to quantify water usage and determine physiological response of tall fescue and *Zoysia* species at four irrigation levels in a high sand content soil.

Materials and Methods

This experiment was conducted at the Texas Tech Plant and Soil Science greenhouses in Lubbock, Texas. 'ATF-1434′ tall fescue (NexGen Turf Research, LLC, Albany, OR), 'Jamur' Japanese lawngrass (*Zoysia japonica* Steud.), and 'Zeon' Manilagrass [*Zoysia matrella* (L.) Merr.] plugs [6 cm (2.4 in) diameter by 6.4 cm (2.5 in) height] were collected from field plots in October 2017 using a Turf-Tec Plugger (Turf-Tec International, Tallahassee, FL). Native soil was removed from the plug prior to planting in a 10 cm (4 in) diameter by 17.8 cm (7 in) tall polyvinyl chloride (PVC) container. Containers were filled with a 4:1 (v:v) sand and calcareous clay mixture (Greens Grade Profile Mix, Profile Products, LLC, Buffalo Grove, IL) with weed fabric (Vigoro Weed Barrier Landscape Fabric with PowerGrid, Vigoro Corp, Chicago, IL) attached to the base to hold the soil substrate, and turfgrasses were allowed to establish under greenhouse conditions from October 2017 to April 2018 when experiments were initiated. To reduce water runoff potential, additional sand mixture was added to leave a 0.8 cm (0.13 in) gap from the soil surface to the top of the container. During the establishment phase, containers were watered three times per week to saturation and fertilized monthly with a soluble fertilizer (24N-3.5P-14.1K plus micronutrients Plant Food, Scotts Miracle-Gro Products, Inc., Marysville, OH) at 18.5 kg N·ha^{-1}. Two trials were replicated over time with the first initiated on April 5 lasting 26 d and the second trial started on April 17 and run for 22 d.

Irrigation treatments were initiated at the beginning of each experiment and supplied 44, 59, 74, or 89 ml water per pot three times per week for a total of 16.5, 21.9, 27.3, or 32.7 mm·wk^{-1} (0.65, 0.86, 1.1, or 1.3 in·wk^{-1}). The highest irrigation level was chosen to maximize water input with no drainage from the container. High evaporational demand resulted in this highest irrigation application causing water deficit stress in these species. Each container was weighed before and after each irrigation event to calculate mean daily gravimetric water loss (GWL). Containers were arranged in a randomized complete block design with four replications per species (n = 3) and irrigation (n = 4) combination to include 12 containers per block. Blocks were aligned linearly away from an evaporative cooling system to account for greenhouse air temperature variation.

Turfgrass quality and leaf discoloration, determined visually, were rated on a 1-9 National Turfgrass Evaluation Program scale by three researchers two days per week prior to applying irrigation. Turf quality estimated density, color, and uniformity within each container with 9 being best, 1 poorest, and 5 representing minimum acceptability for lawn-managed turfgrasses (Krans and Morris 2007). Leaf discoloration was expressed by turfgrasses experiencing drought stress initially as chlorosis at the leaf tip, which progressed into drought-induced dormancy symptoms (Carrow 1996). A leaf discoloration rating of 9 indicated no visible leaf discoloration and 1 would be a completely brown canopy. Three rating values determined for each container were averaged to obtain a single rating per experimental unit. Percent green cover was determined from digital image analysis (DIA) in conjunction with visual ratings. A light box was constructed from a bucket with light emitting diode (LED) tape (Ribbon Flex Pro Series, Armacost Lighting, Baltimore, MD) adhered near vertical center in the bucket. The light box was attached to a blue foam board with a 10 cm (4 in) diameter cutout in the center to place on top of each container. A single image of each experimental unit was obtained using a Canon PowerShot G15 camera (Canon USA, Melville, NY) with custom settings of: 80 ISO, 1/80 aperture, and 2.8 F-stop. Green turfgrass coverage analysis was conducted using

Turf Analyzer Software (Green Research Services, LLC, Fayetteville, AR) (Karcher and Richardson 2013). A frame analysis was conducted to only calculate green cover within the 10 cm cutout with green turfgrass identified as pixels within hue of 62-140, saturation of 10-100, and brightness of 0-100.

To determine the photosynthetic rate of each species at four irrigation levels, a custom photosynthesis chamber (Li-COR 6400-19 Custom Chamber Kit PPS-234, LI-COR Biosciences, Lincoln, NE) was connected to a Li-Cor 6400-XT Portable Photosynthesis instrument. Volume of the clear custom chamber was 540 cm^3 (34 in^3). Area of the custom chamber base (54 cm^2) was included as leaf area used in calculating gas exchange measurements, and CO_2 level within the chamber was maintained at 400 ppm. Photosynthetic measurements were conducted weekly between 1100 and 1300 h on cloud-free days. Each experimental unit was measured under full light conditions. Following each full light measurement, a covered measurement was made to determine soil and canopy respiration. The absolute value of the dark measurement was added to the sun lit measurement to calculate gross photosynthesis (Bremer and Ham 2005, Su et al. 2008). Each trial consisted of four measurement dates with trial 2 conducted earlier due to forecasted rain and heavy cloud conditions in the final week of the experiment.

Root length and dry root mass were determined at the conclusion of each trial. The bulk of the sand substrate was removed from roots by shaking contents after the plants were removed from the container. Remaining sand particles were more delicately removed by placing turfgrass and roots in a bucket of water. After soil removal, root length was measured as the maximum length from the crown to the longest root extension using a tape measure. Cleaned root systems were separated from turfgrass by cutting just below the crowns of tall fescue or stolons of the zoysiagrass species and dried at 85 C (185 F) for 4 to 5 d for root mass determination.

Sensors were not available in 2018 to monitor greenhouse environmental conditions during either experiment. However, greenhouse environmental data obtained from a 2017 greenhouse evaluation (Culpepper 2019, Culpepper et al. 2019) were regressed against 2017 hourly weather data from the Lubbock USDA Agricultural Research Service weather station (Stout 2017). Regression equations from 2017 for incoming daily solar radiation ($y = 1{,}500.41 + (-22{,}908.42 / x^{0.5})$, $R^2 = 0.91$), daily greenhouse air temperature ($y = 42.72 + (-551.69 / x^{1.5})$, $R^2 = 0.78$), and greenhouse relative humidity ($y = 5.97 + (0.0896x)$, $R^2 = 0.94$) were developed in TableCurve 2D (Systat Software, San Jose, CA). Daily greenhouse solar radiation, air temperature, and humidity in 2018 were estimated by incorporating hourly weather data from the USDA site (1.25 km from the Plant and Soil Science greenhouse) into respective equations. Maximum, daily 2018 greenhouse evaporative demand (vapor pressure deficit) was estimated using saturated vapor pressure and ambient vapor pressure of the 2018 hourly maximum air temperatures and corresponding relative humidity data (Jones 1992).

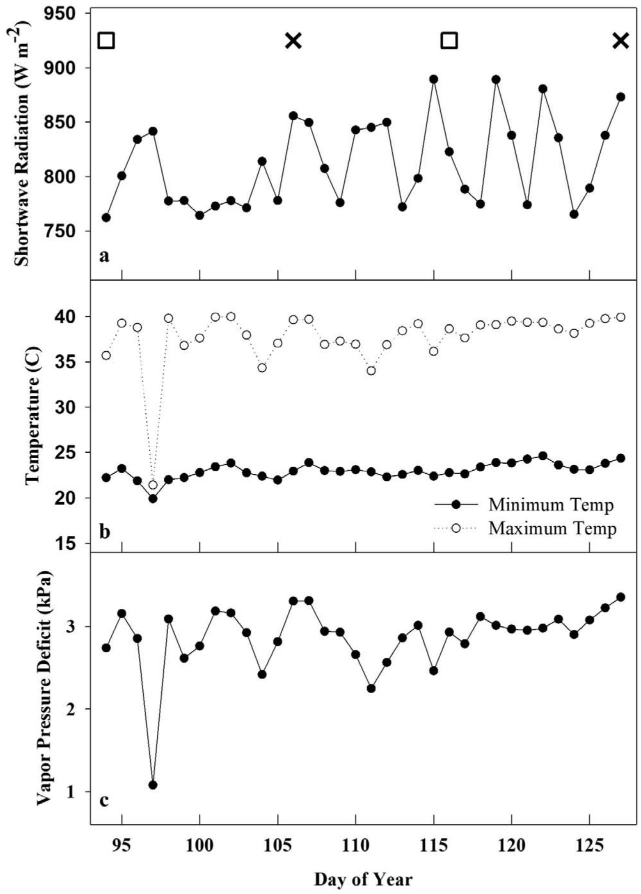

Fig. 1. Daily maximum shortwave radiation (a), air temperature (b), and vapor pressure deficit (c) estimated for the greenhouse during Trial 1 (day of year 94-116) and Trial 2 (day of year 106-127). Initiation and conclusion of Trial 1 is noted by an open square symbol and Trial 2 by an X symbol.

Statistical analysis was performed using Proc GLIMMIX (SAS 9.4, SAS Institute, Cary, NC). Analysis of variance (ANOVA) was initially conducted for all measured response variables (turf quality, leaf discoloration, green cover, daily GWL, gross photosynthesis, root length, and root mass) to determine if trials should be pooled or analyzed separately. Trials were pooled for response variables having no trial by main effect (species or irrigation) interactions. Those response variables exhibiting significant trial by main effect interactions were analyzed separately, and day was included in the model along with species and irrigation. Block was included as the random factor in all analyses. Fisher's least significant difference values were calculated for each significant test at $\alpha = 0.05$ to conduct mean separation tests.

Results and Discussion

Estimated greenhouse environmental conditions for both trials are provided (Fig. 1). Mean estimated daily maximum shortwave radiation was 808 and 825 $W \cdot m^{-2}$ in trials 1 and 2, respectively. Natural sunlight was reduced by 26% in trial 1 and 28% in trial 2 due to the greenhouse cover. Minimum and maximum daily temperature during Trial 1 averaged 22.7 and 37.0 C, respectively. Minimum

Table 1. Analysis of variance for response variables analyzed separately for trials conducted under greenhouse conditions in Lubbock, TX evaluating 'Jamur' Japanese lawngrass, 'Zeon' Manilagrass, and 'ATF 1434′ tall fescue at four irrigation levels[z].

	Effect	Turf quality	Leaf discoloration
Trial 1	Day (D)	***	***
	Species (S)	***	***
	D*S	*	*
	Irrigation (I)	***	***
	D*I	NS	NS
	S*I	*	*
	D*S*I	NS	NS
Trial 2	Day (D)	***	***
	Species (S)	***	***
	D*S	***	***
	Irrigation (I)	***	***
	D*I	***	***
	S*I	NS	NS
	D*S*I	NS	NS

[z]NS *, **, or *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

and maximum daily temperature for trial 2 averaged 23.3 and 38.3 C, respectively. Mean vapor pressure deficit was consistent in both trials with 2.8 (+/- 0.47) and 2.9 (+/- 0.27) kPa determined for trials 1 and 2, respectively.

Turf quality and leaf discoloration ratings had significant trial by main treatment factor interactions, so each trial was analyzed separately. There were significant day by species interactions in regards to the ratings in trial 1 and 2 (Table 1). Tall fescue experienced significant declines in turf quality within the first week of both trials, and remained below acceptable values following initial decline in each trial (Fig. 2). Although zoysiagrass species followed a similar trend in trial 1, turf quality remained significantly greater when compared to tall fescue for the first 12 days.

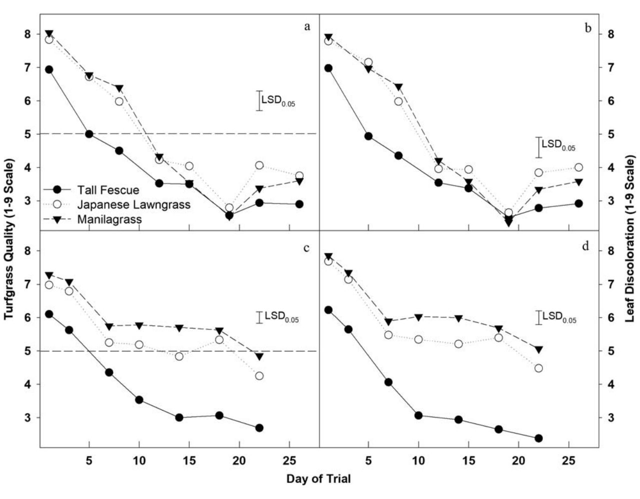

Fig. 2. Mean turf quality (a and c) and leaf discoloration (b and d) for day by species interactions in trial 1 (a and b) and trial 2 (c and d). Turf quality and leaf discoloration were evaluated by three researchers and averaged for statistical analysis. Each rating was conducted on a 1-9 scale with 9 being highest quality or no leaf discoloration, 1 being poorest quality or completely brown turf. Error bars represent LSD values at α = 0.05 for the day by species interactions.

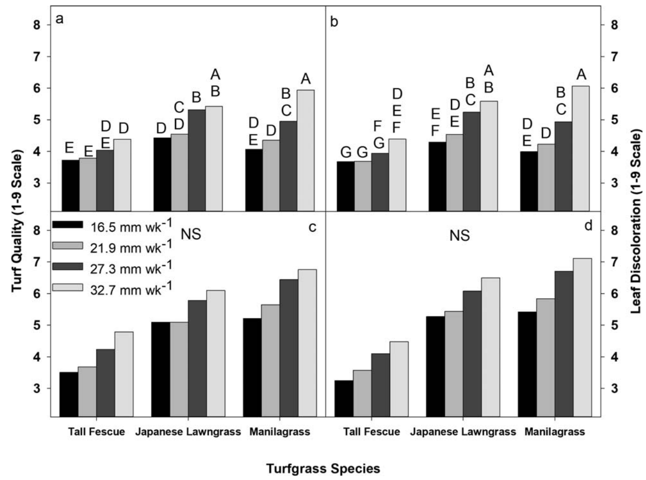

Fig. 3. Mean turf quality (a and c) and leaf discoloration (b and d) for species by irrigation interaction in trial 1 (a and b) and 2 (c and d). Turf quality and leaf discoloration were evaluated by three researchers and averaged for statistical analysis. Each rating was conducted on a 1-9 scale with 9 being highest quality or no leaf discoloration, 1 being poorest quality or completely brown turf. Bars sharing the same letter within a rating are statistically the same at α = 0.05; NS is not significant.

In trial 2, both zoysiagrass species maintained somewhat greater turf quality relative to trial 1 with Manilagrass maintaining acceptable quality through most of the study period (Fig. 2). Leaf discoloration followed similar trends for each species as described for turf quality. Leaf discoloration reduces green cover and uniformity, which reduces turf quality. A species by irrigation interaction for turf quality and leaf discoloration further demonstrated changes in visual appearance of turfgrasses experiencing high temperature and water deficit stress when combining days from Trial 1 (Table 1). Mean turf quality fell below acceptable levels for both zoysiagrass species watered below 27.3 mm·wk^{-1}, but tall fescue did not maintain acceptable turf quality ratings at any irrigation level (Fig. 3). Leaf discoloration was most pronounced in tall fescue, where providing 32.7 mm·wk^{-1} resulted in similar leaf discoloration to Japanese lawngrass irrigated at 21.9 mm·wk^{-1} or Manilagrass receiving 27.3 mm·wk^{-1} of water (Fig. 3). Few greenhouse evaluations have been conducted to compare visual attributes of zoysiagrasses and tall fescue under water deficit stress and restricted rooting depth. Field studies have been conducted, but tall fescue performed better under those conditions in Kansas compared to zoysiagrass when replacing ≤ 60% reference ET (Fu et al. 2004). The restricted rooting depth provided in this study prevented tall fescue from avoiding drought through deeper root production, which it would likely have exploited under field conditions (Bremer et al. 2006, Su et al. 2007, Sun et al. 2013). When combining species from trial 2, there was a significant day by irrigation interaction for turf quality and leaf discoloration (Table 1). Both response variables exhibited similar changes as temperature and water deficit stress increased under greenhouse conditions. Turfgrasses receiving each irrigation treatment declined from day 3 to 7, but the rate of reduction decreased for the two higher

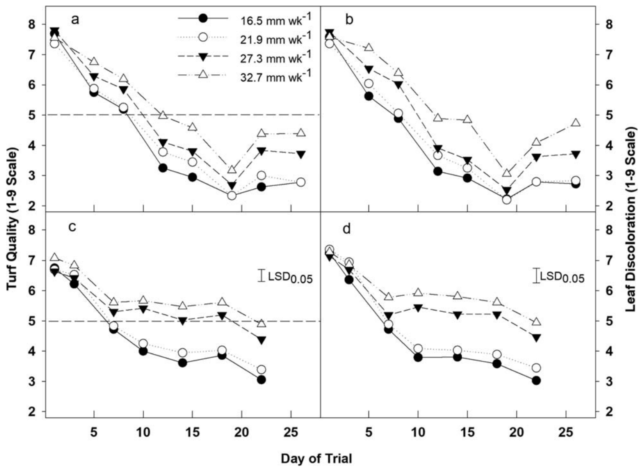

Fig. 4. Mean turf quality (a and c) and leaf discoloration (b and d) for day by irrigation interaction in trial 1 (a and b) and 2 (c and d). Turf quality and leaf discoloration were evaluated by three researchers and averaged for statistical analysis. Each rating was conducted on a 1-9 scale with 9 being highest quality or no leaf discoloration, 1 being poorest quality or completely brown turf. Error bars represent LSD values at α = 0.05 for the day by species interactions in trial 2 (c and d).

irrigation levels after day 7, exhibiting greater turf quality and lower leaf discoloration when compared to the two lower irrigation levels (Fig. 4). There were no turf quality or leaf discoloration differences observed between the two lower or between the higher irrigation levels at any point during trial 2 (Fig. 4).

Significant main effects occurred for green cover, daily GWL, gross photosynthesis, and root length when pooling data from each trial, but no significant interactions were observed (Table 2). When combining trials, days, and irrigation levels, Japanese lawngrass and Manilagrass did not differ in green cover, daily GWL, or gross photosynthesis. However, both *Zoysia* species had higher green cover, daily GWL, and gross photosynthesis compared to tall fescue (Table 3). Greater GWL and gross photosynthesis in zoysiagrass species when compared to tall fescue may provide evidence of continued stomatal conductance under greater temperature and vapor pressure deficit conditions experienced in this greenhouse evaluation. Previous research documented slowing transpiration from cool-season turfgrasses, which included 'Kentucky 31′ tall fescue, as vapor pressure deficit reached a breakpoint of 1.35 kPa (Wherley and Sinclair 2009). In contrast, warm-season turfgrasses never reached a vapor pressure deficit breakpoint as measured values approached 3 kPa, but linear regression models for 'Empire' Japanese lawngrass suggested evapotranspiration (ET) of 3.73 $mm{\cdot}d^{-1}$ as vapor pressure deficit ranged from 0.79 and 2.99 kPa and temperature was maintained near 29.3 C (Wherley and Sinclair 2009). Greenhouse conditions in the current study included greater temperatures, and estimated daily maximum vapor pressure often exceeded 3 kPa during both trials (Fig. 1). Therefore, greater evaporative demand for water and physiological stress were present in the current trial. Calculated values for daily GWL from Japanese lawngrass and Manilagrass were greater than those previously reported from deficit-irrigated Japanese lawngrass (Colmer and Barton 2017). A field study conducted in sandy loam soil identified daily ET of 'Meyer' Japanese lawngrass at 3.54 $mm{\cdot}d^{-1}$ compared to Kentucky 31 (3.69 $mm{\cdot}d^{-1}$) or an improved turf-type tall fescue 'Rebel II' (3.57 $mm{\cdot}d^{-1}$) (Carrow 1995). Mean daily GWL values for tall fescue were consistent with a previous greenhouse evaluation comparing improved turf-type tall fescue lines (Carrow and Duncan 2003). Gravimetric water loss was expected to decrease as soil became drier (Colmer and Barton 2017), which was evident by greater GWL from containers irrigated with 27.3 or 32.7 $mm{\cdot}wk^{-1}$ compared to the two lower irrigation levels (Table 3). Actual weekly GWL replacement varied with irrigation level and species as water deficit stress increased in both trials (Table 4). Actual weekly GWL replacement to tall fescue in trial 1 was numerically greater when compared to both zoysiagrass species or tall fescue in trial 2. All irrigation treatments resulted in water deficit stress following the first week of irrigation when averaging over species. Reductions in green cover combined with stomatal closure as water deficit stress was prolonged, likely lowered cumulative water loss, which resulted in irrigation replacing $\geq$ 100% GWL by the second or third week. The 89 ml irrigation level was initially selected as the amount of water needed to achieve field capacity (i.e., fully irrigate without causing drainage from the container), but water deficit stress symptoms became apparent even in grasses irrigated at this level under greenhouse conditions.

Mean gross photosynthesis increased for Japanese lawngrass and Manilagrass when compared to tall fescue by approximately 5.4 and 4.4 $\mu mol{\cdot}m^{-2}\ s^{-1}$, respectively (Table 3). Increased photosynthetic production from zoysiagrass species reflect improved physiological function

Table 2. Analysis of variance for response variables pooled because of no trial by species or irrigation interactions measured under greenhouse conditions in Lubbock, TX evaluating 'Jamur' Japanese lawngrass, 'Zeon' Manilagrass, and 'ATF 1434′ tall fescue at four irrigation levels[z].

Effect	Green cover	Gravimetric water loss	Gross photosynthesis	Root length	Root mass
Trial (T)	***	*	NS	*	*
Species (S)	***	*	***	***	NS
T*S	NS	NS	NS	NS	NS
Irrigation (I)	***	***	***	NS	NS
T*I	NS	NS	NS	NS	NS
S*I	NS	NS	NS	NS	NS
T*S*I	NS	NS	NS	NS	NS

[z]NS *, **, or *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 3. Mean green cover from digital image analysis, daily gravimetric water loss, gross photosynthesis, root length, and dry root mass for species and irrigation treatments evaluated under greenhouse conditions.

Treatment	Green cover (%)		Gravimetric water loss ($mm \cdot d^{-1}$)		Gross photosynthesis ($\mu mol \cdot m^{-2}\ s^{-1}$)		Root length (cm)		Dry root mass (g)	
Japanese lawngrass	53.5	A[z]	4.12	A	10.34	A	18.9	B	2.41	A
Manilagrass	49.6	A	4.10	A	9.35	A	17.9	B	2.53	A
Tall fescue	31.0	B	3.77	B	4.95	B	21.5	A	2.05	A
32.7 mm wk^{-1}[y]	55.5	A	4.88	A	9.89	A	18.8	A	2.18	A
27.3 mm wk^{-1}	47.4	B	4.25	B	8.81	A	19.6	A	2.27	A
21.9 mm wk^{-1}	39.5	C	3.44	C	7.25	B	19.5	A	2.51	A
16.5 mm wk^{-1}	36.4	C	3.43	C	6.91	B	19.8	A	2.35	A

[z]Mean values followed by the same letter within species or irrigation treatments are statistically the same at $\alpha = 0.05$.

[y]Weekly irrigation provided three days per week to a 10 cm (4 in) diameter container at 44, 59, 74, 89 ml per application.

or drought tolerance under combined heat and water deficit stress as expected from warm-season turfgrasses that do not photorespire (Bell 2011, Fu et al. 2007). Findings from the current work are similar to previous photosynthetic assessments conducted in a field evaluation comparing minimal deficit irrigation requirements and 100% of GWL replacement determined from lysimeters (Fu et al. 2007). The previous work reported net photosynthesis and whole-plant respiration separately, with tall fescue exhibiting reduced photosynthesis at minimal deficit irrigation compared to full replacement of GWL. However, Japanese lawngrass had higher net photosynthesis when compared to tall fescue under minimal deficit irrigation, and did not differ between full replacement or deficit irrigation (Fu et al. 2007). Respiration measurements did not differ between deficit irrigated or 100% replacement of actual GWL in previous research (Fu et al. 2007). This finding suggests a greater affect from water deficit on photosynthetic capacity when compared to respiration. Gross photosynthesis calculated in this research included plant and soil respiration, but measured values were lower when compared to those that would have been calculated from field evaluations previously described. Restricting rooting depth and growing these turfgrasses in sand may have increased a drought response that reduced turf quality and cover from leaf discoloration, which would have had a greater effect on photosynthetic rates for both warm- and cool-season turfgrasses. A high sand content soil medium was selected for this experiment to increase drought development in the grasses, but native soils containing silt or clay particles would have increased water holding capabilities and provide water to turfgrass roots for a longer time period. Furthermore, increased evaporative demand from high temperatures and vapor pressure deficits likely influenced stomatal regulation in tall fescue to a greater extent than either zoysiagrass, as noted by greater daily GWL calculations. This result agrees with previous controlled-environment research that demonstrated loss of transpiration control in tall fescue experiencing exposure to high temperatures and increased vapor pressure deficits (Sermons et al. 2012).

Table 4. Mean weekly gravimetric water loss replacement for species grown in greenhouse conditions at four irrigation levels.

Trial	Species	Week	Weekly cumulative irrigation treatments: 16.5 $mm \cdot wk^{-1}$[z]	21.9 $mm \cdot wk^{-1}$	27.3 $mm \cdot wk^{-1}$	32.7 $mm \cdot wk^{-1}$
			% Actual gravimetric water loss replaced[y]			
Trial 1	Tall fescue	1	67	92	108	108
		2	85	89	85	88
		3	85	104	112	102
	Japanese lawngrass	1	44	54	73	82
		2	81	86	98	92
		3	85	109	116	118
	Manilagrass	1	49	62	70	78
		2	89	104	104	108
		3	93	139	116	114
Trial 2	Tall fescue	1	60	71	78	82
		2	74	104	104	108
		3	72	96	87	90
	Japanese lawngrass	1	35	52	68	66
		2	103	109	104	97
		3	52	62	82	86
	Manilagrass	1	38	55	57	70
		2	78	104	116	105
		3	52	83	76	88

[z]Weekly irrigation provided three days per week to a 10 cm (4 in) diameter container at 44, 59, 74, 89 ml per application.

[y]Weekly gravimetric water loss calculated from sum of differential pot weight before and after each irrigation event.

Even with restricting rooting depth in a 17.8 cm (7 in) tall container, Manilagrass and Japanese lawngrass had a shorter root length when compared to tall fescue (Table 3). There were no differences in dry root mass among species or irrigation treatments. This agrees with previous studies documenting increased rooting near the soil surface in zoysiagrasses compared to other warm-season grasses grown under field conditions in sandy or clay soils (Wherley et al. 2014, Zhang et al. 2019). Similar results were noted with a shorter root length measured in Manilagrass when compared to common bermudagrass [*Cynodon dactylon* (L.) Pers.] grown in greenhouse conditions, but no differences in specific root length were observed (Fuentealba et al. 2015). The lack of differences in root length or dry root mass across irrigation treatments may indicate irrigation depth or frequency of water application with these restrictive containers did not influence root production. Alternatively, this may be a result of the short duration of trial 1 (26 d) and 2 (22 d). Huang et al. (1997) demonstrated loss of root viability in drying soils, which could have reduced water uptake from soil as the water deficit stress continued throughout both trials.

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