INVESTIGATIONS INTO WATER USE RATES AND DROUGHT RESISTANCE OF TURFGRASSES UNDER SHADED CONDITIONS

By

HUANYUN DUAN

Master of Engineering in Environment and Energy
Yunnan Normal University
Kunming, China
2015

Bachelor of Engineering in Environment and Energy
Yunnan Normal University
Kunming, China
2012

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2018

INVESTIGATIONS INTO WATER USE RATES

AND DROUGHT RESISTANCE OF TURFGRASSES

UNDER SHADED CONDITIONS

Thesis Approved:

Dr. Charles Fontanier

Thesis Adviser

Dr. Justin Q. Moss

Dr. Tyson E. Ochsner

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Dr. Charles H. Fontanier for his excellent guidelines, persistent support, and great patience. It is such a great honor to work with him where I have learned passionate work ethic. I give my sincere thanks to Dr. Justin Q. Quetone Moss for his contributions to my thesis study. I owe my great thankfulness to Dr. Tyson E. Ochsner for his throughout comments to my research and for his encouragement to my study.

I would like to thank the Department of Horticulture and Landscape Architecture for providing a great platform for my study and professional development, which made my experience in Oklahoma State University unforgettable and fruitful. I am very grateful to all staff members from the Turfgrass Research Center for their professionalism and support. I especially would like to thank Ms. Becky Cheary for her significant efforts and contribution assisting my experiments in both greenhouse and field. I would also like to thank Mr. Bart Frie for managing my irrigation schedules.

My great thanksgivings go to my families and friends for their endless love and unconditional support. Without their help, I could not even set up my experiments. I give my sincere love and appreciation to my husband Chao Liu for his selfishless love and support.

Name: HUANYUN DUAN

Date of Degree: DECEMBER, 2018

Title of Study: INVESTIGATIONS INTO WATER USE RATES AND DROUGHT RESISTANCE OF TURFGRASSES UNDER SHADED CONDITIONS

Major Field: HORTICULTURE

Abstract: Bermudagrass (*Cynodon* spp.) is the primary of turfgrass species used for residential lawns in Oklahoma. In place of bermudagrass, tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] has often been planted in shaded environments. Zoysiagrass (*Zoysia* Willd.) is a lesser-used turfgrass species that is well-adapted to Oklahoma and could potentially serve as an alternative choice in shaded environments. A one-year field study was conducted in summer 2018 to test the water use rates and turf performance of zoysiagrass including 11 cultivars of zoysiagrass and 1 cultivar of bermudagrass. Grasses were evaluated under 73% shade and open sun. In terms of turf quality, 'Diamond' and 'Meyer' were the top two performers in severe shade, and Celebration was the worst performing cultivar. Additionally, the microclimate coefficient of the top performers and Celebration suggested that bermudagrass respond to shade environment differently than zoysiagrass but there was also variation between cultivars among zoysiagrass.
In addition, one greenhouse experiment tested the hypothesis that turfgrass vary in their morphological response to shade and these changes may result in cultivar-specific changes in water use rates in response to shade. 'Shade' (55% shade) and 'Non-shade' (12-hour supplemental lights) treatments were applied using a neutral black shade fabric on 'Falcon IV', 'Meyer', 'El Toro', and 'Latitude 36'. Irrigation was applied manually being well-watered (100% ET), and data collected included NDVI, Chl, LA, SLA, CY, LER, and evapotranspiration rate. The ET rate of Falcon, Meyer, El Toro, and Latitude 36 reduced under shade by 13%, 23%, 24%, and 29%, respectively. Further, the other measured variables responses were inconsistent and not clearly related to water use rate or shade tolerance. Followed with another study to test the hypothesis that shade will enhance turfgrass drought resistance under progressive soil drying. Within the same shade and non-shade environment, plants were subjected to either daily replacement of evapotranspiration or no irrigation. Plants were evaluated for relative water content, leaf firing, ET rate, and dry roots mass. Results suggested that shade had no effect on the transpiration break point for Falcon IV, Meyer, and El Toro, but the break point of Latitude 36 was delayed.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Problem Statement

The water use rate of turfgrass is affected by environmental conditions (Kim and Beard, 1989). About 25% of turfgrass is affected by some degree of shade (Beard, 1973). Shade can create a microclimate in the landscape which reduce turfgrass water use rates (Bell et al., 2000). Additionally, shade can cause morphological changes to turfgrass that including decreased leaf thickness, decreased shoot density, and increased leaf elongation (Jiang et al., 2004; McBee and Holt, 1966). Ultimately, shade can lead to a decline in turfgrass density and aesthetics. For many turfgrass areas, shade is an inevitable component of the landscape that can create a challenge for turfgrass management.

There is an apparent variation in species and cultivar shade tolerance (Jiang et al., 2004; Trenholm and Nagata, 2005). Bermudagrass is the most popular and widely-used turfgrass species in the southern region (McCarty and Miller, 2002). Turf-type tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] has great shade tolerance and is a popular turfgrass species in northern and transition zone of the United States (Carrow, 1996). Zoysiagrass has better shade tolerance than bermudagrass, and is well-adapted to the transition zone of United States (Patton and Reicher, 2007).

In addition to shade, drought stress is another environmental factor that can affect turfgrass growth and development. Moreover, turfgrass species and cultivars within species can differ in their drought resistance (Carrow, 1995; Huang et al., 1997). Water scarcity is a growing concern across the world, in particular in metropolitan areas where turfgrasses can be the predominant plant species (Beard and Green, 1994). Efforts to decrease water used for turfgrasses can have a meaningful effect on the sustainability of our water resources.

Research Goal and Objectives

The long-term goal of this research is to develop best management practices for landscapes under shade in terms of turfgrass selection and irrigation management.

The objectives of this research are:

1. To quantify the effect of acute shade on leaf morphology of shade tolerant and sensitive turfgrasses;

2. To quantify the effect of shade on water use rate of shade tolerant and sensitive turfgrasses.

3. To compare the drought resistance of four turfgrasses under shade.

4. To compare water use rates of 11 selected zoysiagrass cultivars and 1 bermudagrass cultivar under moderate shade.

Testable hypothesis:

1. Turfgrasses can vary in their morphological response to shade.

2. Turfgrasses will vary in water use rates in response to shade.

3. Shade will enhance turfgrass drought resistance under progressive soil drying.

4. The selected 12 turfgrass cultivars will vary in their water use rates under shade.

CHAPTER II

EFFECTS OF ACUTE SHADE TREATMENT ON TURFGRASS WATER USE RATES

Abstract

The shaded environment poses an irrigation management challenge due to variation in plant response to changing microclimates. Understanding the comparative water use rates of commonly-used turfgrass species in a shaded environment would improve irrigation scheduling recommendations and contribute towards urban water conservation. The objectives of this study were (i) to compare water use rates of selected turfgrasses under two irradiance levels, and (ii) to determine if shade-induced changes in water use rates were related to changes in leaf morphology. An 8-week greenhouse experiment was conducted in fall 2017 using 'Latitude 36' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt Davy], 'Falcon IV' tall fescue [*Schedonorus arundinaceus* (Schreb.) *Dumort.*, nom. cons.], and 'Meyer' and 'El Toro' zoysiagrass (*Zoysia japonica* Steud) grown in 15-cm diameter lysimeters. Each cultivar was subjected to two irradiance levels: shade (55% nominal shade fabric) and non-shade (ambient greenhouse conditions plus supplemental artificial lights). Plants were evaluated for normalized difference vegetation index, specific leaf area (SLA), leaf elongation rate (LER), leaf angle, chlorophyll content, and clipping yield over the study period. The water use rate of each cultivar was obtained gravimetrically between 48-hour periods. Turfgrass ET rates for Falcon IV, Meyer, El Toro, and Latitude 36 declined under shade by 12.8%, 23.1%, 24.1%, and 28.9%. For other

measured variables, cultivar responses were inconsistent and not clearly related to water use rate or shade tolerance. These findings suggest physiological differences between warm- and cool season turfgrasses may be the most important aspect of plant transpiration under varying levels of irradiance.

Introduction

The demand for potable water from industrial and domestic sectors is increasing with the growing population across the U.S., while readily available water resources are finite (Gleick, 1993; Simonovic and Fahmy, 1999; Maggioni, 2015). This predicted deficit of fresh water resources is a major environmental issue for the turfgrass industry in many regions of the country (Pimentel et al., 2004; Pfister et al., 2009; Brown and Matlock, 2011). Efficient management of potable water resources is critical to ensuring continued growth of metropolitan areas (Aitken et al., 1994; Daigger, 2009). Water used for irrigation of residential lawns is a significant component of the annual water budget of most cities, particularly those in arid and semi-arid climates (Bijoor et al., 2014; Bruvold and Smith, 1988; Endter-Wada et al., 2008). Proper selection and management of turfgrasses in the urban landscape can lead to substantial water savings without sacrificing the beneficial properties of turfgrasses (Bormann et al., 2001; Ferguson, 1987).

Turfgrass evapotranspiration (ET) rates can vary considerably across species (Allen et al., 2005; Romero and Dukes, 2016). Cool-season turfgrasses 'Rebel' tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] and Kentucky bluegrass [*Poa pratensis* L. ssp. Pratensis] used 20% more water than warm-season grasses including buffalograss [*Bouteloua dactyloides* (Nutt.) J.T. Columbus] and 'Tifway' hybrid bermudagrass [*Cynodon dactylon* (L.) x *C. transvaalensis* Burtt Davy] (Feldhake et al., 1983). There can also be variation in ET rates among the warm-season turfgrasses (Wherley et al., 2015). The daily ET rates of warm-season turfgrasses under well-watered conditions were reported in a review by Colmer and Barton (2017) to be from 4.40 to 5.55 mm d^{-1} with the water use of zoysiagrass is greater than bermudagrass. Amgain et al. (2018) studying lysimetric ET of ten bermudagrass genotypes reported significant variability even within a species.

Turfgrass ET rates are influenced by environmental conditions such as humidity, temperature, and solar radiation (Allen et al., 1998). Turfgrasses are often managed under some level of shade which is likely to influence many of these environmental contributors to ET. For example, Feldhake et al. (1983) reported that turfgrass ET increased linearly with solar radiation when using neutral density fabrics to simulate shade. However, ET can also be influenced by attributes of the plant (Allen et al., 1998). In the case of turfgrasses, shade can cause morphological changes to plants including increased leaf elongation, decreased leaf thickness, and decreased shoot density (Jiang et al., 2004; McBee and Holt, 1966). Previous research demonstrated that clipping yield decreased with increasing shade for tall fescue and hybrid bluegrass (*P.arachnifera* x *P.pratensis*) (Meeks et al., 2015). Crop reflection, ground coverage, crop height, and crop roughness influence ET rates by changing the aerodynamic and bulk crop resistances to water transfer (Allen et al., 1998). Similarly, changes in turfgrass morphology, anatomy, or physiology may influence ET by influencing surface albedo, stomatal properties, or plant density (Allen et al., 1998).

Turfgrass species and cultivars within a species can vary in shade tolerance (Dunne et al., 2017; Jiang et al., 2004; Sladek et al., 2009; Trenholm and Nagata, 2005). Among the cool-season turfgrasses, tall fescue was reported to have superior shade tolerance to fine fescues (*Festuca* spp), Kentucky bluegrass, roughstalk bluegrass (*Poa trivialis* L.), and perennial ryegrass (*Lolium perenne* L.) (Gardner and Taylor, 2002). A three-year field experiment suggested that *Z. matrella* was better adapted to heavy shade than *Z. japonica* (Wherley et al., 2011). Among bermudagrass cultivars, 'Celebration' [*Cynodon dactylon* L. Pers.] has demonstrated the best shade tolerance (Bunnell et al., 2005; Chhetri et al, in review). In general, cool-season turfgrasses have better shade tolerance than warm-season turfgrass (Qian and Engelke, 1999).

Because of the apparent variation in species and cultivar shade tolerance, I hypothesize that differing morphological responses to shade will result in cultivar-specific changes in water use rates in response to shade. To test this hypothesis, the objectives of this study were (i) to quantify the effect of acute shade on leaf morphology of shade tolerant and sensitive turfgrasses; and (ii) to quantify the effect of shade on water use rate of shade tolerant and sensitive turfgrasses.

Materials and Methods

The study was conducted at the Horticulture Research Greenhouses at Oklahoma State Univeristy in Stillwater, OK (36.136043°N, -97.086767°W) from September 3 through November 3, 2017. Temperature in the greenhouse was maintained at a 30/20 °C (day/night) regime.

Four cultivars were selected for this study: 'El Toro' zoysiagrass (*Z. japonica*), 'Meyer' zoysiagrass (*Z. japonica*), 'Latitude 36' hybrid bermudagrass, and 'Falcon IV' tall fescue. Grasses were planted in May 2017 into polyvinyl chloride (PVC) growth tubes (15 cm diameter and 36 cm long) filled with fritted clay (Turface MVP, Profile LLC., Buffalo Grove, IL) that had been sieved to a particle size ranging from 1mm to 2mm. Pre-plant fertilizer (6-2-0, Milorganite, Milwaukee, WI) was applied on the soil surface at 5 g N m^{-2}. Zoysiagrasses were established as washed sod. Bermudagrass was established from sprigs at the rate of 1.53 x 10^4 ml m^{-2} (Johnson, 1973). Tall fescue was seeded at a rate of 29 g m^{-2} pure live seed (Martin, 1995). Turf height was maintained by clipping weekly at 5 cm with scissors. Two weeks after planting, a soluble complete fertilizer (Peter's 20-20-20, A.M. Leonard, Piqua, OH) was applied at a rate of 0.6 g N m^{-2} every week during the establishment and experiment period. Preventative applications of chlorothalonil (Daconil Weatherstik, Syngenta, Basel, Switzerland) and bifenthrin (Up-Star Gold Insecticide, Seed Ranch, Odessa, FL) were applied every two weeks at label rates for control of *Rhizoctonia* spp. related diseases, bermudagrass mite (*Aceria cynodoniensis* Sayed), and zoysiagrass mite (*Eriophyes zoysiae*). Plants were allowed to establish for three months after planting before subjecting pots to shade treatment.

Experimental Design and Treatment

This experiment was arranged as a completely randomized design (CRD) with eight replications. The treatments were arranged as a modified split plot with the whole main plot being the shade factor and each of the four cultivars arranged factorial within each irradiance level. Shade treatments consisted of a control group (ambient) and experimental group (shaded). The shade treatment was imposed using black woven shade fabric (American Plant Products, Oklahoma City, OK), nominally rated to reduce incoming radiation by 55%. A 3.0 X 1.5 m section of the shade fabric was suspended approximately 1.0 m above the pots. Non-shaded pots received ambient PAR and supplemental lights (700 to 1900 hr) within the greenhouse. Shade fabric was placed on the experiment group from September 2, 2017 to November 3, 2017, and was only removed for data collection, mowing, and fertilization every another day (about 5 hours in total per week).

Data Collection and Analysis

Photosynthetically active radiation (PAR) was recorded on a 30 min resolution using a quantum sensor (WatchDog 1000, Spectrum Technologies, Inc., Plainfield, IL). The ambient temperature and humidity were recorded every 30 minutes using WatchDog 1000 (Spectrum Technologies, Inc., Plainfield, IL). A daily light integral (DLI) was calculated as the sum of PAR reaching pots within a day.

The ET rate over a 48-hour period was determined gravimetrically under non-limiting conditions. The day before initiating the study, a cork was inserted into each drain hole with 1 cm diameter and which is at the bottom of each pot, and pots were then irrigated by hand until free water was evident on the surface. Pots were maintained under saturated conditions for one hour before the corks were removed and pots allowed to drain for 24 hours. After this period, corks were reinserted to prevent further water loss, and pots weighed to measure the field capacity mass. Pots were subsequently weighed and watered back to field capacity every 48 hours for the remainder of the study.

Clippings were oven-dried at 80°C for 48 hours and weighed to quantify clipping yield (CY, collected weekly). Discrete measurements of specific leaf area (SLA), leaf elongation rate (LER), leaf angle (LA), and chlorophyll content (Chl) were taken at 1, 4, and 8 weeks after treatment (WAT). Clipping yield was collected weekly during the experiment period, and CY was collected by a plastic collection box with 0.8 x 0.5 x 0.4 m volume. Canopy height was measured weekly using a ruler, and LER calculated as the difference between height measurements immediately after mowing and similar measurements 7 days after mowing. Chlorophyll content was estimated using a handheld chlorophyll content meter (CCM-300, Opti-Sciences, Inc.). A small protractor was used to measure the leaf angle (from the soil level) of the second fully-expanded leaf using six shoots per pot. Leaf area of the second fully-expanded leaf was measured on five shoots per pot using the mobile app Leafscan (Department of Radiation Oncology, University of Michigan) and a smartphone (Model A1662 iPhone SE, Apple, Inc.). Image files were converted to area units using the reference markers provided by the developer. After measuring leaf area, the leaves were oven-dried at 80°C for 48 hours before being weighed to obtain dry mass. Specific leaf area was calculated as the leaf area divided by the leaf dry mass (Fontanier and Steinke, 2017).

Daily ET data were averaged across each measurement date within a week (weekly ET) as well as for the entire experimental period (average ET) prior to further analysis. The fraction of maximal ET (ET ratio) for shaded treatments was also calculated as the average daily ET rate of non-shaded pots divided by the corresponding average daily ET Rate in shade for each cultivar. Weekly ET was calculated from the ET ratio within each week during experiment. All data were subjected to analysis of variance (ANOVA) using PROC GLIMMIX (SAS Institute, 2011). The analysis was conducted to determine the effects of cultivar, shade, time, or their interactions on weekly ET, average ET, ET ratio, CY, LER, LA, Chl, and SLA. Means for each group were compared with Tukey's LSD, and a significance level of $p \leq 0.05$ was used for all tests.

Results

Light Condition

The DLI for shaded pots was about 38% of that for non-shaded pots resulting in 6.4 mol m^{-2} d^{-1} and was 18.1 mol m^{-2} d^{-1} for the shaded and non-shaded conditions, respectively (Table 1).

Comparative Water Use (ET)

The average ET rate demonstrated significant cultivar and shade main effects (Table 2). Shade decreased ET for each cultivar ranging from a 13% decrease in Falcon IV to a 29% decrease in Latitude 36 (Table 3). Tall fescue demonstrated the highest ET rate, being 38% greater than all warm-season turfgrasses in non-shaded condition, and being 47% greater than all warm-season turfgrasses in shaded treatment.

Analysis of weekly ET resulted in a significant three-way interaction, therefore subsequent analyses were conducted within week and shade treatment (Table 2). In general, the main effect of cultivar remained similar across weeks (i.e., tall fescue > other species), although the relative ranking among warm-season turfgrasses varied with week. El Toro had a higher ET rate than Meyer in three weeks and five weeks in shaded treatments, respectively (Table 4). El Toro had higher ET than Latitude 36 in five of eight weeks under shade treatment. In the non-shaded treatment, Latitude 36 demonstrated a greater ET rate than El Toro in Week 1, but the reverse occurred in Weeks 5 and 6.

Analysis of the ET ratio (fraction of ET in shade versus non-shaded) demonstrated significant cultivar and time main effects (Table 2). Analysis of the ET ratio for each week resulted in significant main effects both by cultivar and by time but not the interaction of cultivar by time

(Table 2). For the eight weeks, only the weekly ET ratio of Falcon IV was found to be significantly higher from other cultivars in week 3, week 5, week 6, and week 8 (Table 5). Moreover, the weekly ET ratio means by cultivar main effect of Falcon IV also demonstrated significantly higher than Meyer, El Toro, and Latitude 36 over the experiment period (Table 5). The weekly ET ratio of Falcon IV was greater than the average weekly ET ratio of other tree grasses by 14%.

Leaf Morphology

The SLA and LA data each demonstrated significant cultivar, shade, and time main effects (Table 6). The LA data showed significant cultivar by shade and cultivar by time interaction effects. A three-way interaction of cultivar by shade and time was found significant for SLA. Therefore, subsequent analyses of LA and SLA were conducted within each measurement date.

Shade increased SLA of Latitude 36 at 1WAT, 4WAT, and 8WAT, and increased SLA of Falcon IV at 1WAT and 8WAT. Shade had no effect on SLA of Meyer and El Toro at any measurement date (Table 7). Shade increased the LA for Meyer and Falcon IV at 4 WAT and increased the LA for each warm-season turfgrass at 8WAT (Table 8). Shaded Meyer and Latitude 36 demonstrated the largest increases in LA from 1WAT to 8WAT.

Chlorophyll Content

The Chl data demonstrated significant cultivar, shade, and time main effects (Table 6). A three-way interaction of cultivar by shade by time was significant for Chl. Therefore, subsequent analyses of Chl were conducted within each shade treatment and measurement date. Chlorophyll content of each cultivar was unaffected by shade with the exception of Latitude 36 (Table 9). At 1WAT and 4WAT, shade increased Chl for Latitude 36 but the reverse was observed at 8WAT.

Clipping Yield and Leaf Elongation Rate

The LER and CY each demonstrated significant cultivar, shade, and time main effects (Table 6). The LER and CY showed significant cultivar by shade interaction effects, while the three-way interaction of cultivar by shade by time was found significant for CY.

During the first three WAT, Latitude 36 demonstrated the greatest CY under each light treatment, although shade reduced CY for each of these three weeks (Table 10). For the remainder of the experiment, shade had either no effect (three of five dates) or actually increased CY (two of five dates) for Latitude 36. Shade increased CY of Meyer from 4WAT to 7WAT and El Toro from 4WAT to 8WAT. Shade also increased the CY of Falcon IV as early as 3WAT but the effect varied from week to week.

Latitude 36 had the lowest LER both under non-shaded and shaded environments (Table 11). At 1WAT, shade increased the LER of El Toro and Falcon IV but not other cultivars. At 4WAT and 8WAT, each cultivar with the exception of Latitude 36 showed a significant increase in LER under the shaded treatment. Despite this, Latitude 36 did follow a similar pattern as the other cultivars (in terms of numerical mean), and the lack of a significant shade effect for Latitude 36 may have been an artifact of its smaller LER in general.

Discussion

Leaf Morphology

Changes in turfgrass morphology can occur within four to seven days under a reduced irradiance environment (Bunnell et al., 2005). We hypothesized that the timing and magnitude of such changes might be influenced by turfgrass species. For the most part, our results were not in agreement with this hypothesis, and each cultivar responded fairly quickly to the onset of shade.

Patten et al. (2017) reported the SLA of non-mowed Meyer as 23.8 m^2 kg^{-1} which was similar to values reported in the present study for Meyer in shade. Shade has been reported to increase leaf length and average leaf area, while increasing specific leaf area due to changes in leaf thickness (Allard et al., 1991). Changes in organic N compounds, hemi-cellulose or lignin content have been associated with differences in SLA (Patton et al., 2017). Increasing SLA is thought to be an ecological response to competition for light that improves a plants ability to harvest light more efficiently (Reich et al., 1998). The lack of shade-induced change in SLA for either zoysiagrass suggests poor plasticity for this trait and perhaps some other mechanism of shade tolerance within this species. Fontanier and Steinke (2017) suggested zoysiagrasses compete in mixed species swards by being resource efficient while bermudagrasses are more likely to adapt canopy morphology to be more competitive for light.

Chlorophyll Content

Increasing Chl under shade has been reported as one of the adaptive mechanisms for species like St. Augustinegrass, tall fescue, and seashore paspalum to improve light absorbing capacity through photochemistry (Jiang et al., 2004; Wherley et al., 2005; Chin, 2012). Previous studies demonstrated that shaded turfgrass retain a better greenness than non-shaded plants by increasing leaf area and chlorophyll content (Barnes et al., 2014). Moreover, morphological acclimatization of turfgrass to decreased light intensity is an adaptive mechanism to compensate for the lower photosynthetic rate under shade (Wong, 1982). In contrast, Gaussoin et al. (1988) and Bunnell et al. (2005) discovered that bermudagrass had significant reduction in Chl in response to shade treatment. The present study suggests bermudagrasses may initially increase Chl in response to acute shade, but Chl ultimately declines to reduced levels as shade remains. Surprisingly, the Chl for other cultivars was not sensitive to irradiance level, suggesting shade severity was not sufficient to induce a response.

Clipping Yield and Leaf Elongation Rate

Barriors et al. (1984) stated that CY of warm-season turfgrasses decreases with decreasing light. This differs from results of the present study wherein CY generally increased under shade -

although after an initial decline. To some extent, this can be explained by the increased LER and the short duration of the experiment. In a prior study, turfgrass LER was 35% higher under 65% shade treatment compared with a non-shaded condition (Huylenbroeck and Bockstaele, 2001). The increased LER in this and other studies is likely due to increased endogenous gibberellin (GA1) concentration which can promote stem elongation in turfgrass species (Tan and Qian, 2003).

Comparative Water Use (ET)

Feldhake et al. (1982) demonstrated that the ET rates of turfgrass increases linearly with solar radiation. Further, ET can be affected species and cultivar (Biran et al., 1981; Zhang et al., 2013). In this research, all shaded pots had lower water use than non-shaded pots, illustrating that reduced light intensity will decrease plants water use. Further, the study illustrated that cool-season grasses have higher ET rates than warm-season grasses as has been commonly reported (Biran et al., 1981). Interestingly, the ET rate for the cool-season grass (Falcon IV) was apparently less affected by shade in comparison to the warm-season grasses. Whether the apparent insensitivity of cool-season turfgrass ET to irradiance is due to unusually large ET rates in shade or unusually low ET rates in the non-shaded treatment is uncertain.

In addition to reduction in available energy, ET may have been reduced by shade-induced changes in physiological, morphological, anatomical properties of the plants. Sills and Carrow (1983) reported that the lower ET rate under shade could be due to reduced biomass production and more vertical growth habit. It has also been suggested that the ET rate differences among turfgrasses were related to LA, SLA, and LER (Kim and Beard, 1988). In the present study, these variables did not provide consistent influence over turfgrass ET rates. The author speculates that the contribution of these variables to ET may have been muted by the controlled environment of the greenhouse.

This experiment contributed to understanding of water use rates of turfgrasses under shaded conditions. However, plant water requirements are also affected by drought resistance, and how shade may influence drought resistance remains unknown. Future research to understand the effect of shade on drought resistance of turfgrass varying in shade tolerance is needed. Further, these results were obtained under greenhouse conditions using artificial shade, and the findings should be validated under field conditions.

Conclusion

Falcon IV had the highest ET rate under both non-shaded and shaded environments but the relative magnitude of its difference with warm-season turfgrass varied with environment. These findings suggest crop coefficient-based irrigation scheduling in shaded environments may vary with shade tolerance of the turfgrass species. Changes in canopy morphology did not demonstrate substantial influence on ET rates suggesting physiological or other mechanisms are more important for plant response to shade.

Table 1. The daily light integral (DLI) during the experiment period.

Month	Shade†	Non-shaded‡	% Shade §
	mol m^{-2} d^{-1}	mol m^{-2} d^{-1}	-
September	7.63	25.03	0.70
October	4.97	11.12	0.55

† Shade treatment was defined as ambient greenhouse conditions plus a 55% shade fabric.

‡ Non-shaded treatment was defined as ambient greenhouse conditions plus supplemental high-pressure sodium lights.

§ Percentage Shade (% shade) was defined as the DLI of shaded environment divided by the DLI for non-shaded environment.

Table 2. Analysis of variance for average ET, weekly ET, and weekly ET ratio.

Source	Average ET †	Weekly ET‡	Weekly ET Ratio §
Cultivar (C)	***	***	***
Shade (S)	***	***	-
Time (T)	-	***	***
C x S	ns	ns	-
C x T	-	***	ns
S x T	-	***	-
C x S x T	-	*	-

†Average ET was calculated as the mean daily ET rate across all measurement dates (N=64).

‡ Weekly ET was calculated as the average ET across each week (N=512).

§ Weekly ET Ratio was calculated as the fraction of ET for shaded versus non-shaded treatments (N=256).

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level. ns, not significant at the 0.05 probability level.

Table 3. Average ET rate as affected by cultivar and shade treatment.

Treatment	Falcon IV	Meyer	El Toro	Latitude 36
	——mm d^{-1}——			
Non-shaded	4.9aA †	2.9aB	3.1aB	3.1aB
Shade	4.3bA	2.3bB	2.4bB	2.2bB

† Means followed by the same upper case letter within a row and means followed by the same lower case letter within a column are not significantly different ($p \leq 0.05$).

Table 4. Weekly ET as affected by cultivar and time interaction.

Treatment	Cultivar	1WAT†	2WAT	3WAT	4WAT	5WAT	6WAT	7WAT	8WAT
		mm d^{-1}							
Non-shaded	Falcon IV	5.9a‡	4.7a	4.4a	4.9a	4.0a	4.9a	5.0a	5.5a
	Meyer	3.6d	3.1d	2.8cd	3.0cd	2.4d	3.0cd	2.7d	2.8d
	El Toro	3.7d	3.3cd	2.9c	3.3c	2.5c	3.2c	3.0c	3.1c
	Latitude 36	4.0c	3.4c	2.9c	3.1c	2.3d	2.9e	3.0c	3.4c
Shade	Falcon IV	4.6b	4.3b	3.8b	4.5b	3.6b	4.5b	4.2b	4.9b
	Meyer	2.7ef	2.3f	2.1f	2.2f	1.8f	2.3f	2.2f	2.4e
	El Toro	2.9e	2.5e	2.2e	2.4e	1.9e	2.4f	2.3e	2.4e
	Latitude 36	2.7ef	2.3f	2.2e	2.2f	2.2g	2.2g	2.1f	2.5e

† Week after treatment (WAT). 1 WAT, 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively.

‡ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 5. Weekly ET ratio as affected by the cultivar by time interaction.

Cultivar	1WAT†	2WAT	3WAT	4WAT	5WAT	6WAT	7WAT	8WAT	Average‡
	—— % § ——								
Falcon IV	73.1a§	93.5a	91.7a	85.4a	91.5a	92.2a	88.2a	89.3a	88.1a
Meyer	69.8a	87.6a	71.1b	75.8a	72.7b	77.5b	80.3a	84.3a	77.4b
El Toro	74.1a	91.8a	70.4b	77.6a	76.4b	74.1b	78.8a	76.0b	77.4b
Latitude 36	63.2a	82.4a	71.8b	71.1a	74.7b	75.4b	70.7a	73.1b	72.8b

† Week after treatment (WAT). 1 WAT, 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively. ET ratio over the whole experiment, where only cultivar effect was considered.

‡ ET ratio is defined as the ET of shaded pots divided by the ET of non-shaded pots times 100.

§ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 6. Analysis of variance for specific leaf area (SLA), leaf angle (LA), chlorophyll content (Chl), leaf elongation rate (LER), and clipping yield (CY).

Source	SLA	LA	Chl	LER	CY
Cultivar (C)	***	***	***	***	***
Shade (S)	***	***	***	***	***
Time (T)	**	**	***	***	***
C x S	ns	**	**	*	**
C x T	**	ns	**	***	***
S x T	ns	***	**	***	***
C x S x T	***	ns	***	ns	**

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level. ns, not significant at the 0.05 probability level.

Table 7. Specific leaf area as affected by the cultivar by shade by time interaction.

Treatment	Cultivar	1 WAT †	4 WAT	8 WAT
			$m^2\ kg^{-1}$	
Non-shaded	Falcon IV	26.6b‡	31.3b	22.4bc
	Meyer	17.4cd	18.2bc	16.9cd
	El Toro	17.7c	16.0d	15.6d
	Latitude 36	31.1b	33.5b	29.4b
Shade	Falcon IV	34.3a	32.4b	36.9a
	Meyer	23.8bc	25.2bc	23.0bc
	El Toro	17.7c	16.3cd	19.4bcd
	Latitude 36	40.0a	46.4a	36.9a

† Week after treatment (WAT). 1 WAT, 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively.

‡ Means followed by the same letter in a given column are not significantly different ($p < 0.05$).

Table 8. Leaf angle as affected by the cultivar by shade by time interaction.

Treatment	Cultivar	1 WAT †	4 WAT	8 WAT
		——degrees——		
Non-shaded	Falcon IV	53.5a‡	48.8b	50.8bc
	Meyer	39.3bc	30.6d	34.2d
	El Toro	43.5b	35.1c	35.3d
	Latitude 36	51.7ab	46.7b	49.9bc
Shade	Falcon IV	53.6a	55.9a	57.3ab
	Meyer	37.2cd	48.4b	52.9b
	El Toro	36.2cd	36.5c	42.1c
	Latitude 36	50.2ab	51.1ab	66.0a

† Week after treatment (WAT). 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively.

‡ Means followed by the same letter in a given column are not significantly different ($p < 0.05$).

Table 9. Chlorophyll content as affected by the cultivar by shade by time interaction.

Treatment	Cultivar	1 WAT †	4 WAT	8 WAT
		——mg m^{-2}——		
Non-shaded	Falcon IV	440.3bc‡	354.3cd	366.7cd
	Meyer	472.0b	395.8b	395.4a
	El Toro	383.2cd	353.3cd	368.3bc
	Latitude 36	365.6d	391.7bc	393.7ab
Shade	Falcon IV	427.6bc	353.7cd	379.9b
	Meyer	485.8ab	395.3b	391.7ab
	El Toro	419.3c	374.7c	393.3ab
	Latitude 36	520.8a	414.7a	366.8cd

† Week after treatment (WAT). 1 WAT, 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively. The means comparison is within each data collection week.
‡ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 10. Clipping yield as affected by the cultivar by shade by time interaction.

Treatment	Cultivar	1WAT†	2WAT	3WAT	4WAT	5WAT	6WAT	7WAT	8WAT
		———————g m^{-2} wk^{-1}———————							
Non-shaded	Falcon IV	13.6f‡	12.5de	10.8d	14.7d	14.7d	10.2e	18.1bc	7.9c
	Meyer	17.0e	15.3cd	11.3cd	15.3d	15.9d	10.8e	19.2b	6.2cd
	El Toro	24.9bc	17.0c	14.2c	19.8cd	17.6cd	15.9d	19.2b	7.4c
	Latitude 36	34.0a	36.2a	20.4a	20.9c	19.2c	18.7c	13.6d	6.2cd
Shade	Falcon IV	15.9ef	15.9cd	14.7c	20.9c	20.4c	15.9d	19.8b	10.2a
	Meyer	15.9ef	13.6d	10.8d	24.3bc	27.2a	24.9a	26.0a	8.5b
	El Toro	21.5d	17.6c	14.7c	28.3a	24.9b	21.5b	25.5a	9.1ab
	Latitude 36	28.9b	29.4b	17.6b	26.0ab	24.3b	18.7c	17.6bc	6.2cd

† Week after treatment (WAT). 1 WAT, 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively.

‡ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 11. Leaf elongation rate as affected by shade by time interaction.

Treatment	Cultivar	1 WAT †	4 WAT	8 WAT
		——mm d^{-1}——		
Non-shaded	Falcon IV	0.28cd‡	0.39bc	0.42bc
	Meyer	0.40bc	0.36c	0.35c
	El Toro	0.46b	0.36c	0.34c
	Latitude 36	0.11d	0.10d	0.10d
Shade	Falcon IV	0.53a	0.70a	0.73a
	Meyer	0.49b	0.60ab	0.63ab
	El Toro	0.54a	0.54b	0.55b
	Latitude 36	0.19cd	0.24cd	0.26cd

† Week after treatment (WAT). 1 WAT, 4 WAT, and 8 WAT mean after 1, 4, and 8 weeks' shade treatment, respectively.

‡ Means followed by the same letter in a given column are not significantly different ($p < 0.05$).

CHAPTER III

EFFECT OF REDUCED IRRADIANCE ON DROUGHT RESISTANCE OF FOUR TURFGRASSES

Abstract

Irrigation management of turfgrass in shade can be complicated by interactions between reduced evaporative demand, shade tolerance, and competition for soil water from tree roots. A greenhouse study was conducted to understand how shade influences the drought resistance of four turfgrasses. The turfgrasses used in this study were ‘Falcon IV’ tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.], ‘Latitude 36’ hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt Davy], and ‘Meyer’ and ‘El Toro’ zoysiagrass (*Zoysia japonica* Steud). Plants were established in 15-cm diameter lysimeters and subjected to two irradiance levels: shade (55% nominal shade fabric) and non-shade (ambient greenhouse conditions with supplemental lights). Within each irradiance level, plants were subjected to either well-watered conditions (daily replacement of evapotranspiration) or drought stress (no irrigation). Plants were assessed for leaf relative water content, visual leaf firing, water use rate, and dry root mass. The fraction of transpirable soil water (FTSW) was used to compare the break point where transpiration began to decline due to soil water stress. Transpiration began to decline at 48 to 53% of FTSW under the non-shaded environment. Shade had no effect on the transpiration break point for tall fescue, Meyer, or El Toro, while the break point was delayed

(was drier) for bermudagrass. Results suggest shade affects stomatal regulation of turfgrasses under declining soil water differently for shade tolerant species and shade sensitive species.

Introduction

Drought stress is one of the main factors that limits turfgrass growth and development (Huang, 1999; Yu et al., 2013; Su et al., 2013). Drought resistance is a term to describe plants' mechanisms to withstand the drying condition (drought). Drought resistance can be attributed to either drought tolerance, drought avoidance, or some combination of the two (Carrow, 1996; Touchette et al., 2007). Drought tolerance describes a plant's ability to maintain an adequate cell turgor under diminishing leaf hydration, whereas drought avoidance is associated with increased stomatal resistance, changes in leaf orientation, reductions in leaf area, and deep rooting (Huang, 1999; Touchette et al., 2007).

Huang and Fry (2000) defined turfgrass water use as the total amount of water required for plant growth and the water loss through evapotranspiration (ET). When the transpiration rate surpasses the plant's water uptake rate, wilting and desiccation can take place. During a soil drying process, plants can reduce stomatal conductance thereby slowing transpiration and sustaining cell turgor over time (Cathey et al., 2013). The relationship between transpiration and soil water content is characterized by a segmented linear function whereby the transpiration rate remains fairly constant under a range of soil moisture conditions (Allen et al., 1998). Eventually, the plant and soil water status reaches a critical threshold which induces a downward shift in transpiration. The ability of a plant to reduce its stomatal conductance under wetter soil conditions is thought to contribute to the potential drought resistance of the plant (Jiang and Huang, 2000).

Turfgrasses are often managed in areas of reduced irradiance (i.e., shade) which can have important effects on plant growth and development. Shade reduces the evaporative demand of the surface thereby serving as a drought avoidance mechanism of sorts. However, interception of rainfall from tree canopies and competition for soil moisture from tree roots can mitigate the potential benefit of shade on turfgrass water requirements. Thus, understanding how turfgrasses respond to drought stress under shaded conditions may have useful implications for water conservation of irrigated mixed-species landscapes.

Turf type tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] is a popular turfgrass in northern and transition zone of the United States and has excellent shade tolerance (Carrow, 1996). Bermudagrass [*Cynodon dactylon* (L). pers] is the most widely-used turfgrass species in tropical and subtropical regions of the country and is considered as having good drought resistance but poor shade tolerance (Etemadi et al. 2005; McCarty and Miller, 2002; Dunn and Diesburg, 2004). Zoysiagrass (*Zoysia japonica* Steud.) is well-adapted to the transition zone climate and has intermediate drought and shade tolerance in comparison to tall fescue and bermudagrass (Patton and Reicher, 2007). Understanding how shade interacts with drought for these species could contribute to a more sustainable turfgrass industry in the transition zone of United States.

The objective of this study was to compare the drought resistance of four turfgrasses under shade. My hypothesis was that shade will enhance turfgrass drought resistance under progressive soil drying similarly for each cultivar in the study.

Materials and Methods

The study was conducted at the Oklahoma State University Horticulture Research Greenhouses in Stillwater, OK (36.136043°N, -97.086767°W) from April through May 2018. Temperature in the greenhouse was maintained at a 30/20 °C (day/night) regime.

Four cultivars were included in this study: ‘El Toro’ and ‘Meyer’ zoysiagrass, ‘Latitude 36’ hybrid bermudagrass (*C. dactylon* × *C. transvaalensis*), and ‘Falcon IV’ tall fescue. All cultivars were planted in May 2017 in polyvinyl chloride (PVC) growth tubes (15 cm diameter and 36 cm long) filled with fritted clay (Turface MVP, Profile LLC., Buffalo Grove, IL) that had been sieved to a particle size ranging from 1 mm to 2 mm. Pre-plant fertilizer (6-2-0, Milorganite, Milwaukee, WI) was applied on the soil surface at 5 g N m^{-2}. Zoysiagrasses were established as washed sod. Bermudagrass was established from sprigs at the rate of 153 ml m^{-2} (Johnson, 1973). Tall fescue was seeded at a rate of 29 g m^{-2} pure live seed (Martin, 1995). Turf height was maintained by clipping weekly at 5 cm with scissors. A soluble complete fertilizer (Peter's 20-20-20, A.M. Leonard, Piqua, OH) was applied at a rate of 0.6 g N m^{-2} at two weeks after planting and subsequently every week during the establishment and experiment period. Preventative applications of chlorothalonil (Daconil Weatherstik, Syngenta, Basel, Switzerland) and bifenthrin (Up-Star Gold Insecticide, Seed Ranch, Odessa, FL) were applied every two weeks at label rates for control of *Rhizoctonia* spp. related diseases, bermudagrass mite (*Aceria cynodoniensis* Sayed), and zoysiagrass mite (*Eriophyes zoysiae*).

Experiment Design

The experiment was arranged as a completely randomized design with four replications. The treatments were arranged as a modified split plot with the whole main plot being the shade factor and each of the four cultivars and two irrigation levels arranged factorial within each irradiance level. The shade treatment was imposed using black woven shade fabric (American Plant Products, Oklahoma City, OK), nominally rated to reduce incoming radiation by 55%. A 3.0 x 1.5m section of the shade fabric was suspended approximately 1 m above the pots. Non-shaded pots received supplemental lighting from a high pressure sodium lamp and are hereafter referred to as the non-shaded treatment. Shade fabric was placed on the experiment group for 8 weeks prior to initiation of irrigation treatments and was only removed for data collection, mowing, or fertilization (about 7 to 8 hours per week).

There were two irrigation treatments included in this study: (i) well-watered (daily replacement of 100% ET), and (ii) dry-down (water withheld for the duration of the study). The day before initiating the dry-down treatment, all pots were trimmed and watered to saturation for an hour. After 24 hours of drainage, pots were weighed to determine the field capacity weight (W_{fc}).

Measurements

Photosynthetically active radiation (PAR) within each irradiance treatment was measured on a 30 min resolution using a quantum sensor (WatchDog 1000, Spectrum Technologies, Inc., Plainfield, IL). A daily light integral (DLI) was calculated as the sum of PAR reaching pots within a day.

After initial saturation and drainage to field capacity, pots were weighed daily at 1300 hr, and ET calculated as the difference in mass between days. A transpiration ratio (TR) was calculated as the ET of dry-down pots (ET_{dry}) divided by the ET of well-watered (ET_{ck}) pots. The study end point was defined as when TR reached 25%. The final weight (Wt_{final}) was recorded for each pot and used to calculate the total transpirable soil water (TTSW) as the difference between the Wt_{fc} and the Wt_{final} (Sadras and Milroy, 1996; Fuentealba et al., 2016; Zhang et al., 2017). In order to describe the relationship between TR and soil water status, the fraction of transpirable soil water (FTSW) was calculated as the difference between the daily pot weight (Wt_{daily}) and Wt_{final} divided by TTSW. FTSW represents the soil water status of each pot. In order to reduce noise, a normalized transpiration ratio (NTR) was calculated for each pot by dividing the TR by the average TR over the first few days (Fuentealba et al., 2016).

Leaf relative water content (RWC) was measured on the second fully expanded leaf from 10 randomly selected shoots per pot. Measurements were timed to occur when TR of half of the replicates for a given cultivar by irradiance treatment combination reached 100, 75, 45, and 25%. After sampling, leaves were weighed immediately to obtain a fresh weight (FW) and then placed in petri dishes filled with deionized water for four hours. Leaves were patted dry and reweighed to obtain a turgid weight (TW). The turgid leaves were oven-dried for 48 hours at 80 °C and re-weighed to obtain a dry weight (DW). Leaf RWC was calculated using the following equation:

$$\text{RWC} = 100 * \frac{(\text{FW}- \text{DW})}{(\text{TW}-\text{DW})}$$ (Jiang and Huang, 1999).

Normalized difference vegetation index (NDVI) was measured every other day using a spectral reflectance sensor (SRS, METER Group, Inc. USA). Visual estimates of leaf firing were collected daily following the National Turfgrass Evaluation Program (NTEP) guidelines using a 1 to 9 scale (1 = 100% leaf firing, and 9 = no leaf firing) (Morris and Shearman, 1998).

Root dry mass (RDM) was measured at the conclusion of the study. Roots were washed free of soil, then separated into three depths: 0 – 10, 10-20, and 20-30 cm. Roots were oven-dried for 48 hours at 80 °C and weighed.

Data Analysis

The response of NTR to decreasing FTSW was analyzed using a segment linear regression model (GraphPad Prism 2.01, Software, Inc., SanDiego, CA). A separate model was developed for each replication as well as a global model that was fit to the treatment means. The model was used to estimate a break point ($FTSW_{BP}$) parameter for each genotype. The break point was defined as the FTSW at which NTR started to decline, which may reflect the water use pattern and stomatal activity during soil drying process (Fuentealba et al., 2016). Measured and derived variables were analyzed using the GLIMMIX procedure (SAS Institute Inc., 2011). Tukey's HSD method was used to detect significant differences among treatments means at 0.05 probability level.

Leaf firing in response to declining soil moisture was not a good fit for the segment linear regression model. Therefore, a nonlinear regression analysis (IBM Corp, 2015) was used to predict leaf firing in response to FTSW. The data were fit to a logistic function having the following formula:

$$\text{LF} = \frac{9}{1 + (\frac{\text{FTSW}}{\text{midpoint}})^{\text{slope}}}$$

where midpoint is defined as the point where 50% of leaf firing had occurred, slope was a fitting parameter, and 9 was the maximum value for LF. Data were compared for midpoint, slope, and the FTSW required to reach a LF rating of 6.

Results

Light Condition

The average DLI of non-shaded pots was 25.96 mol $m^{-2}d^{-1}$, and the average DLI of shade pots was 11.34 mol $m^{-2}d^{-1}$. Light was reduced 49% in April and 62% in May by the shade treatment.

Transpiration Response during Soil Drying

The two segment linear regression model provided good fit for the relationship between NTR and FTSW resulting in R^2 values ranging from 0.92 to 0.98 for the global model (Table 12). Shade increased the number of days to reach the $FTSW_{BP}$, but the magnitude of this change varied among cultivars such that days to reach the breakpoint increased by 0.4, 1.9, 1.6, and 5.1 days for Falcon IV, Meyer, El Toro, and Latitude 36, respectively (Table 12, Figure 1-4). Under the non-shaded treatment, there was no effect of cultivar on the $FTSW_{BP}$. Shade similarly had no effect on this value with the exception of Latitude 36 for which $FTSW_{BP}$ decreased (soil became drier).

Leaf firing data were compared among treatment combinations at 100, 75, 45, and 25% TR (Table 13). Leaf firing was significantly affected by a shade by drought interaction at 75% TR. At TR 45% and TR 25%, LF was significantly affected by the three-way interaction. In general, Falcon IV incurred LF more quickly than the warm-season turfgrasses (Table 14). At 75% TR, shade reduced LF of Falcon IV compared to the non-shaded treatment, while other cultivars were unaffected by shade. At 45% TR, shade reduced LF of El Toro as compared to the non-shaded treatment, while other cultivars were unaffected by shade. At 25% TR, shade reduced LF of Latitude 36 compared to the non-shaded treatment while other cultivars were unaffected by shade. Shade increased the $FTSW_{LF6}$ (became drier) for each cultivar except Meyer (Table 15). Latitude 36 had the highest $FTSW_{LF6}$ for shade and non-shade conditions among all grasses. A similar pattern was evident in regards to the midpoint parameter of the nonlinear regression model, wherein shade increased or had no effect on the midpoint for each cultivar except Meyer.

Sampling timing for relative water content varied with treatment combination and is reported in Table 16. The initial measurement of leaf RWC at 100% TR resulted in a significant cultivar main effect (Table 17). At 75% TR, data demonstrated a significant interaction between cultivar and shade. At this point in the dry-down, shade had increased the RWC of Falcon IV but not other cultivars (Table 18). At the 45% and 25% TR thresholds, the three-way interaction (cultivar by shade by drought) was significant. At 45% TR, the main effect of shade increased RWC for each cultivar, although only Latitude 36 showed a similar response at 25% TR.

The cultivar by shade interaction significantly affected NDVI at 75%, 45%, and 25% TR thresholds (Table 19). At 75% TR, shade had little effect on cultivar NDVI with the exception of decreasing the NDVI of El Toro compared to non-shaded conditions (Table 20). At 45% TR, shade increased NDVI for Meyer and Latitude 36 but decreased it for Falcon IV. At 25% TR, shade increased the NDVI for each warm-season turfgrass but had no effect on Falcon IV.

The analysis of dry root mass data resulted in a significant cultivar main effect for the total DRM and DRM at each soil depth. Shade had significant main effect on the total DRM but not within each depth (Table 21). The total DRM varied with cultivar in the following order: Falcon IV (10.76g) > Latitude 36 (9.28g) > El Toro (7.89g) > Meyer (5.59g) (Table 22). Shade reduced the total DRM for all grasses. The shaded average DRM over all non-shaded cultivars is greater than shaded cultivars by 1.81 g (Table 23). Latitude 36, Meyer, and El Toro had over half of their respective DRM at the 0-10 cm soil depth. At the 10-20 cm soil depth, the DRM percentage of Falcon IV (29%) was higher than the other three cultivars, followed by El Toro, Meyer, and Latitude 36 (Table 23). At the bottom soil layer, tall fescue had the highest percentage (23%)

compared to the other three cultivars, and Latitude 36 had the lowest percentage in the bottom soil layer (11%).

Discussion

Breakpoint Responses

Bermudagrass, tall fescue, and zoysiagrass have been found to have different drought resistance (Huang et al., 1997). The results from this study provide evidence that shade is a significant factor that can impact grasses' drought resistance.

Savermutlu et al. (2011) reported that bermudagrass possessed superior drought resistance than zoysiagrass and tall fescue. This experiment found similar results with Latitude 36 having drought resistance than the other three grasses despite not being considered an exceptionally drought resistant cultivar within the species.

The faster use of soil water by Falcon IV as compared to the other three grasses is not surprising since cool-season turfgrasses have inherently higher water use rates (Biran et al., 1981). Further, it is thought that the more prolific root system of tall fescue provided less resistance to water movement from soil into the plant (Beard, 1973; Biran et al., 1981). Carrow (1996) reported that tall fescue is associated with higher root density and greater rooting depth. Qian et al. (1996a) reported tall fescue had 39% to 140% greater root length than warm-season turfgrasses, followed by bermudagrass and zoysiagrass. This trait seems to be particularly important for extracting water from deeper in the profile. For example, the high RDM at the 20-30 cm depth for Falcon IV likely contributed to sustained extraction as compared to Meyer which had the lowest RDM at the 20-30 cm depth.

Leaf Firing Response

The drought resistance of turfgrasses is commonly evaluated by their visual ratings. A previous study reported that zoysiagrass had little firing when FTSW was low (Cathey et al., 2011). This is comparable to what this experiment has found for zoysiagrasses in non-shaded at a certain FTSW point. Different from earlier studies, the shaded grasses demonstrated various response to drought in terms of leaf firing, which may result in each grasses' response to shade.

Conclusion

This study provided information about four commonly used turfgrasses and how they differ in their response to soil drying process under shaded conditions. Shade in the presence of increasing drought stress affected the transpiration rate of the shade-sensitive genotype (bermudagrass) differently than the shade tolerant genotypes. Results will contribute to our understanding of turfgrass water use and irrigation water requirements in shaded environments.

Table 12. Transpiration curve parameters as affected by shade and cultivar.

Cultivar	Shade	BP †	$FTSW_{BP}$ ‡	EP	R^2
		day		day	
Falcon IV	Non-shade	3.6d§	0.48ab	10	0.93
	Shade	4.1d	0.58a	18	0.92
Meyer	Non-shade	5.6bcd	0.48ab	18	0.97
	Shade	7.5b	0.54a	28	0.98
El Toro	Non-shade	4.7cd	0.53a	18	0.97
	Shade	6.3bc	0.52a	23	0.92
Latitude 36	Non-shade	5.4cd	0.53a	20	0.96
	Shade	10.5a	0.34b	23	0.92
Cultivar (C)		***	*		
Shade (S)		***	ns		
C x S		***	***		

† BP, days at break point when transpiration started to decline.

‡ $FTSW_{BP}$, total transpirable soil water at the break point.

§ Means followed by the same letter in a given column are not significantly different ($p < 0.05$).

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level, ns, not significant at the 0.05 probability level.

Table 13. The analysis of variance for leaf firing (LF) at transpiration rate (TR) 100%, 75%, 45%, and 25% for all pots.

Source	TR 100% †	TR 75%	TR 45%	TR 25%
Cultivar (C)	ns	ns	***	***
Shade (S)	ns	***	ns	ns
Drought (D)	ns	***	***	***
C x S	ns	ns	*	***
C x D	ns	ns	***	***
S x D	ns	***	ns	ns
C x S x D	ns	ns	*	***

† LF, leaf firing at transpiration rate 100%, 75%, 45%, and 25%, respectively.

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level, ns, not significant at the 0.05 probability level.

Table 14. The means table for leaf firing at 100%, 75%, 45%, and 25% transpiration levels for all pots under drought stress.

Cultivar	Shade	TR 100%	TR 75%	TR 45%	TR 25%
Falcon IV	Non-shade	9.0a†	8.3b	5.0e	3.0b
	Shade	9.0a	9.0a	5.3d	2.3c
Meyer	Non-shade	9.0a	9.0a	7.3b	3.8a
	Shade	9.0a	9.0a	6.5c	3.8a
El Toro	Non-shade	9.0a	8.5ab	6.5c	3.8a
	Shade	9.0a	9.0a	8.0a	3.5ab
Latitude 36	Non-shade	9.0a	8.5ab	7.8a	2.3c
	Shade	9.0a	9.0a	8.0a	4.0a

† Means followed by the same letter in a given column are not significantly different ($p < 0.05$).

Table 15. Non-linear regression analysis for leaf firing (LF) in response to the depleting fraction of transpirable soil water (FTSW).

Cultivar	Shade	Midpoint†	Slope‡	R^2	FTWS $_{LF6}$§
Falcon IV	Non-shade	0.77±0.02¶	5.99±0.95	0.94	0.69
	Shade	0.88±0.03	4.23±0.85	0.84	0.75
Meyer	Non-shade	0.96±0.02	6.84±0.99	0.92	0.87
	Shade	0.87±0.02	4.84±0.68	0.85	0.75
El Toro	Non-shade	0.93±0.02	5.55±0.93	0.89	0.82
	Shade	0.94±0.01	13.24±1.36	0.95	0.89
Latitude 36	Non-shade	0.91±0.01	8.48±1.43	0.87	0.84
	Shade	0.97±0.01	12.75±1.56	0.93	0.91

† Midpoint was a fitted parameter indicating the point where 50% of the leaf firing had occurred.

‡ Slope was a fitted parameter indicating the leaf firing rate.

§ $FTSW_{LF6}$, is the depleted fraction of transpirable soil water at leaf firing = 6.

¶ ± Standard error with 95% confidence interval.

Table 16. Relative water content (RWC) sampling time and soil moisture content on the sampling time.

Cultivar	Shade	Days After Soil Drying ($FTSW_{RWC}$) †			
		RWC 1‡	RWC 2	RWC 3	RWC 4
Falcon IV	Non-shade	0 (0.85)	4 (0.44)	7 (0.20)	10 (0.03)
	Shade	0 (0.89)	4 (0.69)	10 (0.17)	18 (0.02)
Meyer	Non-shade	0 (0.89)	4 (0.61)	10 (0.18)	18 (0.02)
	Shade	0 (0.93)	4 (0.74)	18 (0.20)	28 (0.02)
El Toro	Non-shade	0 (0.89)	7 (0.43)	11 (0.14)	18 (0.02)
	Shade	0 (0.91)	6 (0.56)	13 (0.22)	23 (0.02)
Latitude36	Non-shade	0 (0.90)	7 (0.42)	11 (0.20)	20 (0.01)
	Shade	0 (0.92)	6 (0.61)	13 (0.27)	23 (0.02)

† $FTSW_{RWC}$, soil moisture that is available for transpiration on RWC sampling day for four transpiration ratio points (100%, 75%, 45%, and 25%).

‡ RWC1 is the relative water content at 100% transpiration rate (TR) level for all grass, RWC2 is relative water content at 75% TR level; RWC3 is relative water content at 45% TR level; RWC4 is relative water content at 25% TR level.

Table 17. The analysis of variance for relative water content (RWC) at 100%, 75%, 45%, and 25% TR levels for all grasses.

Source	TR† 100%	TR 75%	TR 45%	TR 25%
Cultivar (C)	*	**	***	***
Shade (S)	ns	**	***	ns
Drought (D)	ns	***	***	***
C x S	ns	*	*	ns
C x D	ns	ns	**	***
S x D	ns	ns	ns	ns
C x S x D	ns	ns	***	*

† TR, transpiration ratio at 100%, 75%, 45%, and 25%.

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level, ns, not significant at the 0.05 probability level.

Table 18. The effect of the cultivar by shade interaction on leaf relative water content at 100%, 75%, 45%, and 25% transpiration ratio (TR) thresholds.

Cultivar	Shade	TR‡ 100%	TR 75%	TR 45%	TR 25%
			———— $g\ g^{-1}$ ————		
Falcon IV	Non-shade	0.84ab†	0.77c	0.69b	0.55c
	Shade	0.92a	0.88a	0.60c	0.50c
Meyer	Non-shade	0.86a	0.88a	0.69b	0.69ab
	Shade	0.92a	0.90a	0.86a	0.71a
El Toro	Non-shade	0.86a	0.85a	0.77b	0.69ab
	Shade	0.91a	0.89a	0.87a	0.77a
Latitude 36	Non-shade	0.84ab	0.82ab	0.72b	0.55c
	Shade	0.82b	0.81b	0.81a	0.73a

† Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 19. The analysis of variance for normalized vegetation difference index (NDVI) at 100%, 75%, 45%, and 25% transpiration ratio (TR) thresholds.

Source	TR† 100%	TR 75%	TR 45%	TR 25%
Cultivar (C)	ns	***	***	***
Shade (S)	ns	***	***	***
Drought (D)	ns	***	***	***
C x S	ns	***	***	***
C x D	ns	*	***	*
S x D	ns	*	***	***
C x S x D	ns	ns	***	*

† TR, transpiration ratio at 100%, 75%, 45%, and 25%.

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level, ns, not significant at the 0.05 probability level.

Table 20. The effect of cultivar by shade interaction on normalized vegetation difference index (NDVI) of dry-down treatments at 100%, 75%, 45%, and 25% transpiration ratio (TR) thresholds.

Cultivar	Shade	NDVI †			
		TR[‡] 100%	TR 75%	TR 45%	TR 25%
Falcon IV	Non-shade	0.81a[§]	0.79a	0.76a	0.63bc
	Shade	0.82a	0.76ab	0.72bc	0.68ab
Meyer	Non-shade	0.81a	0.77ab	0.67cd	0.59c
	Shade	0.83a	0.71b	0.75ab	0.72a
El Toro	Non-shade	0.81a	0.79a	0.64d	0.58c
	Shade	0.86a	0.71b	0.68cd	0.69ab
Latitude 36	Non-shade	0.83a	0.71b	0.57e	0.51d
	Shade	0.82a	0.72b	070cd	0.68ab

† NDVI, normalized vegetation difference index, at 100%, 75%, 45%, and 25% transpiration rate level for all grass.

‡ 0 means non-shaded condition or well-watered condition, 1 means shade condition or soil drying process.

§ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 21. The analysis of variance for dry root mass (DRM) at selected soil depths.

Source	0~30cm†	0~10cm	10~20cm	20~30cm
Cultivar (C)	***	***	**	***
Shade (S)	***	ns	ns	ns
Drought (D)	ns	ns	ns	ns
C x S	ns	ns	ns	ns
C x D	ns	ns	ns	ns
S x D	ns	ns	ns	ns
C x S x D	ns	ns	ns	ns

† Soil profile depths used to extract root samples.

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level, ns, not significant at the 0.05 probability level.

Table 22. The effect of cultivar main effect on dry root mass (DRM) at 0~10cm, 10~20cm, 20~30cm, and 0~30cm depths.

Cultivar	0~30cm†	0~10cm	10~20cm	20~30cm
	—— $g\ m^{-2}$ ——			
Falcon IV	609.2a‡	269.5b	184.0a	155.7a
Meyer	316.5d	172.7d	81.0c	62.8c
El Toro	446.1c	224.2c	129.7b	92.3b
Latitude 36	525.4b	344.2a	131.9b	49.3c

† Soil profile depths used to extract root samples.

‡ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

Table 23. The effect of the irradiance treatment main effect on dry root mass (DRM).

Treatment	DRM (0~30cm)
	g m^{-2}
Non-shade ‡	525.4a ‡
Shaded	422.9b

† Shade treatment was defined as ambient greenhouse conditions plus a 55% shade fabric. Non-shaded treatment was defined as ambient greenhouse conditions plus supplemental high-pressure sodium lights.

‡ Means followed by the same letter in a given column are not significantly different ($p \leq 0.05$).

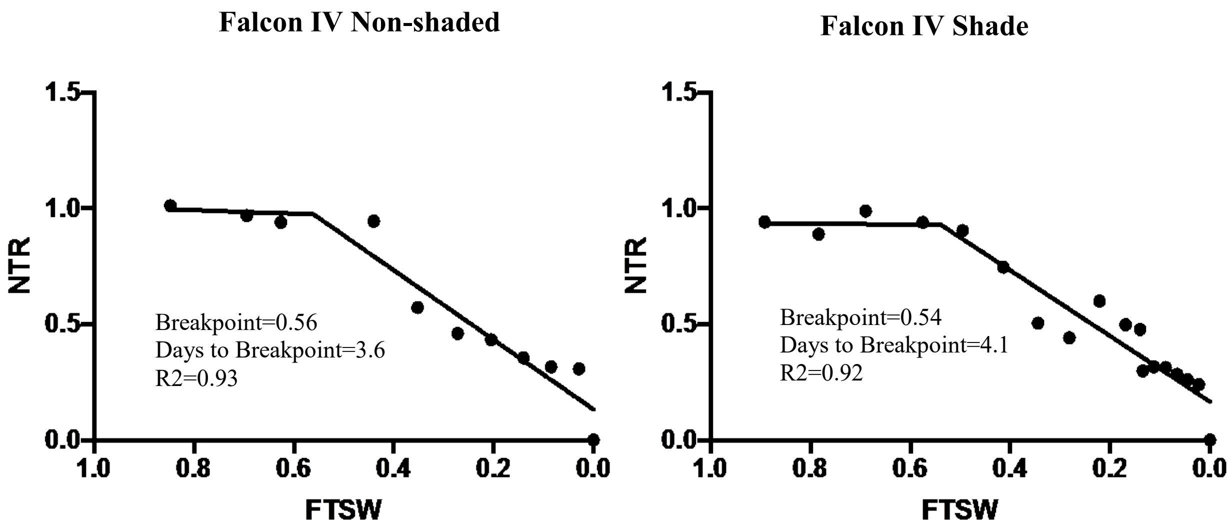

Figure 1. The segmented linear relationship between normalized transpiration ratio (NTR) and fraction of transpirable soil water (FTSW) during soil drying process for Falcon IV tall fescue under non-shaded (left) and shaded (right) conditions. Breakpoint refers to the point at which NTR starts to decline.

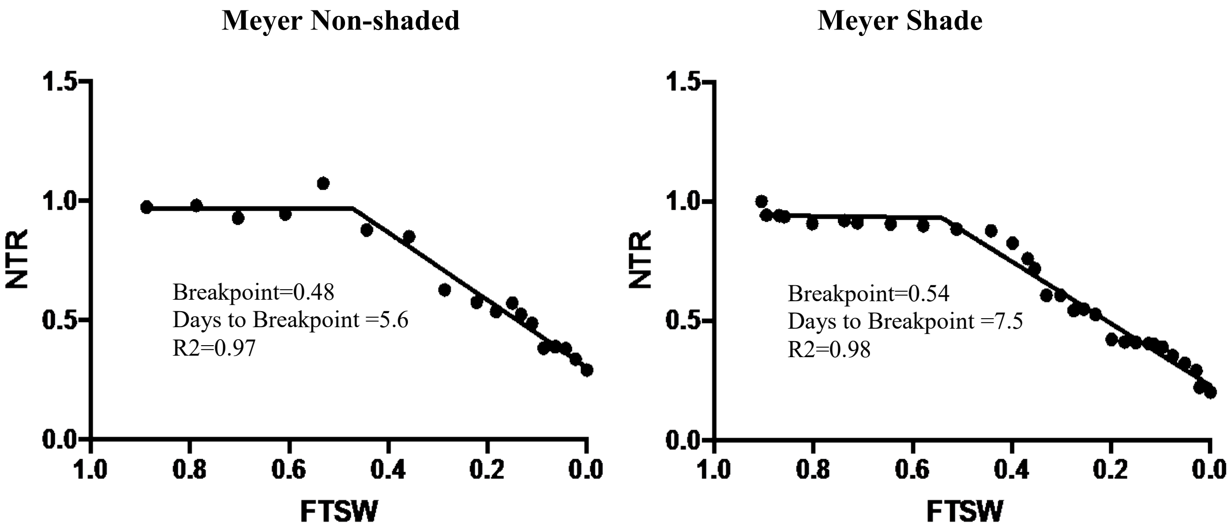

Figure 2. The segmented linear relationship between normalized transpiration ratio (NTR) and fraction of transpirable soil water (FTSW) during soil drying process for Meyer zoysiagrass under non-shaded (left) and shaded (right) conditions. Breakpoint refers to the point at which NTR starts to decline.

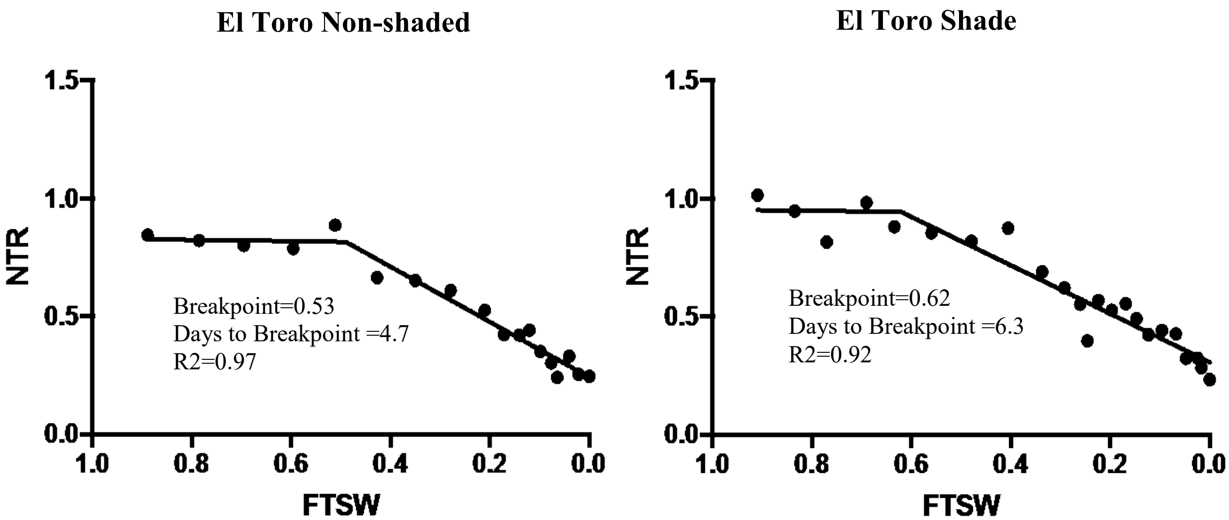

Figure 3. The segmented linear relationship between normalized transpiration ratio (NTR) and fraction of transpirable soil water (FTSW) during soil drying process for El Toro zoysiagrass under non-shaded (left) and shaded (right) conditions. Breakpoint refers to the point at which NTR starts to decline.

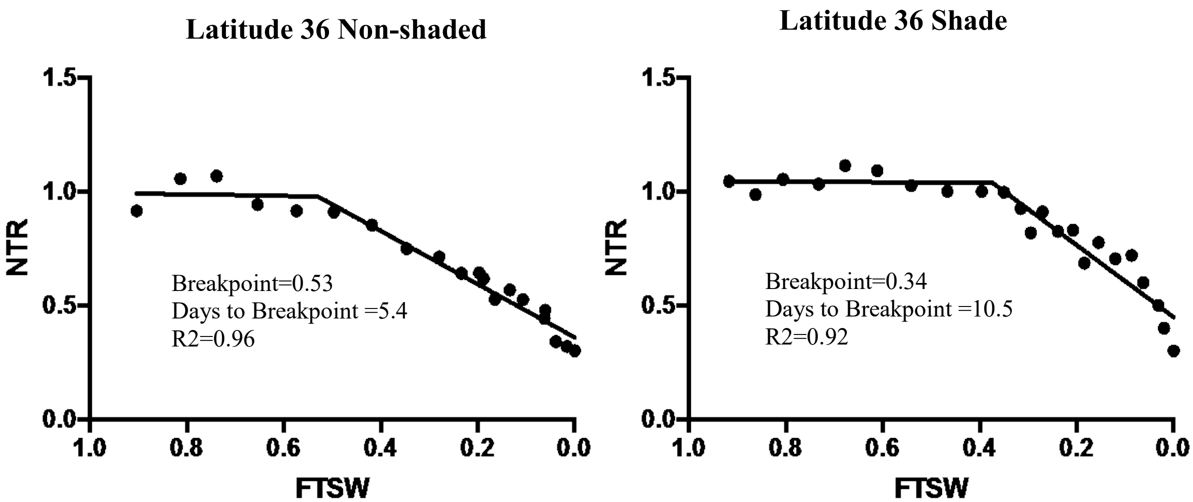

Figure 4. The segmented linear relationship between normalized transpiration ratio (NTR) and fraction of transpirable soil water (FTSW) during soil drying process for Latitude 36 bermudagrass under non-shaded (left) and shaded (right) conditions. Breakpoint refers to the point at which NTR starts to decline.

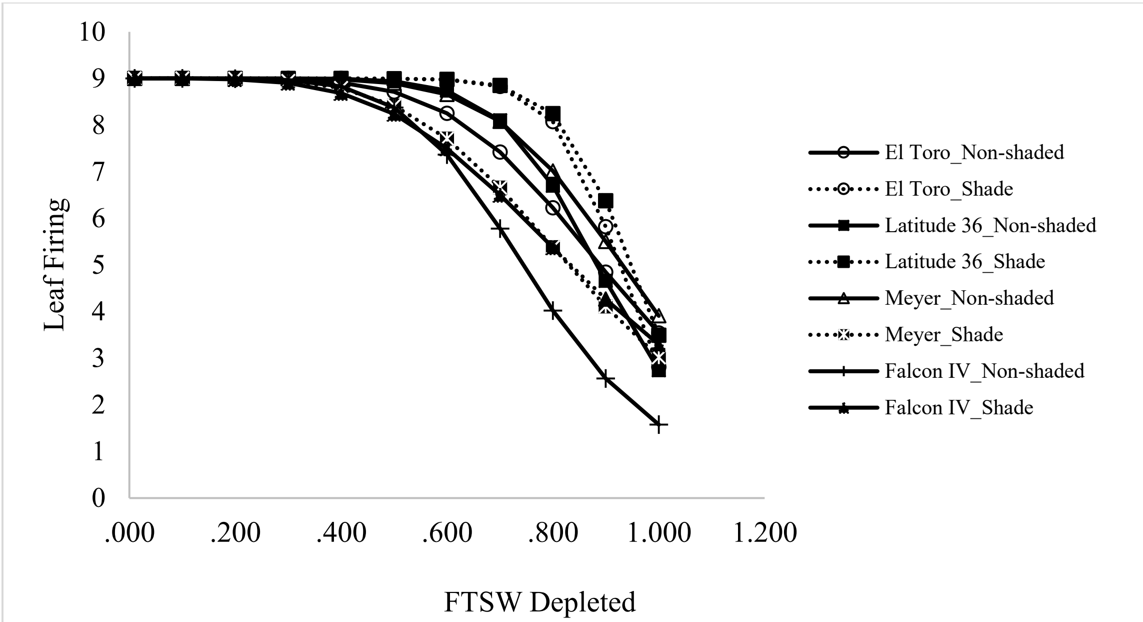

Figure 5. The fitted change in leaf firing (LF) with depleting fraction of transpirable soil water (FTSW). Leaf firing was rated visually on a scale of 1-9 (9 = no leaf firing).

CHAPTER IV

PERFORMANCE AND COMPARATIVE WATER USE OF ZOYSIAGRASS CULTIVARS UNDER SHADE

Abstract

The shaded environment poses a turfgrass irrigation management challenge due to microclimate effects on evapotranspiration (ET) and genotypic variation in response to reduced irradiance. In Oklahoma, bermudagrass (*Cynodon* spp.) represents the majority of turfgrass species used for residential lawns in non-shaded conditions. Zoysiagrass (*Zoysia* spp. Willd.) is a lesser-used turfgrass species that is well adapted to the transition zone through the central part of USA and has superior shade tolerance to bermudagrass. As such, zoysiagrasses serve as an alternative choice to bermudagrass – particularly in moderately shaded lawns. In order to understand the comparative water use rate of zoysiagrass and bermudagrass in a shaded environment, a field study was conducted using 11 zoysiagrass cultivars and one bermudagrass cultivar managed under artificial shade (73% of ambient). Soil moisture at five depths was measured every three to four days throughout the growing season. A water balance approach was used to estimate ET under shaded and non-shaded conditions and calculate a crop coefficient (K_c) and microclimate coefficient (K_{mc}). Normalized difference vegetation index and turf quality (TQ) were measured concurrently with soil moisture measurements. In the shaded treatment, 'Diamond' demonstrated

the highest TQ, while ‘Celebration’ bermudagrass showed the lowest TQ. ‘Meyer’ was among the highest water users (K_c = 0.31) among the zoysiagrasses in shade, although it was not statistically different from ‘Diamond’ (K_c = 0.29).

Introduction

The predicted deficit of fresh water resources is a major environmental issue for turfgrass industry in many regions of the country (Brown and Matlock, 2011; Pfister et al., 2009; Pimentel et al., 2004). The demand for potable water from industrial and domestic sectors is increasing with the growing population across the U.S., while readily available water resources are finite (Gleick, 1993; Maggioni, 2015; Simonovic and Fahmy, 1999). Efficient management of potable water resources is critical to ensuring continued growth of metropolitan areas (Aitken et al., 1994). Water used for irrigation residential lawns is a significant component of the annual water budget of most cities, particularly those in arid and semi-arid climates (Bijoor et al., 2014; Bruvold and Smith, 1988; Endter-Wada et al., 2008). Proper selection and management of turfgrasses in urban landscapes can contribute to substantial water savings without sacrificing the beneficial properties of turfgrasses (Bormann et al., 2001; Ferguson, 1987). Shade is a multi-faceted phenomenon for the turfgrass ecosystem that can influence the atmospheric, edaphic, and plant systems. The shaded environment is characterized by changes in energy flux, temperature, and other microclimatic conditions. Turfgrasses have varying levels of tolerance to reduced light quantity or quality, and often shade involves the presence of tree root competition. These factors create a complex environment that can be difficult to manage.

Plant water use is defined as the total amount of water required for turfgrass growth plus the quantity lost by transpiration from the plant and evaporation from the soil surface (Beard and Weyl, 1973). Evapotranspiration (ET) is a combined loss of water simultaneously from transpiration and plant and soil surfaces. Turfgrass ET rates can vary within and across species (Allen, et al., 2005; Romero and Dukes, 2016).

Plant ET rates are strongly influenced by atmospheric conditions such as the vapor pressure deficit and solar radiation (Allen et al., 2005). Reference evapotranspiration (ET_o) is an estimate of the ET from an idealized reference crop based on the micrometeorological properties of a location. The ET_o can be adjusted using crop coefficients (K_c) to estimate a particular crop ET rate (Carrow, 1995; Brown et al., 2001; McCready et al., 2009). Factors that can impact turfgrass K_c's include soil moisture stress, plant canopy characteristics, plant growth rates, and season (Allen et al., 2005; Carrow, 1985). Brown et al. (2001) reported that mowing height, fertility, and irrigation frequency can also influence crop coefficients. Warm-season turfgrass is commonly reported to have a K_c ranging from 0.6 to 0.7 (Carrow, 1995).

Most K_c's have been developed for non-shaded environments with the assumption of similar micrometeorological conditions between the irrigated field of interest and the weather station site used to calculate ET_o. The typical home lawn rarely meets this assumption, and a better understanding of how K_c's should be adjusted for a shaded landscape is warranted. Feldhake et al (1983) reported a linear relationship between solar radiation and ET rates of various turfgrasses. However, others have shown genotypic by environment interactions for water use rates of turfgrasses (Brown et al., 2001; Green et al., 1991). One possible explanation for this inconsistency in ET rates across varying environments is the potential for morphological and physiological changes to plant growth and development that can violate assumptions of the ET_o model (Bell et al., 2000; Dudeck and Peacock, 1992; Feldhake and Butler, 1983).

Z*oysia* spp. are well adapted to the transition zone of the United States and have good performance under moderate shade (Patton and Reicher, 2007). However, there can be substantial intra-specific variability in shade tolerance among zoysiagrasses (Sladek et al., 2009; Trappe et al., 2011; Wherley et al., 2011). Several new zoysiagrass cultivars have been released with promise for use in the transition zone, but knowledge of their performance in shaded environments is limited (Chandra et al., 2014; Chandra et al., 2017). A better understanding of turfgrass water use rates and turf performance under moderately shaded environments would contribute to development of best management practices for shaded lawns in the region.

Therefore, a field study was conducted to quantify the ET rates of 11 selected zoysiagrass cultivars and one bermudagrass cultivar under moderate shade. My hypotheses were 1) that cultivars would vary in their ET rates under shade and 2) that relative rankings of ET rates among cultivars would vary with irradiance level.

Materials and Methods

Location, Plant Materials, and Experiment Conditions

The experiment was conducted at the Oklahoma State University Turfgrass Research Center in Stillwater, OK (36.136043°N, -97.086767°W). The experiment was conducted from 11 June to 1 September 2018. The soil series for the research field was an Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustolls). Plots were established from sprigs in the previous year (May 2017) and demonstrated full coverage at the time of the study. The size for each plot is 1.8 m x 1.8m.

There were 11 zoysiagrass cultivars included in this field study: 'Zeon' (*Z. matrella*), 'Innovation' (*Z. matrella* × *Z. japonica*), 'Meyer' (*Z. japonica*), 'Chisolm' (*Z. japonica*), 'Y2' (*Z. japonica*), 'Zorro' (*Z. matrella*), 'El Toro' (*Z. japonica*), 'KSUZ1201' (*Z. japonica* × *Z. pacifica*), 'JaMur' (*Z. japonica*), 'Palisades' (*Z. japonica*), and 'Diamond' (*Z. matrella*). In addition, one bermudagrass (*C. dactylon* L. Pers. 'Celebration') was selected for this study to provide comparison against a relatively shade tolerant cultivar in an otherwise shade sensitive species (Chhetri et al., in review).

Turf height was maintained by mowing weekly at 5 cm with a self-propelled smart drive lawn mower (GCV160, Honda, Inc.). Fertilizer (TCS GrowStar 25-0-10, TurfCare, OH) was applied at a rate of 1.2 g N m^{-2} every two weeks. Preventative applications of chlorothalonil (Daconil

Weatherstik, Syngenta, Basel, Switzerland) and bifenthrin (Up-Star Gold Insecticide, Seed Ranch, Odessa, FL) were applied every two weeks for control of *Rhizoctonia* spp. related diseases, bermudagrass mite (*Aceria cynodoniensis* Sayed), and zoysiagrass mite (*Eriophyes zoysiae*).

Experiment Design

The experiment was arranged as a randomized complete block design with three replications. Each of the 12 cultivars were subjected to artificial shade imposed by black woven shade fabric (American Plant Products, Oklahoma City, OK), nominally rated to reduce incoming radiation by 73%. Three 6 x 8 m steel structures supported by pneumatic tires were used to maintain the fabric approximately 35 cm above the canopy similar to those used by Trappe et al. (2011). The structures can be easily moved off of plots to collect data or perform maintenance. Shade fabric was placed on the plots on 9 June 2018 and remained in place until 1 September 2018. Additional shade was provided by a row of pine trees along the western edge of the plots which provided shade across the plots beginning at approximately 1500 hours.

In addition to the shaded plots, six of the cultivars (Celebration, El Toro, Meyer, Diamond, Zeon, and Palisades) were also maintained under ambient light conditions. Shaded blocks and non-shaded blocks were randomized such that the six cultivars used under both conditions were arranged as a split-plot design with shade serving as the whole main plots.

Irrigation Scheduling

Irrigation was scheduled every two weeks to apply 89 mm over the course of the night by five irrigation cycles. When timely rainfall occurred, scheduled irrigation events were delayed to ensure sufficient rain/irrigation-free measurement intervals. Because of above-average normal rainfall, irrigation was only applied four times: June 11, July 12, July 25, and August 14 (Table 26).

Measurements

Data were collected every three or four days in the early morning to limit the amount of sunlight reaching shaded plots. On measurement days, plots were assessed for soil moisture content, visual turf quality (TQ), and normalized difference vegetation index (NDVI). Surface soil moisture content was measured using a handheld soil moisture meter (POGO, Stevens Water Monitoring Systems Inc., OR, USA) reaching a depth of 6 cm. Soil moisture was also measured at discrete depths (10, 20, 30, and 40 cm) using a handheld soil moisture meter (PR2, Delta-T Devices, Ltd, England) and previously installed access tubes. Turf quality was assessed on each data collection day following the methods of the National Turfgrass Evaluation Program taking into account turf density and uniformity (Morris and Shearman, 1998). A TQ score of 9 was considered outstanding turf, 1 was considered the poorest turf, and 6 or above was considered acceptable.

Photosynthetically active radiation (PAR) was measured on a 30 minute resolution using a quantum sensor (Spectrum Technologies, Inc., Aurora, IL). One sensor was placed under the shade cloth near the canopy height and another sensor was placed under ambient conditions. A daily light integral (DLI) was calculated as the cumulative PAR reaching plots within a day.

Water use rates were estimated from the soil moisture data using a water balance approach. The daily soil water depth was estimated by integrating data across the five sensors using an assumed rootzone depth of 45cm. Changes in soil moisture during rain-free days were considered to be due to ET. Crop coefficients (K_c) were calculated as the ratio of measured ET to Mesonet reference ET (Stillwater site) over the measurement interval. A separate K_{mc} was calculated for the shaded microclimate as the reduction in K_c from sun to shaded environment for each specific cultivar. In total, ET and K_c data were calculated for seven intervals across the months of June, July, and August (Figure 6).

In order to monitor the turf performance of each genotypes throughout the experiment period, a handheld crop reflectance meter (RapidSCAN CS-45, Holland Scientific, NE, USA) was used to measure NDVI. The instrument was held approximately 1 m from the canopy and applied to collect an average response for the entire plot.

Data Analysis

Turf performance data (i.e., visual ratings and NDVI) were averaged across dates within each month prior to analysis. Data were subjected to an analysis of variance (ANOVA) using a generalized linear model (IBM Corp, 2015). Data were analyzed first for all twelve cultivars under shaded conditions alone with time, cultivar, and their interaction as the only fixed factors. Subsequently, data for the six cultivars represented under both shade and sun were analyzed using a different model which included shade and its interactions as additional factors. Means of each variable were separated using Fisher's protected least significant difference (LSD). A significance level of $p \leq 0.05$ was used for all statistical tests.

Results

Environmental Conditions

Shaded plots received about 23% of the total PAR reaching non-shaded plots (Table 25). The DLI of non-shaded plots ranged from 37.0 to 44.2 mol $m^{-2}d^{-1}$, and DLI of shaded plots ranged from 7.9 to 12.5 mol m^{-2} d^{-1}. The soil volumetric water content of shaded plots was higher on average than the non-shaded plots, particularly in the upper 20 cm (Figure 6).

Turf Performance and ET Rates under Shade

Each measured variable demonstrated a significant cultivar and time main effect, while the time by cultivar interaction was not significant (Table 26). Each zoysiagrass cultivar maintained an acceptable average TQ score of six or better under shade (Table 26). Diamond demonstrated the highest TQ and NDVI compared to other cultivars, while Celebration had the lowest TQ and NDVI. Zeon was also a good performing cultivar resulting in a higher TQ and NDVI than three and seven other cultivars, respectively. Innovation also demonstrated good performance in shade having a similar TQ and NDVI to Zeon.

Crop coefficients for shaded turfgrasses ranged from 0.18 for Celebration to 0.31 for Meyer (Table 26). The K_c and ET rate of Meyer was greater than all other cultivars except for Diamond, while the majority of the other zoysiagrass cultivars were similar to each other (Table 26).

Comparison of Shaded and Non-Shaded Turfgrasses

For the six selected cultivars, a three-way interaction of genotype by shade by month was significant for TQ, while NDVI was affected by a significant genotype by shade interaction (Table 27). Turf quality under the shaded environment declined each month, while the TQ of ambient plots remained constant (Table 28). No significant difference in NDVI was found among Diamond, Meyer, Palisades, and Zeon under shade.

A two-way interaction of cultivar and shade was significant for K_c and ET; therefore, data were pooled across date (Table 27). The K_c for each cultivar decreased from the ambient to shade condition with the K_c for shaded turf ranging from 24% to 42% of the K_c for ambient turf in Celebration and Meyer, respectively. The cultivar and time main effects were significant for K_{mc}, therefore means were pooled across date (Table 27). Bermudagrass demonstrated the lowest K_{mc} although this was not different from Zeon (Table 28).

Discussion

The shaded environment used in this study is artificial and not likely to simulate most shaded conditions in the real world. However, the findings contribute to our understanding of how plants adapt to their environment and can be used to guide future research in this field.

The soil moisture content at field capacity for a loam was reported by Datta et al. (2017) as 0.27 m^3 m^{-3}. In the present study, shaded plots stabilized around a soil moisture content of 0.36 m^3 m^{-3} suggesting a slightly higher than expected field capacity moisture content. This is likely due to variation in soil water holding capacity even within a soil textural class and proximity of the plots to a nearby water table (Cow Creek).

Green et al. (1991) conducted a three-year experiment studying the ET rates of 11 zoysiagrasses and found no significant difference among ET rates in their field study. However, the same report showed differences among cultivars when studied in a controlled environment. In the present study, there was little variation between cultivars under non-shaded conditions (high evaporative potential) but significant differences under shade (low evaporative potential). These findings contribute further evident suggesting microclimate can influence the relative transpiration rates of cultivars within a species and among species.

Carrow (1995) reported that the crop coefficient of Meyer was higher (0.81) than bermudagrass (0.67). Wherley et al (2015) reported the K_c for bermudagrass (0.66) to be similar to that of zoysiagrass (0.68). These K_c values are comparable to those reported in the present study for non-shaded conditions. Apparently the relative ranking of bermudagrass and zoysiagrass K_c's can vary with location suggesting a genotype by environment interaction or some other artifact of the specific cultivars used.

To the author's knowledge, this is the first direct measurement of a K_{mc} for turfgrasses. Previous work by Feldhake et al. (1983) suggested turfgrass ET rates should decrease linearly with diminishing solar radiation. Assuming measured reductions in PAR were equivalent to the reduction in total shortwave radiation, the expected K_{mc}'s should be approximately 0.33 (the mean reduction in PAR over the study period). In contrast, there was significant variability among cultivars suggesting a strict linear relationship with radiation may not be adequate to accurately describe ET in the shade for all turfgrasses.

Under shade, turfgrasses can demonstrate noticeable changes to growth and development including a reduced leaf width, reduced shoot density, reduced tillering, increased leaf length, longer internodes, and more vertical growth habit (McBee and Holt, 1966; Sladek, et al., 2009; Tegg and Lane, 2004). Managing warm-season turfgrasses in shade can be challenging, but zoysiagrasses have often shown good performance in moderately shaded environments (Sladek, et al., 2009). Our study is generally in agreement with these previous reports as each zoysiagrass cultivar maintained an acceptable annual mean turf quality under 10.9 mol m^{-2} d^{-1} light regime in summer. However, the clear decline in TQ with month suggests additional years of study will be needed to confirm the relative shade tolerance of these cultivars.

In regards to relative shade tolerance among cultivars, the present study agrees with the work of Qian and Engelke (1999) who identified Diamond as an exceptionally shade tolerant cultivar and Green (2008) who reported the minimum DLI of Diamond to be 11.3 mol m^{-2} d^{-1} in summer. In contrast, Wherley et al. (2011) reported that zoysiagrass cultivars 'Zorro', 'Royal', and 'Shadow Turf' were better performers under 89% shade than Zeon, Diamond, Meyer, and Palisades. 'Innovation', 'KSUZ1201', and 'Chisolm' are relatively new or experimental cultivars and limited information is known about their shade tolerance. Chandra et al. (2014) reported that Chisolm has higher TQ and establishment rate from vegetative plugs than Meyer under shade. Innovation and KSUZ1201 were reported to be fine-textured interspecific zoysiagrass hybrids having good TQ and better density than Meyer (Fry, 2016; Chandra et al., 2017). Our results suggest Innovation as having average to above-average shade tolerance compared to other cultivars used in this study. Differences in establishment timing (before or after shade treatment), shade source (trees versus fabric), or the distance between shade and turfgrass canopy may have contributed to the variation in published results.

Celebration has in several papers been shown to be one of the most shade tolerant bermudagrass cultivars (Baldwin et al., 2007; Bunnell et al., 2009; Chhetri et al., in review). According to Bunnell et al. (2005), Celebration demonstrated acceptable TQ when receiving 11.9 mol m^{-2} d^{-1} DLI from August to October. The light quantity in the present study was slightly less than this and results confirm it was insufficient to maintain acceptable TQ for Celebration.

Conclusion

This study provided information on a comparative water use rates of 11 different zoysiagrasses and one bermudagrass under shaded conditions. In general, K_{mc}'s used to estimate the effect of microclimate on ET can be assumed to be similar to reductions in PAR, although this may be affected by genotype.

Table 24. The effect of shade treatment on the daily light integral (DLI) during the experiment period.

DLI†	Shade‡	Non-shaded	% Shade§
	mol m^{-2} d^{-1}	mol m^{-2} d^{-1}	-
June	12.54	44.15	0.72
July	8.55	43.59	0.80
August	8.21	36.97	0.78

† DLI was measured on 15 min intervals using a quantum sensor and summed for each day before averaging within month.

‡ Shade was applied using a black fabric nominally rated to reduce light by 55%. Non-shaded was the conditions without any shade treatment.

§ % Shade was defined as the DLI of shaded condition over non-shaded condition.

Table 25. The analysis of variance and means of turf quality (TQ), normalized vegetation difference index (NDVI), crop coefficient (K_c), and ET of twelve warm-season turfgrasses under artificial shade.

Cultivar	TQ†	NDVI	K_c‡	ET	LER§
				mm d^{-1}	mm wk^{-1}
Celebration	5.5e¶	0.64g	0.18d	1.2e	18.13ef
Chisolm	6.3d	0.70f	0.24c	1.6bcd	38.25ab
Diamond	7.5a	0.82a	0.29ab	1.9ab	14.66f
El Toro	6.6c	0.70f	0.23c	1.5cd	29.76cd
JaMur	6.4cd	0.69f	0.23c	1.5cd	29.98cd
Innovation	6.8bc	0.74bc	0.22c	1.5d	31.48c
KSUZ1201	6.3d	0.71def	0.27bc	1.8bc	16.66ef
Meyer	7.0b	0.74bcd	0.31a	2.0a	33.11bc
Palisades	6.9bc	0.73bcd	0.27bc	1.7bcd	40.65a
Y2	6.3cd	0.71ef	0.25bc	1.7bcd	20.41ef
Zeon	6.8bc	0.76b	0.23c	1.5cd	31.00c
Zorro	6.4cd	0.73cde	0.24c	1.6cd	23.49de
Cultivar (C)	***‡	***	***	***	***
Time (T)	***	***	***	***	**
C x T	ns	ns	ns	ns	ns

† TQ, turf quality, was measured following the NETP guidance. 6 was referred as acceptable TQ, and 9 was regarded as excellent TQ.

‡ K_c, crop coefficient.

§ LER, leaf elongation rate was measured tree times in total and in different tree weeks.

¶ Means followed by the same letter in a given column are not significantly different (LSD 0.05).

*** Significant at the 0.0001 probability level. ** Significant at the 0.001 probability level. * Significant at the 0.05 probability level. ns means no significance. (Significance at alpha = 0.05).

Table 26. The analysis of variance of all factors and their interactions on turf quality (TQ) for the six cultivars.

Source	TQ[†]	NDVI	K_c[‡]	ET	K_{mc}[§]
Replication	*	ns	**	**	-
Cultivar (C)	***	***	ns	ns	***
Shade (S)	***	***	***	***	-
Time (T)	***	***	***	***	***
C * S	***	***	**	**	-
C * T	**	ns	ns	ns	ns
S * T	***	***	***	***	-
C * S * T	***	ns	ns	ns	-

† TQ, turf quality. NDVI, normalized vegetation difference index. K_c, crop coefficient. ET, plants water use rates.

‡ K_c, crop coefficient.

§ K_{mc}, microclimate coefficient, which is essentially the ratio of K_c from the shade to K_c from the sun.

*** Significant at the 0.0001 probability level. ** Significant at the 0.001 probability level. * Significant at the 0.05 probability level. ns means no significance. (Significance at alpha = 0.05).

Table 27. The mean values of turf quality (TQ) in June, July, and August; the averaged NDVI, Kc, and ET over experiment period.

Cultivar	Treatment	--------TQ†--------			NDVI	K_c‡	ET	LER	K_{mc}§
		June	July	August	-------- Average --------				
							mm d^{-1}	mm wk^{-1}	
Celebration	Non-shade	6.9ef¶	8.2bc	7.7b	0.761c	0.74a	4.8a	5.03e	0.29d
Diamond	Non-shade	8.4a	8.8ab	8.5a	0.827a	0.71a	4.6a	0f	0.42ab
El Toro	Non-shade	7.2de	8.3ab	8.9a	0.726e	0.73a	4.8a	16.27cd	0.36bc
Meyer	Non-shade	7.4cde	7.6d	7.1cd	0.721e	0.73a	4.8a	11.67d	0.45a
Palisades	Non-shade	8.1ab	8.8a	8.8a	0.769bc	0.75a	4.9a	13.16cd	0.39bc
Zeon	Non-shade	8.1ab	7.7cd	7.3bc	0.786b	0.76a	4.9a	13.64cd	0.33cd
Celebration	Shade	6.6f	5.5g	4.5h	0.643g	0.18d	1.2d	18.13c	-
Diamond	Shade	8.4a	7.3de	6.6de	0.823a	0.29bc	1.9bc	14.66cd	-
El Toro	Shade	7.5cd	6.8ef	5.5g	0.695f	0.23cd	1.5cd	29.76b	-
Meyer	Shade	7.7bcd	7.2de	6.1ef	0.736de	0.31b	2.0b	33.11b	-
Palisades	Shade	8.2ab	6.9ef	5.6fg	0.733de	0.27bc	1.7bc	40.65a	-
Zeon	Shade	7.9abc	6.6f	5.9fg	0.757cd	0.23cd	1.5c	31b	-

† TQ, turf quality, was measured following the NETP guidance. 6 was referred as acceptable TQ, and 9 was regarded as excellent TQ.

‡ K_c, crop coefficient.

§ K_{mc}, microclimate coefficient, which is essentially the ratio of K_c from the shade to K_c from the sun.

¶ Means followed by the same letter in a given column are not significantly different (LSD 0.05).

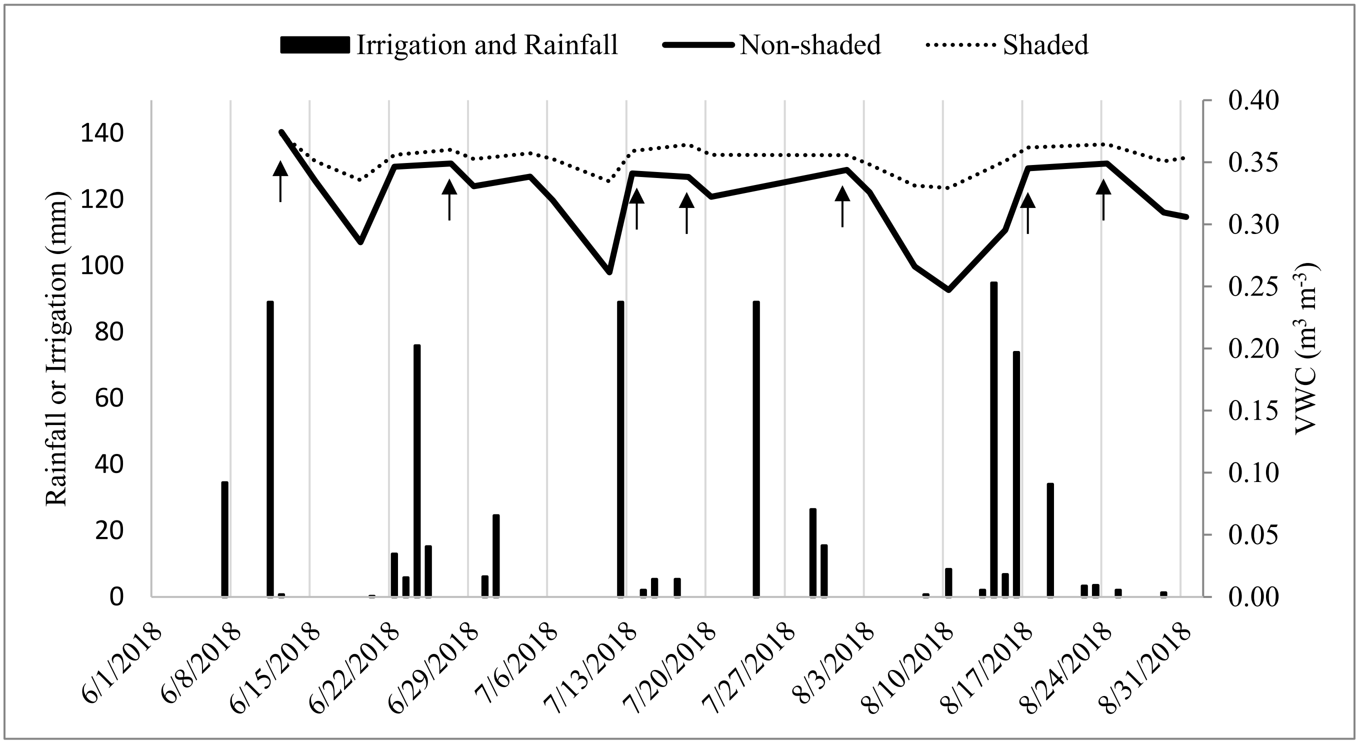

Figure 6. Rainfall, irrigation, and soil volumetric water content (VWC %) during the experimental period. Arrows indicate initial dates for each period used to calculate water use rates.

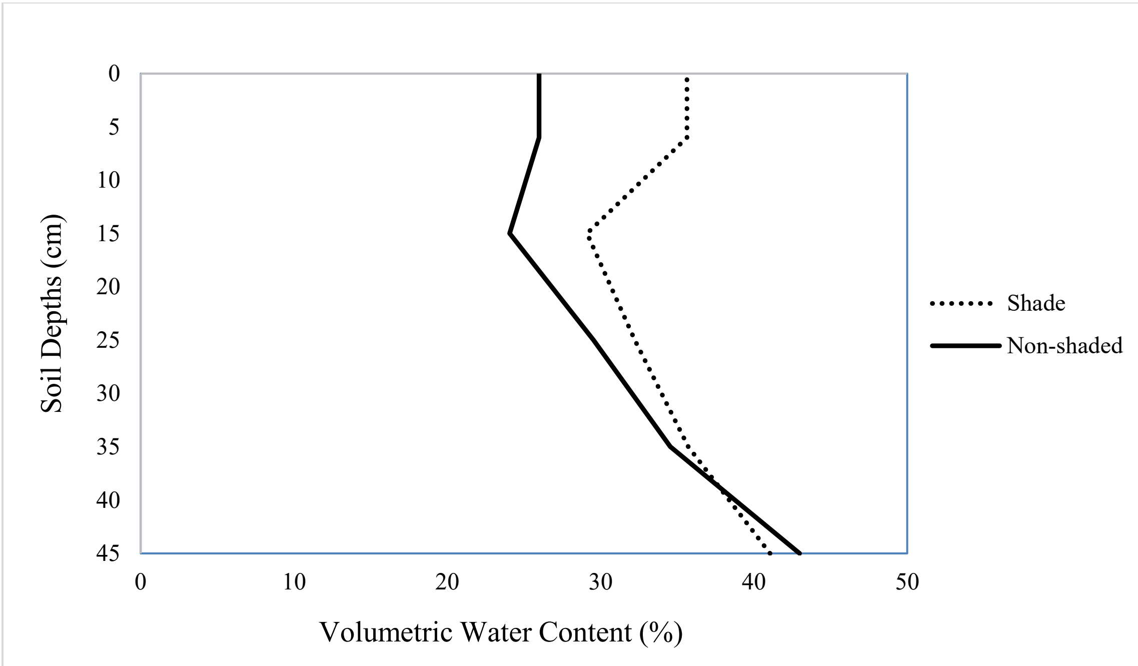

Figure 7. The soil moisture content for shaded and non-shaded conditions within 0-40 cm roots zone depth during experiment period.

CHAPTER V

CONCLUSION

Turf-type tall fescue is a popular turfgrass in the transition zone of the United States, and it had an excellent shade tolerance. Bermudagrass is one of the most widely used turfgrass species in tropical and subtropical areas. In addition, zoysiagrass is well-adapted to the transition zone and is reported to have superior shade tolerance to bermudagrass. The three studies presented herein were designed to help understand how these three species vary in response to shade regarding their water use rates and drought resistance.

REFERENCES

Aitken, C.K., T.A. McMahon, A.J. Wearing and B.L. Finlayson. 1994. Residential water use: Predicting and reducing consumption. J. Applied Social Psychology 24:136-158.

Allard, G., C. Nelson and S. Pallardy. 1991. Shade effects on growth of tall fescue: I. Leaf anatomy and dry matter partitioning. Crop Sci. 31:163-167.

Allen, R., M. Smith, A. Perrier and L.S. Pereira. 1994. An update for the definition of reference evapotranspiration. ICID Bull. 43:1-34.

Allen, R.G., L.S. Pereira, M. Smith, D. Raes and J.L. Wright. 2005. FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. J. Irr. Drainage Engineer. 131:2-13.

Allen, R., L. Pereira, D. Raes and M. Smith. 1998. Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, FAO-Food and Agriculture Organisation of the United Nations, Rome (http://www. fao. org/docrep) ARPAV (2000), La caratterizzazione climatica della Regione Veneto, Quaderni per. Geophysics 156: 178.

Aitken, C.K., T.A. McMahon, A.J. Wearing and B.L. Finlayson. 1994. Residential water use: predicting and reducing consumption. J. Applied Social Psych. 24:136-158.

Amgain, N. R., D. K. Harris, S. B. Thapa, D. L. Martin, Y. Wu, and J. Q. Moss. 2018. Evapotranspiration rates of turf bermudagrasses under nonlimiting soil moisture conditions in Oklahoma. Crop Sci. 58:1409-1415. doi:10.2135/cropsci2017.08.0493

Aronson, L., A. Gold and R. Hull. 1987. Cool-Season turfgrass responses to drought Stress. Crop Sci. 27:1261-1266.

Aronson, L., A. Gold, R. Hull and J. Cisar. 1987. Evapotranspiration of cool-Season turfgrasses in the humid northeast. Agron. J. 79:901-905.

Baldwin, Christian M., and L. B. McCarty. 2007. Diversity of 42 bermudagrass cultivars in a reduced light environment. II International Conference on Turfgrass Science and Manage. Sports Fields 783.

Baldwin, C.M., H. Liu, L.B. McCarty, H. Luo, C.E. Wells and J.E. Toler. 2009. Impacts of altered light spectral quality on warm season turfgrass growth under greenhouse conditions. Crop Sci. 49:1444-1453.

Barnes, et al. 2014. Examining the impact of shade on above-ground biomass and normalized difference vegetation index of C3 and C4 grass species in North-Western NSW, Australia. J. British Grassland Soc. 5:324-334.

Barrios, E.P., F.J. Sundstorm, D. Babcock, and L. Leger. 1984. Quality and yield response of four warm-season lawngrasses to shade conditions. Agron. J. 78:170-173.

Barrios, E., F. Sundstrom, D. Babcock and L. Leger. 1986. Quality and yield response of four warm-season lawngrasses to shade conditions. Agron. J. 78:270-273.

Barnes, B.D., Kopecký, D., Lukaszewski, A.J. and Baird, J.H. 2014. Evaluation of turf-type interspecific hybrids of meadow fescue with perennial ryegrass for improved stress tolerance. Crop Sci. 54:355-365.

Beard, J.B. 1965. Factors in the Adaption of Turfgrass to Shade. Agron. J. 57:457-459.

Beard, J. B. 1973. Turfgrass: science and culture. Prentice-Hall, Englewood Cliffs, NJ.

Beard, J. B. 1973. Cool season turfgrasses. Turfgrass: science and culture. Englewood Cliffs, NJ: Prentice-Hall:54-131.

Beard, J. B. 1985. An assessment of water use by turfgrasses. p.45-62. *In* V.A. Gibeault and S.T.

Beard, J. B. and R. L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 23:452-460. doi:10.2134/jeq1994.00472425002300030007x

Beard, J.B., and S.I. Sifers. 1997. Genetic diversity in dehydration avoidance and drought resistance within the *Cynodon* and *Zoysia* species. Int. Turfgrass Soc. Res. J. 8:603-610.

Beard, D. and P. Weyl. 1973. Influence of texture on porosity and permeability of unconsolidated sand. AAPG Bull. 57:349-369.

Bell, G.E. 1997. Understanding light: a resource for turfgrass management. The Ohio State Uni.

Bell, G.E., T.K. Danneberger, and M.J. McMahon. 2000. Spectral irradiance available for turfgrass growth in sun and shade. Crop Sci. 40:189–195.

Bijoor, N.S., D.E. Pataki, D. Haver and J.S. Famiglietti. 2014. A comparative study of the water budgets of lawns under three management scenarios. Urban Ecosystems 17:1095-1117.

Biran, I., B. Bravdo, I. Bushkin-Harav and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture. Agron. J. 73:85-90.

Bormann, F.H., D. Balmori and G.T. Geballe. 2001. Redesigning the American lawn: a search for environmental harmony. Yale University Press.

Bradley S. Sladek, Gerald M. Henry, Dick L. Auld. 2009. Evaluation of zoysiagrass cultivars for shade tolerance. HortScience 44:1447-1451.

Brown, P. W., C. F. Mancino, M. H. Young, T. L. Thompson, P. J. Wierenga, and D. M. Kopec. 2001. Penman Monteith crop coefficients for use with desert turf systems. Crop Sci. 41:1197-1206. doi:10.2135/cropsci2001.4141197x

Brown, A. and M.D. Matlock. 2011. A review of water scarcity indices and methodologies. White paper. 106:19.

Brown, A. and M.D. Matlock. 2011. A review of water scarcity indices and methodologies. White Paper 106:19.

Bruvold, W.H. and B.R. Smith. 1988. Developing and assessing a model of residential water conservation. JAWRA 24:661-669.

Bunnell, B. T., L. B. McCarty, and W. C. Bridges. 2005. 'TifEagle' bermudagrass response to growth factors and mowing height when grown at various hours of sunlight. Crop Sci. 45:575-581. doi:10.2135/cropsci2005.0575

Burton, G.W., G.M. Prine and J.E. Jackson. 1957. Studies of drouth tolerance and water use of several southern grasses. Agron. J. 49:498-503.

Caldeira, C.F., Bosio, M., Parent, B., Jeanguenin, L., Chaumont, F. and Tardieu, F., 2014. A hydraulic model is compatible with rapid changes in leaf elongation rate under fluctuating evaporative demand and soil water status. Plant Physiol. 164:1718-1730.

Carrow, R. N. 1995. Drought resistance aspects of turfgrasses in the southeast: evapotranspiration and crop coefficients. Crop Sci. 35:1685-1690.

Carrow, R. N. 1996. Drought resistance aspects of turfgrasses in the southeast: root-shoot responses. Crop Sci. 36:687-694. doi:10.2135/cropsci1996.0011183X003600030028x doi:10.2135/cropsci1995.0011183X003500060029x

Carrow, R. and R. Duncan. 2003. Improving drought resistance and persistence in turf-type tall fescue. Crop Sci. 43:978-984.

Cathey, S.E., J.K. Kruse, T.R. Sinclair and M.D. Dukes. 2013. Transpiration and visual appearance of warm season turfgrasses during soil drying. Environmental and Experimental Botany J. 89:36-43.

Cecilio F. C., Mickael B., Boris P., Linda J., Francois C., Francois T. 2014. A hydraulic model is compatible with rapid changes in leaf elongation rate under fluctuating evaporative demand and soil water status. Plant Physiol. 13:11-28

Chandra, A., J. D. Fry, M. C. Engelke, A. D. Genovesi, B. G. Wherley, J. A. Reinert, S. P. Metz, Q. Zhang, and D. Okeyo. 2015. Registration of 'Chisholm' zoysiagrass. J. Plant Registrations 9(1):21-26.

Chandra, A., J. D. Fry, A. D. Genovesi, M. Meeks, M. C. Engelke, Q. Zhang, D. Okeyo et al. 2017. Registration of 'KSUZ 0802'zoysiagrass. J. Plant Registrations 11(2):100-106.

Cockerham(ed.) turfgrass water conservation. Univ. of California Publ. 21405.

Cockerham, S., S. Ries, G. Riechers and V. Gibeault. 2002. Turfgrass growth response under restricted light: Growth chamber studies. Calif. Turfgrass Cult. 52:13-15.

Colmer, T. D., and L. Barton. 2017. A review of warm-season turfgrass evapotranspiration, responses to deficit irrigation, and drought resistance. Crop Sci. 57(Suppl): S-98-S-110. doi:10.2135/cropsci2016.10.0911

Datta, S., Taghvaeian, S. and Stivers, J. 2017. Understanding soil water content and thresholds for irrigation management. Oklahoma State Univ.

Devitt, D., R. Morris and D. Bowman. 1992. Evapotransportation, crop coefficients, and leaching fractions of irrigated desert turfgrass systems. Agron. J. 84:717-723.

Dudeck, A.E., and C.H. Peacock. 1992. Shade and turfgrass culture. p.269–284. *In* D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison, WI.

Dunn, J.H., and K. Diesburg. 2004. Turf management in the transition zone. John Wiley & Sons, Hoboken, NJ. Turf management in the transition zone. John Wiley & Sons, Hoboken, NJ.

Dunn Regan E., Thien-Y. T. Le, and Caroline A. E. Strömberg. 2015. Light environment and epidermal cell morphology in grasses. 176:832-847.

Endter-Wada, J., J. Kurtzman, S.P. Keenan, R.K. Kjelgren and C.M. Neale. 2008. Situational waste in landscape watering: residential and business water use in an urban Utah community. JAWRA. 44:902-920.

Engelke, M.C., and S.J. Anderson. 2003. Zoysiagrasses. p. 271–286. In M.D. Casler and R.R. Duncan (ed.) Turfgrass biology, genetics, and breeding. John Wiley & Sons, Hoboken, NJ.

Ervin, E., C. Ok, B. Fresenburg and J. Dunn. 2002. Trinexapac-ethyl restricts shoot growth and prolongs stand density of 'Meyer' zoysiagrass fairway under shade. HortScience 37:502-505.

Etemadi, N., A. Khalighi, K. Razmjoo, H. Lessani and Z. Zamani. 2005. Drought resistance of selected bermudagrass [*Cynodon dactylon* (L.) Pers.] accessions. Int. J. Agric. Bio 4:612-615.

Fry, J.D., Q. Zhang, D. Okeyo, M. Engelke, and D.Genovesi. 2008. Improved *Zoysia* cultivar could have use in transition zone. TurfGrass Trends, Golfdom, Cleveland, OH. p.58: 60–61.

Feldhake, C., R. Danielson and J. Butler. 1983. Turfgrass evapotranspiration. I. factors influencing rate in urban environments Agron. J. 75:824-830.

Ferguson, B.K. 1987. Water conservation methods in urban landscape irrigation: an exploratory overview. JAWRA. 23:147-152.

Fontanier, C., and K. Steinke. 2017. Competitiveness of three warm-season turfgrasses during spring transition of overseeded turfs. Int. Turf Res. J. 13:1-9.

Fuentealba, M., J. Zhang, K. Kenworthy, J. Erickson, J. Kruse, and L. Trenholm. 2016. Transpiration responses of warm-season turfgrass in relation to progressive soil drying. Sci. Hortic. (Amsterdam) 198:249–253. doi:10.1016/j.scienta.2015.11.042

Fry, J., and Ambika Chandra. Release of KSUZ 0802 Zoysiagrass. 2016. Kansas agricultural experiment station research reports 2(4):1.

Fry, Jack, Ambika Chandra, Dennis Genovesi, Kevin Morris, and Mingying Xiang. 2017. Winter injury of fine-textured interspecific z*oysia hybrids* in the upper transition zone of the USA. Int. Turfgrass Soc. Res. J. 13 (1):601-603.

Gardner, D. and J. Taylor. 2002. Change over time in quality and cover of various turfgrass species and cultivars maintained in shade. HortTechnology 12:465-469.

Gaskin, T. 1965. Light quality under saran shade cloth. Agron. J. 57:313-314.

Gleick, P.H. 1993. Water and conflict: fresh water resources and international security. International Security 18:79-112.

Green, R., S. Sifers, C. Atkins and J. Beard. 1991. Evapotranspiration rates of eleven *Zoysia* genotypes. J. Am. Soc. HortScience 116:965-969.

Huang, B. 1999. Water relations and root activities of *Buchloe dactyloides* and *Zoysia japonica* in response to localized soil drying. Plant and Soil. 208:179-186.

Huang, B., R. Duncan and R. Carrow. 1997. Drought-resistance mechanisms of seven warm-season turfgrasses under surface soil drying: I. Shoot response. Crop Sci. 37:1858-1863.

Huang, B., R. R. Duncan, and R. N. Carrow. 1997. Drought-resistance mechanisms of seven warm-season turfgrasses under surface soil drying: II. root aspects. Crop Sci. 37:1863-1869. doi:10.2135/cropsci1997.0011183X003700060033x

Huang, B., R. R. Duncan, and R. N. Carrow. 1997. Drought-resistance mechanisms of seven warm-season turfgrasses under surface soil drying: I. shoot response. Crop Sci. 37:1858-1863. doi:10.2135/cropsci1997.0011183X003700060032x

Huang, B. and J.D. Fry. 2000. Turfgrass evapotranspiration. J. Crop Production 2:317-333.

IBM Corp. 2015. IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp.

Jiang, Y., R. R. Duncan, and R. N. Carrow. 2004. Assessment of low light tolerance of seashore paspalum and bermudagrass. Crop Sci. 44:587-594. doi:10.2135/cropsci2004.5870

Jiang, Y., and B. Huang. 2000. Effects of drought or heat stress alone and in combination on Kentucky bluegrass contribution No. 99-508-5 from the Kansas Agricultural Experiment Station. Crop Sci. 40:1358-1362. doi:10.2135/cropsci2000.4051358x

Jiang, Y. and Huang, B. 2001. Drought and heat stress injury to two cool-season turfgrasses in relation to antioxidant metabolism and lipid peroxidation. Crop Sci. 41:436-442.

Kim, K.S. 1983. Comparative evapotranspiration rates of thirteen turfgrasses grown under both non-limiting soil moisture and progressive water stress conditions. Texas A&M Univ.

Kim, K.S., S.I. Sifers and J.B. Beard. 1987. Comparative drought resistances among major warm-season turfgrass species and cultivars. Tex. Turfgrass Res. Consolidated Progress Report. 4521:28-30.

Kim, K.W., and J.B. Beard. 1987. Comparative turfgrass evapotranspiration rates and associated plant morphological characteristics. Crop Sci. 28:328-331.

Kim, K. and J. Beard. 1988. Comparative turfgrass evapotranspiration rates and associated plant morphological characteristics. Crop Sci. 28:328-331.

Kramer, P.J. 1983. Problems in water relations of plants and cells. Int. review of cytology. Elsevier. 253-286.

Lunt, I.A., Hubbard, S.S. and Rubin, Y., 2005. Soil moisture content estimation using ground-penetrating radar reflection data. J. hydrology 307(1-4):254-269.

Maggioni, E. 2015. Water demand management in times of drought: What matters for water conservation. Water Res. Research 51:125-139.

McCarty, L.B., and G.L. Miller. 2002. Managing bermudagrass turf: Selection, construction, cultural practices and pest management strategies. Sleeping Bear Press, Chelsea, MI.

McKee, G.W. 1963. Use of a color temperature meter to characterize light quality in the field. Crop Sci. 3:271-273.

McBee, G. G., and E. C. Holt. 1966. Shade tolerance studies on bermudagrass and other turfgrasses. Agron. J. 58:523-525. doi:10.2134/agronj1966.00021962005800050021x

McCarty, L.B., and G.L. Miller. 2002. Managing bermudagrass turf: selection, construction, cultural practices and pest management strategies. Sleeping Bear Press, Chelsea, MI.

McCready, M., M.D. Dukes and G. Miller. 2009. Water conservation potential of smart irrigation controllers on St. Augustinegrass. Agricultural Water Manage. 96:1623-1632.

Meeks, M., A. Chandra and B.G. Wherley. 2015. Growth responses of hybrid bluegrass and tall fescue as influenced by light intensity and trinexapac-ethyl. HortScience 50:1241-1247.

Morris, Kevin N., and Robert C. Shearman. 1998. NTEP turfgrass evaluation guidelines. *In* NTEP turfgrass evaluation workshop, Beltsville, MD:1-5.

Morton, S., M. Engelke and R. White. 1991. Performance of four-warm-season turfgrass genera cultured in dense shade. III. *Zoysia spp*. PR-Texas Agricultural Experiment Station (USA).

Njoku, E.G., T.J. Jackson, V. Lakshmi, T.K. Chan and S.V. Nghiem. 2003. Soil moisture retrieval from AMSR-E. IEEE Transactions on Geoscience and Remote Sensing 41:215-229.

Patton, A. J., and Z. J. Reicher. 2007. Zoysiagrass species and genotypes differ in their winter injury and freeze tolerance. Crop Sci. 47:1619-1627. doi:10.2135/cropsci2006.11.0737

Patton, A.J., B.M. Schwartz, and K.E. Kenworthy. 2017. Zoysiagrass (*Zoysia* spp.) history, utilization, and improvement in the United States: A review. Crop Sci. 57 (supplement1): S-37–S-72. doi:10.2135/ cropsci2017.02.0074

Patton, A.J. and Z.J. Reicher. 2007. Zoysiagrass species and cultivars differ in their winter injury and freeze tolerance. Crop Sci. 47:1619-1627.

Patton, A.J. 2009. Selecting zoysiagrass cultivars: turfgrass quality, growth, pest and environmental stress tolerance. Applied Turfgrass Sci. 6:6-7.

Patton, A.J. 2010. Selecting zoysiagrass cultivars: turf quality and stress tolerance. Golf Course Mgmt. 78:90-95.

Pfister, S., A. Koehler and S. Hellweg. 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environmental Sci. Technol. 43:4098-4104.

Pimentel, D., B. Berger, D. Filiberto, M. Newton, B. Wolfe, E. Karabinakis, et al. 2004. Water resources: agricultural and environmental issues. BioScience 54:909-918.

Pimentel, D., B. Berger, D. Filiberto, M. Newton, B. Wolfe, E. Karabinakis, et al. 2004. Water resources: agricultural and environmental issues. BioScience 54:909-918.

Qian, Y. and M. Eneelke. 2000. ‘Diamond’ zoysiagrass as affected by light intensity. J. Turfgrass Mgmt. 3:1-13.

Qian, Y. and M. Engelke. 1999. Influence of trinexapac-ethyl on Diamond zoysiagrass in a shade environment. Crop Sci. 39:202-208.

Qian, Y. and J. Fry. 1996. Irrigation frequency affects zoysiagrass rooting and plant water status. HortScience 31:234-237.

Qian, Y., J. Fry and W. Upham. 1997. Rooting and drought avoidance of warm-season turfgrasses and tall fescue in Kansas. Crop Sci. 37:905-910.

Reich, P.B., Ellsworth, D.S. and Walters, M.B., 1998. Leaf structure (specific leaf area) modulates photosynthesis–nitrogen relations: evidence from within and across species and functional groups. Functional Eco. 12:948-958.

Romero, C.C. and M.D. Dukes. 2016. Review of turfgrass evapotranspiration and crop coefficients. Transactions of the ASABE 59:207-223.

SAS Institute. 2011. The SAS system for Windows. Release 9.3. SAS Inst., Cary, NC.

Severmutlu, S., N. Mutlu, E. Gurbuz, O. Gulsen, M. Hocagil, O. Karaguzel, et al. 2011. Drought resistance of warm-season turfgrasses grown in Mediterranean region of Turkey. HortTechnology. 21:726-736.

Sladek, B.S., G.M. Henry and D.L. Auld. 2009. Evaluation of zoysiagrass cultivars for shade tolerance. HortScience. 44:1447-1451.

Sophocleous, M., 2002. Interactions between groundwater and surface water: The State of The Science. Hydrogeology J.10(1):52-67.

Steduto, P., Hsiao, T.C. and Fereres, E., 2007. On the conservative behavior of biomass water productivity. Irrigation Sci. 25(3):189-207.

Sills, M. J., and R. N. Carrow. 1983. Turfgrass growth, N use, and water use under soil compaction and N fertilization. Agron. J. 75:488-492. doi:10.2134/agronj1983.00021962007500030017x

Su, K., J.Q. Moss, G. Zhang, D.L. Martin and Y. Wu. 2013. Bermudagrass drought tolerance associated with dehydrin protein expression during drought stress. J. American Soc. HortScience. 138:277-282.

Simonovic, S.P. and H. Fahmy. 1999. A new modeling approach for water resources policy analysis. Water Resources Res. 35:295-304.

Tegg, R. and P. Lane. 2004. A comparison of the performance and growth of a range of turfgrass species under shade. Australian J. Experimental Agriculture 44:353-358.

Touchette, B.W., L.R. Iannacone, G.E. Turner and A.R. Frank. 2007. Drought tolerance versus drought avoidance: a comparison of plant-water relations in herbaceous wetland plants subjected to water withdrawal and repletion. Wetlands. 27:656-667.

Trenholm, L.E., Nagata, R.T. (2005) Shade tolerance of St. Augustinegrass cultivars. Hort Technology 15:267–272.

Trenholm. 2017. Comparative performance and daily light integral requirements of warm-season turfgrasses in different seasons. Crop Sci. 57:2273-2282. doi:10.2135/cropsci2017.01.0052

Trappe, J.M., A.J. Patton, D.E. Karcher and M.D. Richardson. 2009. Shade and traffic tolerance among bermudagrass and zoysiagrass cultivars. Arkansas Turfgrass Report 2008, Arkansas Agricultural Experiment Station Research Series. 568:158-162.

Trappe Jon M., Douglas E. Karcherb, Michael D. Richardsonb and Aaron J. Patton. 2010. Shade and traffic tolerance varies for bermudagrass and zoysiagrass cultivars. Crop Sci. 51:870-877.

Van Huylenbroeck, J.M. and Van Bockstaele, E. 2001. Effects of shading on photosynthetic capacity and growth of turfgrass species. Intl. Turfgrass Soc. Res. J. 9:353-359.

Wherley, B., P. Skulkaew, A. Chandra, A. Genovesi and M. Engelke. 2011. Low-input performance of zoysiagrass (*Zoysia* spp.) cultivars maintained under dense tree shade. HortScience 46:1033-1037.

Wherley B. G., D. S. Gardner, and J. D. Metzger. 2004. Tall fescue photomorphogenesis as influenced by changes in the spectral composition and light intensity. Crop Sci. 45:562-568. doi:10.2135/cropsci2005.0562

Wherley, B., Dukes, M.D., Cathey, S., Miller, G. and Sinclair, T. 2015. Consumptive water use and crop coefficients for warm-season turfgrass species in the Southeastern United States. Ag. Water Manage. 156:10-18.

Williams, L. and J. Ayars. 2005. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agricultural and Forest Meteorology 132:201-211.

Wherley, B. G., P. Skulkaew, A. Chandra, A. D. Genovesi, and M. C. Engelke. 2011. Low-input performance of zoysiagrass (Zoysia spp.) cultivars maintained under dense tree shade. HortScience 46 (7):1033-1037.

Wong, C.C. 1991. Shade tolerance of tropical forages: a review. In Forages for plantation crops. ACIAR Proceedings 32:64-69.

Yu, X., G. Bai, S. Liu, N. Luo, Y. Wang, D.S. Richmond, et al. 2013. Association of candidate genes with drought tolerance traits in diverse perennial ryegrass accessions. J. Experimental Botany. 64:1537-1551.

Zhang, J., B. Glenn, J. B. Unruh, J. Kruse, K. Kenworthy, J. Erickson, D. Rowland, and L.

Zhang, J., K. Kenworthy, J. B. Unruh, B. Poudel, J. E. Erickson, D. Rowland, and J. Kruse. 2017. Physiological responses to soil drying by warm-season turfgrass species. Crop Sci. 57(Suppl):S-111-S-118. doi:10.2135/cropsci2016.05.0316

Zhang, and D. Okeyo. 2015. Registration of ‘Chisholm’zoysiagrass. J. Plant Registrations 9 (1): 21-26.

VITA

Huanyun Duan

Candidate for the Degree of

Master of Science

Thesis: INVESTIGATIONS INTO WATER USE RATES AND DROUGHT RESISTANCE OF TURFGRASSES UNDER SHADED CONDITIONS

Major Field: Horticulture

Biographical:

Education:

Completed the requirements for the Master of Science in Horticulture at Oklahoma State University, Stillwater, Oklahoma in December, 2018.

Completed the requirements for the Master of Engineering in Environment and Energy at Yunnan Normal University, Kunming, China in 2015.

Completed the requirements for the Bachelor of Engineering in Environment and Energy at Yunnan Normal University, Kunming, China in 2012.

Experience:

Graduate Research Assistant
- Oklahoma State University, Stillwater, OK
  Department of Horticulture and Landscape Architecture

Graduate Research Assistant
- Yunnan Normal University, Kunming, China
  School of Energy and Environment Science

Project Manager, Board Member
- Eco-Watch Institute (NGO)
  Kunming City, Yunnan, China

Professional Memberships:
- American Society of Agronomy
- Crop Science Society of America