EFFECTS OF IRRIGATION AND TRAFFIC STRESSES ON PHYSIOLOGICAL RESPONSES AND WATER USE CHARACTERISTICS OF CREEPING BENTGRASS AND ANNUAL BLUEGRASS

By

Kevin Laskowski

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences—Master of Science

2017

ABSTRACT

EFFECTS OF IRRIGATION AND TRAFFIC STRESSES ON PHYSIOLOGICAL RESPONSES AND WATER USE CHARACTERISTICS OF CREEPING BENTGRASS AND ANNUAL BLUEGRASS

By

Kevin Laskowski

Creeping bentgrass (CBG; *Agrostis stolonifera*) and annual bluegrass (ABG; *Poa annua*) are two golf course putting green species that are sensitive to drought and traffic stress. A two-year field study evaluated the effects of irrigation treatments [8, 12, and 16% volumetric water content (VWC)] and traffic stress (none, low, and moderate) on CBG and ABG putting green plots. Leaf relative water content (RWC), leaf electrolyte leakage (EL), canopy chlorophyll content, normalized difference vegetative index (NDVI), root biomass, ethylene production, ABG invasion into CBG, quantity of water leached and soil VWC from plots were measured. A 12% irrigation treatment was determined to be optimal when compared to 8% (deficit) and 16% (excessive) when measuring leachate volumes and soil VWC. Moderate traffic treatments decreased turfgrass quality and increased ABG invasion into CBG plots. However, CBG had significantly higher turfgrass quality (through measuring RWC, EL, NDVI and chlorophyll content) than ABG under irrigation and traffic treatments. Ethylene gas production increased at the 8 and 16% irrigation treatment and increased in response to traffic treatments on ABG. The method of quantifying ethylene gas production in this study may be a practical technique to detect turfgrass stress incidence from putting green canopies. A more in depth analysis of ethylene gas production under other abiotic stress conditions may be necessary to investigate the role of ethylene gas within CBG and ABG.

To
My parents Daniel and Christine Laskowski
And my wife Emily Laskowski,
For their love and support.
Thank you.

ACKNOWLEDGEMENTS

I would like to thank my major professor and advisor, Dr. Emily Merewitz, for her belief in my potential and guidance through developing my research skills at Michigan State University. I would also like to thank my guidance committee Dr. Kevin Frank and Dr. Joseph Vargas for their help and support in teaching me and giving me the opportunity to be a turfgrass scientist.

I would like to thank my friends, research associates, and officemates, Aaron Hathaway and Eric Chestnut, for helping lighten the mood and make life easier when times were stressful. Furthermore, I want to give a special thanks to Mark Collins, Jesse Sholl and the rest of the HTRC crew for their help and advice with all of my undertakings.

I would like to give great thanks to my parents, Dan and Christine for their support and love that gave me the ambition to get to where I am today, without you this accomplishment would not have been able to be reached.

Thank you to my loving wife, Emily Laskowski who has been there by my side the whole time. Your love and support helped me get through this step in my life and I look forward too many more years of love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Creeping bentgrass (CBG) and annual bluegrass (ABG) are two predominant turfgrass species on golf course putting greens in northern climates. A significant amount of research has been devoted to understanding the interaction of these two species. This research has been largely based on the perspective that ABG is a weed, with aims to identify the faults and physiological weaknesses of the species. A great deal of research has gone into the removal of ABG from CBG putting greens (Isgrigg et al., 1999; Johnson and Murphy, 1995; McCullough et al., 2005; Reicher et al 2015; Woosley et al., 2003). Significant breeding efforts have been undertaken to improve greens type ABG (La Mantia and Huff, 2011). The aim of this breeding has been to identify greens-type ABG with more desirable characteristics to prevent turf managers from only viewing the species as an undesirable weed. This breeding has not resulted in widespread availability of desirable ABG types. Another strategy to improve ABG performance on putting greens is to improve the understanding of ABG responses to abiotic stresses (drought) and management strategies (irrigation levels). With more informed management of ABG it may be possible to reduce expenditures and pesticide usage by golf courses (Bigelow and Tudor, 2012; Gaussoin and Branham, 1989; Kaminski and Hsiang 2007, Vargas and Turgeon, 2003).

Comparing ABG to CBG is a useful strategy to better understand ABG responses since a large amount of research has been conducted on the best management strategies for CBG. CBG and ABG can have significantly different attributes related to irrigation requirements and drought stress performance based on rooting habits, and other physiological characteristics (Bigelow and Tudor, 2012). Best irrigation practices for ABG are not widely available for multiple regions of the country, as ABG has significant ecotype variability (La Mantia and Huff, 2011). Water use requirement recommendations and the effects of drought on CBG are more widely available compared to ABG. For example, CBG exhibits a decrease in growth rate, cellular water content, and chlorophyll content under drought stress (Dacosta and Huang, 2006c; McCann and Huang, 2007). During stresses, such as heat and drought stress, ABG viability is significantly reduced (McCarty, 1999). CBG is also shown to have greater root biomass when compared with ABG (Lyons et al., 2001). Under drought stress conditions, the lack of deep roots is often cited as a primary cause of the susceptibility of ABG to drought stress symptoms (Murphy et al., 1994). The cause of the lack of deep rooting and drought sensitivity of ABG is not well understood and would be valuable information especially with more recent drastic changes in weather and climate patterns.

Recent weather patterns in the United States and around the world are becoming increasingly unpredictable causing severe flooding for extended periods of time as well as long durations of drought. Recently, California has gone through extreme drought which has caused for legislation to cut back water usage. In California, legislation required the population to reduce water use by 25% (Stevens et al., 2015), the included golf course superintendents, but not other forms of agriculture. The other extreme is the recent widespread flooding in Texas (Zoroya, 2015). This type of extreme weather can cause a significant monetary loss for golf courses. Golf courses often face the challenge of maintaining healthy, aesthetically appealing, and playable turfgrasses under excessive and limited water conditions, not only in California but across the United States. In Michigan, 3% of the total water consumption goes towards irrigation of crops, parks, and golf courses (Morenz et. al. 2005). Golf course putting greens are particularly susceptible to water stress due to intensive management. Preferences of drier conditions for playability, and high expectations of turfgrass quality are experienced in these areas. Most often during drought stress incidence, golf play is not able to be restricted, which causes the turf to endure both drought and traffic stresses. The combined treatments of drought and traffic more readily represent real golf course conditions that are typically not used together as factors in controlled research studies.

Serious injury to turfgrass is commonly caused by concentrated traffic to turf stands (Beard, 1973). Traffic to turf stands typically includes both wear and soil compaction stress (Carrow and Johnson., 1996). On sandy soils, wear stress is the primary form of traffic stress, while soils with high silt and clay contents are subject to greater amounts of compaction stress (Carrow and Wiecko, 1989). Excessive foot traffic can cause scuffing, tearing, or crushing of the turfgrass plants (Beard, 1973). Gibeault et al. (1983) observed that the average golfer takes about 52 steps per putting green while Pelz and Mastroni (1989) observed a foursome leaving behind more than 500 footsteps on a putting green as they entered, putted, and exited a putting green. That is an average of 125 footsteps per golfer (Pelz and Mastroni, 1989). Observational research conducted within a golf course observed that 70% of putting green foot traffic occurred around the pin (Hathaway and Nikolai, 2005). This gives evidence that the amount of traffic can vary between golfers, calling for a need of research involving different levels of traffic stress. An understanding of stress related and hormonal responses of CBG and ABG to water and traffic stress could help to elucidate stress susceptibility characteristics between the two species and could help turfgrass managers efficiently manage these two grasses.

Plant stress is defined as a state in which regular physiological processes are interrupted, leading to injury (Nilsen and Orcutt, 1996). Ethylene is an important gaseous hormone involved in plant stress that can cause growth inhibition and leaf senescence (Abeles et al. 1992). Ethylene has been associated with abscission of leaves, flowers, buds, gravitropic responses, fruit ripening, and senescence (Taiz and Zeiger, 2006). The gaseous nature of this hormone allows it to effectively signal communities or multiple plant organs via rapid diffusion from plant tissues. Apelbaum and Yang, (1981) found that wheat leaves undergoing water deficit conditions increased in ethylene production. Beltrano, (1999) found similar results in which wheat leaves under drought stress produced more ethylene when compared to well-watered wheat leaves. Significant differences in hormonal responses and sensitivity of various species under non-stress and stress conditions within the Poa genus exist. Fiorani et al. (2002) have shown that faster growing ABG species are less sensitive to the accumulation of the growth inhibiting, senescence stimulating hormone, ethylene. Simultaneously, it was found that the fast growing ABG species produce greater levels of the hormone when compared to slower growing species. These influences were evaluated only within the ABG genera and only on plant leaves. CBG has greater sensitivity to this hormone, which has been demonstrated by the greater sensitivity of CBG to Ethephon (Bayer Crop Science) treatment (i.e. effective ethylene) compared to ABG (McCullough et al., 2006). Therefore, this hormone could be a major factor in CBG and ABG whole canopy responses to irrigation and traffic stress.

In addition to physiological and ethylene responses of CBG and ABG, it is possible that the competition between the two species could be affected by water and traffic treatments (Beard et al., 1978; Hathaway, 2006; Mahdi and Stoutmeyer, 1953; Younger, 1959; Youngner et al., 1981). It has been observed that an increase in golf foot traffic on a putting green has been associated with an increase in the ABG population of a putting green (Beard, 1978; Hathaway, 2006). ABG depends on quick growth and seed production to spread and propagate, while CBG relies on stoloniferous growth characteristics to spread. In a four-month period, it was estimated that ABG could produce up to 360 seeds per plant (Renney, 1964). Law et al. (1977) determined that each ABG plant could produce 80 viable seeds per year. These seeds can thus be spread through foot traffic on putting greens (Hathaway, 2006). This can change management strategies for a golf course putting green if removal of ABG is desired with the addition of other plant growth regulators to control ABG (Reicher et al 2015; Woosley et al., 2003). Golf course superintendents do not desire the characteristics inherent to ABG seed production such as flowering which can disrupt surface uniformity and smoothness. Therefore, it is important to evaluated ABG invasion in CBG plots, in order to have a better understanding of the dynamic of the competition between ABG and CBG under differing levels of traffic and irrigation.

Thus, the research objectives were to investigate the effects of irrigation and traffic treatments on leaching volumes, soil VWC, hormone response, and rooting characteristics of ABG and CBG on a sand based putting green. Previous studies have shown that these two species differ under irrigation or traffic stress but do not combine the effects of both stresses on ABG and CBG.

MATERIALS AND METHODS

Construction

A two-year experiment was conducted in 2013 and 2014 on a turfgrass field (2229.7m^2) consisting of plots of CBG and ABG maintained as a putting green at the Hancock Turfgrass Research Center in East Lansing, MI. The putting green was established in 2008 according to the United States Golf Association recommendations for putting green construction. Within the field there were 18 main plots (120.4 m^2) with independent irrigation control, of which nine were ABG and nine were CBG 'Penn-A4'. Irrigation was delivered by four irrigation heads per main plot (Model Eagle 751, Rainbird Bird Corp., Azusa/Glendora, CA).

Lysimeters were installed in Aug 2008 into the 54 subplots within this putting green. Lysimeters were constructed out of a 265 L stock water tank (1.02 x 0.81 x 0.61 m) (Rubbermaid Commercial Products LLC, Winchester, VA). Two 22.7 kg bags of concrete (Quikrete, Atlanta, GA) were distributed into the bottom of these tanks at an angle which allowed water flow towards a drain. Schedule 40 PVC couplings (3.8 cm) (Spears Manufacturing, Bolingbrook, IL) were connected to 3.8 cm schedule 40 PVC pipe (Harvel, Easton, PA) and sloped 2% towards the north side of the research green into catch basins where water from each lysimeter could be collected into 19 L collection buckets.

Soil sensors were installed to record and schedule irrigation events (TSM-1, Rain Bird Corp., Azusa/Glendora, CA). The soil sensors were installed at a 7.62 cm depth within the center of each irrigation block in the summer of 2012 and would measure soil VWC, temperature, and salinity. The irrigation system automatically scheduled irrigation to maintain soil VWC to a specified irrigation treatment by recording soil VWC every 20 minutes and adjusting irrigation rates for nightly irrigation cycles.

Climate conditions

Similar climatic conditions between each year during the two-year study provided an opportunity to examine CBG and ABG responses to similar weather patterns (Figure 1).

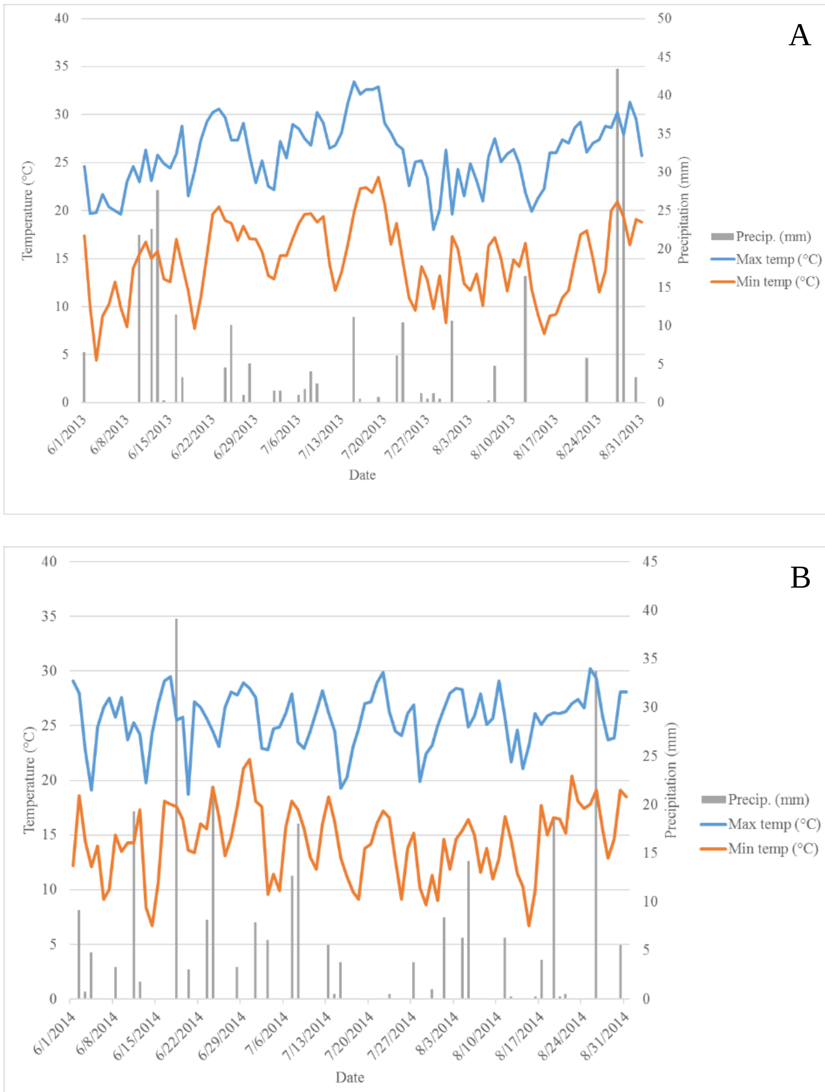

Figure. 1. Daily maximum and minimum temperatures (°C) and precipitation amounts (mm) in East Lansing, MI. throughout the study period in A) 2013 B) 2014.

Turfgrass plot maintenance

Plots were mowed three times weekly during 2013 and 2014 at a height of 3.4 mm using a triplex greens mower (Greensmaster 3150-Q, The Toro Company, Bloomington, MN), with clippings removed from all plots. Sand topdressing was applied at a rate of 0.02 cm every week throughout the experimental period. Sand was vibratory rolled into the green to move sand into the thatch layer. The putting green was aerified on 25 Sept. in 2013 and on 19 Sept. in 2014 with a (ProCore 648, The Toro Company, Bloomington, MN) with 0.95 cm diameter hollow tines at 5 cm spacing. Sand topdressing was applied to fill aerification holes within the research green.

In 2013, plots were fertilized with 24.4 kg N ha^{-1} on 5 May, 2 Aug., and 1 Oct., using a 18-9-18 (N-P-K) granular fertilizer, (Andersons Golf Products, Maumee, OH). Nitrogen was applied as a foliar spray weekly between 14 June to 26 Sept. using a 28-0-0 (N-P-K) liquid fertilizer at a rate of 4.9 kg N ha^{-1}. In 2014, plots were fertilized with 24.4 kg N ha-1 on 5 May, 10 June and, 26 Sept. using a 19-0-15 (N-P-K) granular fertilizer (Andersons Golf Products, Maumee, OH). Nitrogen was applied as a foliar spray weekly between 9 June and 29 Aug. using a 28-0-0 (N-P-K) liquid fertilizer at a rate of 4.9 kg N ha^{-1}. Granular treatments were applied and irrigated with 3.8 mm water to avoid fertilizer burn.

Fungicides were applied preventively and curatively to avoid turf loss. Thiophanate-Methyl and Iprodione (Fluid Fungicide, Andersons Golf Products, Maumee, OH) 0.49 kg ha^{-1} was applied 12 Sept 2013 and 0.37 kg ha^{-1} on 10 Aug. 2013 to control dollar spot (*Sclerotinia homeocarpa* F.T Bennet). Thiophanate-Methyl and Iprodione, (Fluid Fungicide, Andersons Golf Products) 0.49 kg ha^{-1} was applied on 5 June, 26 June, 19 July, and 6 Aug., 2014 to control dollar spot (*Sclerotinia homeocarpa* F.T Bennet). Boscalid (Emerald; BASF, Research Triangle

Park, NC) 0.56 kg ha^{-1} was applied on 27 June and 24 July 2013, to control dollar spot (*Sclerotinia homeocarpa* F.T Bennet). Propiconizole (Banner Maxx, Syngenta, Greenboro, NC) 0.99 kg ha^{-1} was applied on 26 July 2013, to control crown rot anthracnose (*Colletotrichum cereale*). Clothianidin (30.5 kg ha^{-1}) was applied on 9 July 2013 and Carbaryl (9.0 kg ha^{-1}) was applied on 16 July 2014 to control black cut worm (*Agrotis ipsilon*).

Experimental treatments

Strip plots (2.23 x 7.92 m) of moderate, low, and control (no traffic) traffic stress were applied to the plots above the buried lysimeters to create three subplots per irrigation block resulting in 54 total research plots. Traffic treatments were applied by using a golf traffic simulator (49.9 kg) modified with extra weight (68 kg). It consisted of a roller (0.53 x 0.5 m); covering 0.266 m^2 with each revolution with black widow golf spikes and was manually pushed across plots to simulate traffic. Traffic treatments were imposed on each plot 3 times weekly simulating 237 rounds of golf at the low traffic rate and 474 rounds of golf for the moderate rate of traffic each week. The rounds of golf were based on a golf shoe containing an average of 12 spikes per shoe with the average golfer taking about 26 full steps (52 paces) per putting green (Hathaway and Nikolai, 2005).

Three whole plot irrigation treatments were tested in this field experiment. Irrigation treatments were applied using the Rain Bird TSM-1 soil sensor and the central computer. VWC was measured by the soil sensor and updated to the central computer every 20 minutes. Utilizing the Rain Bird Integrated Sensor System (ISS), three VWC irrigation treatments were set at 8, 12, and 16%, which were based from previous observations from the Hancock turfgrass research center (Frank et al., 2012) Irrigation volumes used during 2013 and 2014 are listed (Table 1).

Table 1. Irrigation amounts applied from June 2013 to Sept. 2013 and June 2014 to Sept. 2014 in ABG and CBG at the 8, 12, and 16% irrigation treatments.

	ABG				CBG			
	Water amount (cm)		Water amount (m^3)		Water amount (cm)		Water amount (m^3)	
Irrigation treatment (%)	2013	2014	2013	2014	2013	2014	2013	2014
8	12.0	3.4	14.4	4.1	13.3	6.3	16.0	7.6
12	27.4	16.1	33.0	19.3	24.4	14.2	17.1	17.1
16	97.3	76.2	116.9	91.5	96.3	69.5	115.7	83.5

Measurements

Leachate was collected from the lysimeters on a weekly basis and measured for quantity. Time domain reflectometry (TDR) was utilized to measure VWC at two depths, 3.8 cm, and 12.2 cm (Field Scout TDR-300; Spectrum technologies Inc. Aurora, IL.) measured on a weekly basis.

Visual turf quality (TQ) ratings were taken on a scale from 1- 9 based on a 1 (dead or poor) to 9 (best) rating scale, with 6 being acceptable. (NTEP, 2015). Canopy shoot density was determined by measuring normalized difference vegetation index (NDVI) with the use of a turf color meter (Field Scout TCM-500; Spectrum technologies Inc. Aurora, IL.). These measurements were performed weekly.

Leaf EL measurements were from samples of approximately 0.5 g of leaf tissue taken from each plot and washed in deionized water four times before further analysis. Leaves were then immersed in 7 ml of deionized water and placed on the shaker for 24 h. The conductivity of the immersion water with fresh tissues was measured as initial conductivity (C_i). The samples were then boiled and placed on the shaker for 24 h. The conductivity of the resulting water of dead tissues was measured as maximum conductivity (C_{max}). Percentage EL is calculated as $C_i/C_{max} \times 100$ (Blum and Ebercon, 1981). Chlorophyll content was determined through the use of hand-held chlorophyll meter (CM-1000; Spectrum technologies, Inc. Aurora, IL.). These evaluations were measured on a weekly basis.

Leaf (RWC) was performed on a weekly basis. Leaf RWC was calculated based on fresh (FW), turgid (TW), and dry weight (DW) of approximately 0.1 g of leaf samples using the formula (FW – DW)/(TW – DW) x 100. Leaf FW was determined on a mass balance immediately after being excised from the plots. Turgid weights were determined after soaking the leaves in deionized water for 12 h in a closed petri dish and weighed immediately after they were blotted dry. Leaves were then dried in an 80°C oven for at least 72 h before being weighed for DW (Barrs and Weatherley, 1962).

Ethylene evolution was measured directly in the field using an ethylene gas analyzer equipped with a modified field kit (CID-900; CID Bio-sciences, Camas, Wa). The modified field kit was a 2.0 L, clear plexiglass chamber, which was placed firmly on the surface of the turf stand and measured ethylene gas which evolved from each plot. A wind and sun block box constructed of cardboard (26.7 x 20.3 x 26.7 cm) was developed for this chamber so that conditions within the chamber would remain stable. Once the chamber was placed on a plot, the CID-900 equilibrated for one minute then an initial reading was recorded (E_i). After one minute, a final measurement was recorded (E_f). Ethylene rate of production was determined by the formula ($E_f – E_i$). Measurement rates were recorded in parts per billion per minute. This equipment was tested for effectiveness of determining ethylene production from the turf canopy within field plots.

A rhizotron system was used to measure root length, in situ under all watering and traffic stress treatments. In each subplot, a clear plexiglass tube 0.35 m in length was installed at a 45-degree angle the root imager (CI-600; CID Bio-sciences, Camas, Wa). Images were collected on a weekly basis. Images were then analyzed at a later date (RootSnap, CID Bio-Sciences, Camas, Wa). Three, 2.5 cm diameter, soil core samples were obtained randomly from each plot at a depth of 20.3 cm to evaluate total root biomass. Separation of roots was performed by removing sod and thatch at the thatch/soil interface, the remaining soil core sample was thoroughly washed with water to remove sand and fine mineral particles on a 500-µm sieve. After this, a second washing occurred to remove remaining sand particles and organic debris from the roots by flotation. Roots samples were then dried at 50°C for 72 hours before recording a root dry mass.

ABG invasion in CBG plot was measured three times in both 2013 and 2014. These ratings were determined using a line-intersecting grid count method. A grid of 1.6 x 1.6 m consisted of 441 intersections, each measuring 76 x 76 mm. ABG invasion was measured by counting the number of grid intersections which touched any part of an ABG plant and then divided by the total number of sections to get a percent ABG per plot area (Hathaway, 2006).

Experimental design and statistical analysis

The experiment was a completely randomized design with two whole plot factors, which included species consisting of two levels, irrigation consisting of three levels, and a split plot treatment design consisting of three levels of traffic. All data were subjected to analysis of variance (ANOVA) using SAS 9.4 (SAS institute Inc., Cary, NC) with a GLIMMIX model procedure. When appropriate, mean differences were separated using Fischer's least significant difference (LSD) at the 0.05 P level.

RESULTS AND DISCUSSION

Leachate volume

In 2013 and 2014, species and traffic treatments did not have a significant effect on the amount of water leached through the rootzone (see appendix Table 16 and 17). Fry and Butler (1989) found that ABG required less water 5 out of 7 weeks in their study when compared with CBG. However, climatic, soil, and maintenance differences to the research area could explain why results may differ from those of other experiments. Large spikes in water leachate data are visible due to large rain events such as on 4 Aug 2014. Irrigation treatment had a significant effect on the amount of water leached. On all dates, the 16% irrigation treatment plots leached more water than the 8 and 12% irrigation treatments. The 12% irrigation treatment leached significantly more than 8%, except for three dates in 2013 and one date in 2014 (Figure 2A and B). Ideally, to reduce water consumption and loss of nutrients or pesticides, the amount of water input would be closer to or equal to evapotranspiration (ET) from the turfgrass system. Replacement of 100% ET was excessive and unnecessary for adequate quality of creeping bentgrass (DaCosta and Huang, 2006a; DaCosta and Huang, 2006b). When leaching does occur, the flow through the soil profile can lead to nutrient leaching and possible ground water contamination (Hudak, 2000; Erickson et al., 2005; Shaddox et al., 2016; Guertal, 2007). Future research could include measuring actual ET and correlating it to soil leachate volumes along with soil VWC to determine an accurate method of irrigation to reduce soil water leachate.

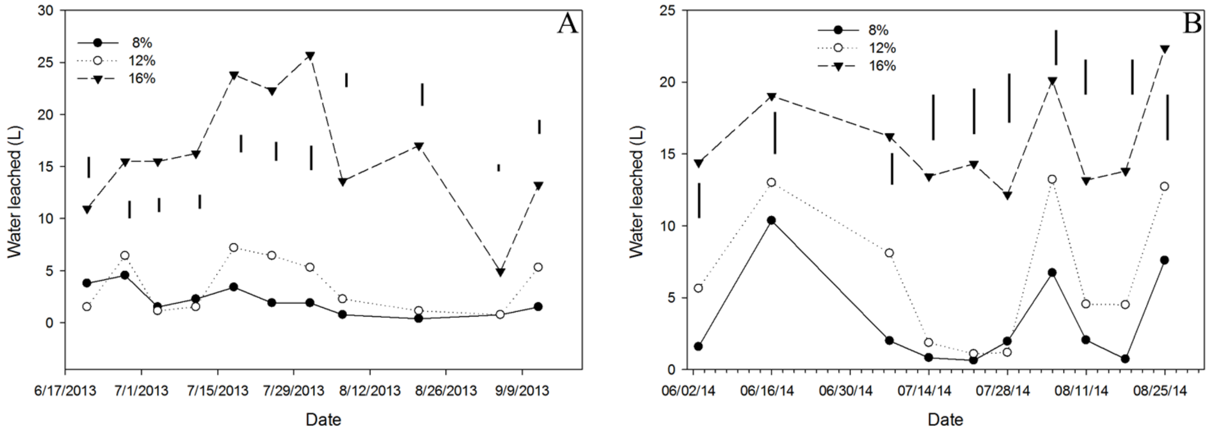

Figure 2. Water leachate volume of 8, 12 and 16% irrigation treatment treatments in (A) 2013 and (B) 2014. East Lansing, MI. Vertical least significant difference (LSD) bars represent Fisher's least significant difference values ($P \leq 0.05$) for irrigation comparison on a given day.

Soil moisture content

On two dates in 2013, there was a species x irrigation interaction, the same interaction occurred on one date in 2014. In 2013, CBG had higher VWC at 12 and 16% irrigation treatments when compared with ABG at the 12 and 16% irrigation targets. (Figure 3A). In 2014, ABG irrigated to the 16% irrigation treatment had higher VWC than CBG at all irrigation treatments (Figure 3B). In 2013, CBG had higher VWC to a 3.8 cm depth when compared with ABG. Soil VWC can be differential under a given irrigation treatment due to turfgrass species or cultivar. For instance, DaCosta and Huang (2006a) found differences in ET between creeping, colonial, and velvet bentgrasses. ET has been correlated with soil VWC (Lu et al., 2011). CBG and ABG can have similar rates of ET (Aronson et al. 1987; Biran et al. 1981; Fry and Butler, 1989; Shearman and Beard 1973). Other research has shown that root content within a soil can affect soil VWC measured by TDR technology (Mojid and Cho, 2004), which is discussed further in the root mass section.

The 16% irrigation treatment had significantly higher VWC when compared to the 8% and 12 % irrigation treatment in 2013 and 2014 (Table 2 and 3). Traffic treatments were significant on two dates, 8 July and 19 Aug 2013. The moderate traffic treatment had higher VWC when compared with the low and control treatments. Traffic treatments were significant on nine dates in 2014, in which the moderate traffic treatment had higher VWC when compared with the low and control traffic treatment. This could be related to mild compaction that may occur in sand based greens due to traffic. CBG and ABG can have similar ET rates (Aronson et al. 1987; Biran et al. 1981; Shearman and Beard 1973). Despite this, ABG has significantly different rooting attributes and stress tolerance mechanisms than CBG (Lyons et al., 2011) and ABG is more sensitive to reduced irrigation conditions compared to CBG (Beard, 1973). Results indicate that irrigating to a 16% irrigation treatment increases soil VWC to a 3.8 cm depth when compared to an 8% irrigation treatment. Results also show that moderate traffic treatments increase VWC to a 3.8 cm depth in a USGA sand based putting green.

VWC from surface to a 12.2 cm depth had a significant interaction within species x irrigation treatments on one date (Table 4). CBG had higher VWC at 12 and 16% irrigation treatments when compared with ABG at 12 and 16% irrigation treatments, respectively (Figure 4). In both 2013 and 2014, CBG had higher VWC at a 12.2 cm depth when compared to ABG (Table 4 and 5) The 16% irrigation treatment had greater VWC at a 12.2 cm depth when compared to the 8% irrigation treatment in 2013 and 2014. Under well-watered conditions CBG can have higher requirements for water than ABG (Fry and Butler, 1989). ABG in a fairway height of cut turf (1.6 cm) required less water than CBG (Blankenship, 2011). Differences in VWC at a 3.8 and 12.2 cm depth could be associated with rooting habits differences between species. Traffic treatments were also shown to increase soil VWC, possibly through compaction on a USGA sand based putting green; however, this was not measured in this study. Future studies may include quantifying soil compaction and porosity on a USGA sand based putting green to make correlations to VWC under various irrigation and traffic treatments.

Table 2. Effects of species (S), irrigation (I), and traffic (T) treatments on volumetric water content (VWC) at a 3.8 cm depth. East Lansing, MI 2013.

2013 Treatment		Volumetric Water Content (0-100%)													
		11-Jun	17-Jun	24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	3-Sep	10-Sep
Species (S)	ABG	16.7 b[u]	15.4 b	19.7 b	17.2	21 b	18.7	19.3 b	18.5 b	18 b	18.8 b	19.5	20.2	18.9	20.6
	CBG	17.8 a	17.5 a	21.1 a	18.4	22.5 a	20.3	22.2 a	20.6 a	19.5 a	20.4 a	20.8	20.7	19.2	20.8
LSD (P=0.05)[x]		0.9	1.1	1.3	NS	1	NS	1.3	1.4	1.4	1.5	NS	NS	NS	NS
Irrigation (I)	8	17	15.8 b	18.2 b	15.7 b	20.2 b	17.3 b	18.8 b	17.5 b	14.9 c	17.3 c	16.9 c	16.9 c	14.8 c	16.9 c
	12	16.8	15.5 b	20.7 b	17.7 ab	21.5 ab	19.4 ab	20.1 b	19 b	19.1 b	19.4 b	20.1 b	20.2 b	18.6 b	20.4 b
	16	18	18 a	22.3 a	20.1a	23.7 a	21.8 a	23.3 a	22 a	22.3 a	22.1 a	23.4 a	24.3 a	23.7 a	25 a
LSD (P=0.05)		NS	1.9	2.9	2.6	2.2	2.1	1.8	2	2.2	1.7	1.9	2.3	2.3	2.2
S x I		NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
Traffic (T)	Low	17.1	16.5	20.2	17.7	21.8 ab	19.5	20.9	19.4	18.6	19.5	20 ab	20.6	18.9	21.1
	Moderate	17.6	16.8	21.2	18.5	22.7 a	20.4	21.8	20.4	19.9	20.8	21.3 a	21.7	20.1	21.6
	Control	17.1	16.1	19.8	17.2	20.7 b	18.6	19.5	18.8	17.8	18.6	19.1 b	19.1	18.1	19.5
LSD (P=0.05)		NS	NS	NS	NS	1.3	NS	NS	NS	NS	NS	1.5	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively

[u] Within columns, means followed by the same letter not significantly different; Fisher's least significant difference at P ≤0.05.

Table 3. Effects of species (S), irrigation (I), and traffic (T) treatments on volumetric water content (VWC) at a 3.8 cm depth. East Lansing, MI 2014.

2014 Treatment		Volumetric Water Content (0-100%)															
		5-Jun	9-Jun	16-Jun	23-Jun	30-Jun	7-Jul	14-Jul	21-Jul	28-Jul	4-Aug	11-Aug	18-Aug	25-Aug	2-Sep	11-Sep	15-Sep
Species (S)	ABG	17.4	17.1	14.2	15.9	19.1	20.3	18	18.1	17.6	17.5	19	18.1	17.7	17.8	18.5	17.2
	CBG	16.5	16.3	13.7	16.5	19.5	21	17.8	18.2	18.6	18.3	19.3	17.2	18.6	18.8	18.7	18.3
LSD (P=0.05)[x]		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	8	16.5 b[u]	15.9 b	11.2 b	12.6 c	16.2 c	18.3 c	14.5 c	13.3 c	13.1 c	11.5 c	11.9 c	11.5 c	11.6 c	13.5 c	14.1 c	12.6 c
	12	16.5 b	16.3 b	13.5 b	16.8 b	19.1 b	20.4 b	17.4 b	18.5 b	19.1 b	18.5 b	20.4 b	18.3 b	19 b	18.9 b	18.8 b	18.1 b
	16	17.9 a	18.1 a	17.3 a	19.1 a	22.7 a	23.3 a	21.9 a	22.7 a	22.1 a	23.6 a	25.2 a	23.2 a	23.8 a	22.7 a	23.1 a	22.6 a
LSD (P=0.05)		1.3	1.6	2.6	1.9	1.8	1.4	1.4	1.6	2.8	3.8	3.6	3.1	2.7	2.6	2.7	2.3
S x I		NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	17.2 b	16.5 ab	14	16	19.5 b	20.6 b	18.1 a	18.2 ab	17.8	17.2 b	19.1	17.6	17.9 b	18 ab	18.9	17.5
	Moderate	17.8 a	17.6 a	14.9	17.6	20.5 a	21.8 a	18.9 a	19.6 a	19.8	20.6 a	21.6	19.8	20.1 a	20 a	20.1	19.4
	Control	15.9 c	16.1 b	13.1	15	18.1 c	19.6 b	16.8 b	16.8 b	16.7	15.9 b	16.8	15.7	16.4 b	17 b	16.9	16.4
LSD (P=0.05)		0.5	0.8	NS	NS	0.6	1	0.9	1.5	NS	3	NS	NS	1.9	2.2	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at $P \leq 0.05$.

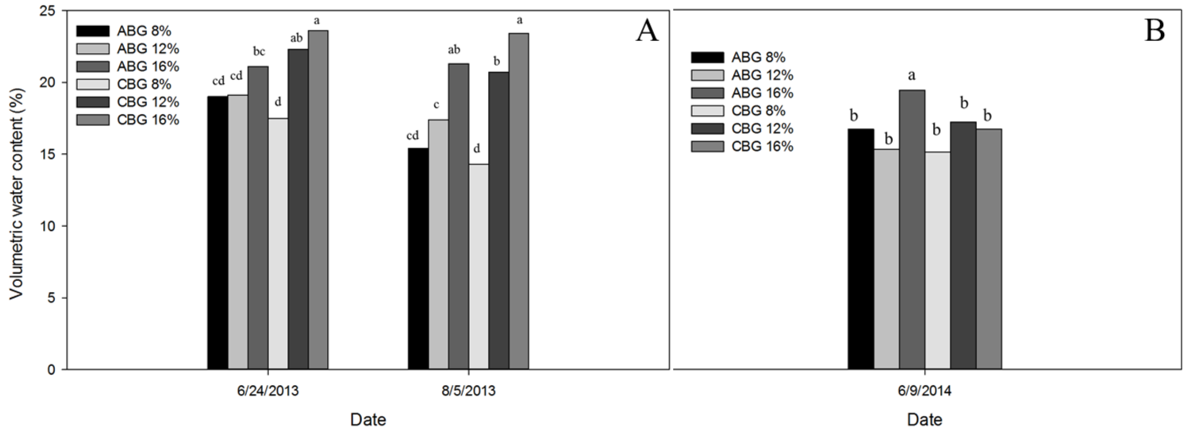

Figure 3. (A) Volumetric water content of the species x irrigation interaction in annual bluegrass (ABG) and creeping bentgrass (CBG) under 8, 12 and 16% irrigation treatment treatments from the surface to a 3.8 cm depth in 2013 on 24 June and 5 August and (B) 2014 on 9 June in East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Table 4. Effects of species (S), irrigation (I), and traffic (T) treatments on volumetric water content (VWC) at a 12.2 cm depth. East Lansing, MI 2013.

2013 Treatment		Volumetric Water Content (0-100%)													
		11-Jun	17-Jun	24-Jun	1-Jul	8-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	3-Sep	10-Sep	16-Sep
Species (S)	ABG	24.2 b[u]	23.3 b	23.8 b	23.5 b	27.3 b	28.8 b	26.3 b	29.1 b	24.8 b	26	26.2 b	24.3	25.7	25.7 b
	CBG	27 a	25.6 a	26.9 a	25.7 a	29.1 a	31.7 a	28.2 a	31.2 a	27.8 a	27.4	27.8 a	25.7	26.9	28 a
LSD (P=0.05)[x]		0.6	1.5	1.9	1.4	1.5	1.6	1.7	1.7	1	NS	1.6	NS	NS	1.4
Irrigation (I)	8	25.1	24.1	22.8 b	21.7 c	25.5 b	27.2 c	24.5 b	26.2 c	24.1 c	23.3 c	23.8 c	20.7 c	22.2 c	23.3 c
	12	25.4	23.6	26 a	24.5 b	28.9 a	30.5 b	27 b	29.7 b	26 b	26.5 b	26.6 b	24.6 b	26.3 b	26.4 b
	16	26.5	25.6	27.2 a	27.6 a	30.2 a	33.1 a	30.2 a	34.5 a	28.7 a	30.3 a	30.5 a	29.8 a	30.3 a	30.9 a
LSD (P=0.05)		NS	NS	2.7	2.3	2	2.2	2.6	2.8	1.6	2.1	2.3	2	2	1.8
S x I		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Traffic (T)	Low	25.5	24.6	25.5	24.5	28.6	30.5 ab	27.5	30.1	26.3	26.9	27.2 a	24.8	25.7	26.6
	Moderate	25.8	24.5	25.9	25.2	28	31.6 a	27.4	31.4	26.9	27.6	27.8 a	26.3	27.6	27.6
	Control	25.6	24.3	24.6	24.1	28	28.8 b	26.8	28.8	25.6	25.7	25.9 b	24	25.6	26.4
LSD (P=0.05)		NS	NS	NS	NS	NS	1.8	NS	NS	NS	NS	1.2	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively

[u] Within columns, means followed by the same letter not significantly different; Fisher's least significant difference at P ≤0.05.

Table 5. Effects of species (S), irrigation (I), and traffic (T) treatments on volumetric water content (VWC) at a 12.2 cm depth. East Lansing, MI 2014.

2014 Treatment		Volumetric Water Content (0-100%)														
		28-May	5-Jun	9-Jun	16-Jun	23-Jun	30-Jun	7-Jul	14-Jul	21-Jul	28-Jul	4-Aug	11-Aug	18-Aug	25-Aug	2-Sep
Species (S)	ABG	25 b[u]	25.6 b	25.5 b	23.5	28.5 b	26.2	26.5 b	24.5 b	24.1	23.2 b	23.9	25.1 b	24.5	24 b	25 b
	CBG	26.4 a	27.4 a	27.3 a	24.8	31.5 a	28.1	29 a	26.4 a	26.3	26.9 a	26.1	27.7 a	25.8	26.7 a	28.1 a
LSD (P=0.05)[x]		1	1	1.2	NS	1.6	NS	1.3	1.8	NS	2	NS	2.4	NS	2.2	1.9
Irrigation (I)	8	25.3	25.8	26	21.1 c	28.6 b	23.6 c	25.3 b	21.5 c	19.2 c	19.4 c	18 c	19.7 c	18.4 c	18.7 c	21.7 c
	12	25.4	26.6	26.3	23.3 b	29.3 b	26.5 b	26.9 b	24.9 b	25.5 b	25.7 b	25.8 b	27.1 b	26.4 b	26.5 b	27.4 b
	16	26.4	27.1	27	28.2 a	32.1 a	31.4 a	31.1 a	30 a	30.9 a	30 a	31.1 a	32.4 a	30.7 a	30.9 a	30.6 a
LSD (P=0.05)		NS	NS	NS	1.7	2.4	2.1	1.9	2.1	2.5	3	3.5	3	2.6	3	3.2
S x I		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	25.5 b	26.3 ab	26	24.3	30.1	27.1	27.5	25.6 ab	25.1	24.9	25 ab	26.3	25.3	25.2	26.5
	Moderate	26.6 a	27.2 a	27.2	24.9	30.9	28	28.5	26.1 a	26.2	26.4	26.9 a	27.9	26.7	26.6	27.5
	Control	25.1 b	26 b	26.1	23.3	29.1	26.5	27.3	24.7 b	24.3	23.8	23 b	25	23.5	24.3	25.7
LSD (P=0.05)		0.6	0.9	NS	NS	NS	NS	NS	0.7	NS	NS	2.8	NS	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at $P \leq 0.05$.

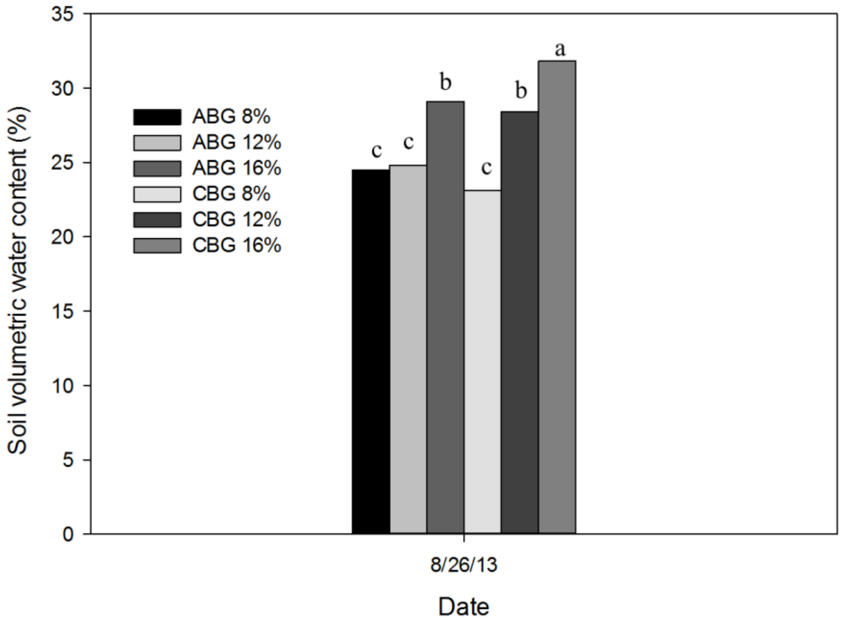

Figure 4. Volumetric water content (VWC) of annual bluegrass (ABG) and creeping bentgrass (CBG) under 8, 12 and 16% irrigation treatments from the surface to a 12.2 cm depth in 2013, results obtained 26 August in East Lansing, MI. Different letters indicate significant differences among irrigation treatments within the given day; Fisher's least significant difference at $P \leq 0.05$.

Relative water content

On one date in 2014, a species x irrigation interaction was significant with CBG having higher RWC at the 8% irrigation treatment when compared with ABG at the 8% irrigation treatment in 2014 (Figure 5A). In 2013, species had a significant effect on three dates in which CBG had higher RWC's when compared with ABG (Table 6). Research conducted on annual grasses (annual ryegrass and ABG) and perennial grasses (perennial ryegrass and rough bluegrass) showed that annual grasses had more of a pronounced decrease in RWC when compared to perennial grasses in response to drought stress (Yang et al., 2014) There were three dates which a significant traffic x irrigation interaction occurred (Figure 5B) concluding that the moderate traffic at the 8% irrigation treatment had higher RWC when compared with the control at the 8% irrigation treatment on all three dates. This could be due to an increase soil water content due to compaction from traffic treatments. Agnew and Carrow (1985) explain that an increase in soil compaction on Kentucky bluegrass plots can increase soil moisture content in a sandy loam soil. The results from the current experiment demonstrate that traffic treatments increasing soil VWC under a deficit (8%) irrigation treatment. This can then be correlated to an increase in leaf internal water status (RWC). Future experiments could quantify compaction in a USGA sand based root putting green from traffic treatments and make correlations to leaf RWC.

Table 6. Effects of species (S), irrigation (I), and traffic (T) treatments on leaf relative water content in East Lansing, MI. 2013.

2013 Treatment		Relative water content (0-100%)									
		7-Jun	18-Jun	2-Jul	9-Jul	16-Jul	23-Jul	30-Jul	6-Aug	20-Aug	3-Sep
Species (S)	ABG	84.4	74.5	84	75.5 b[u]	64.8 b	70.1 b	69.8	76.9	79.1	72.5
	CBG	82.7	76.9	84.1	90.5 a	70.7 a	75.7 a	73.8	80.3	80.1	74.6
LSD (P=0.05)[x]		NS	NS	NS	11.8	5.7	4.8	NS	NS	NS	NS
Irrigation (I)	8	83	79.1	82.9	86	70.7	70.3	71.7	77.8	75.5 b	72.5
	12	85	75.2	85.8	74.9	63.6	70.7	70.7	78.3	80.6 a	73.9
	16	82.6	72.9	83.4	88.1	68.9	77.7	72.9	79.7	82.7 a	74.3
LSD (P=0.05)		NS	NS	NS	NS	NS	NS	NS	NS	4.1	NS
S x I		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	83.6	77.5	84.2	78.7	68.6	72.5	73.4	78.4	81.2 a	74.6 a
	Moderate	83.3	75.9	81.8	87.1	65	75.2	69.6	76.3	75.9 b	71.2 b
	Control	83.7	73.7	86.1	83.2	69.6	70.9	72.3	81.1	81.8 a	74.9 a
LSD (P=0.05)		NS	NS	NS	NS	NS	NS	NS	NS	2.3	1.8
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different; Fisher's least significant difference at P ≤0.05.

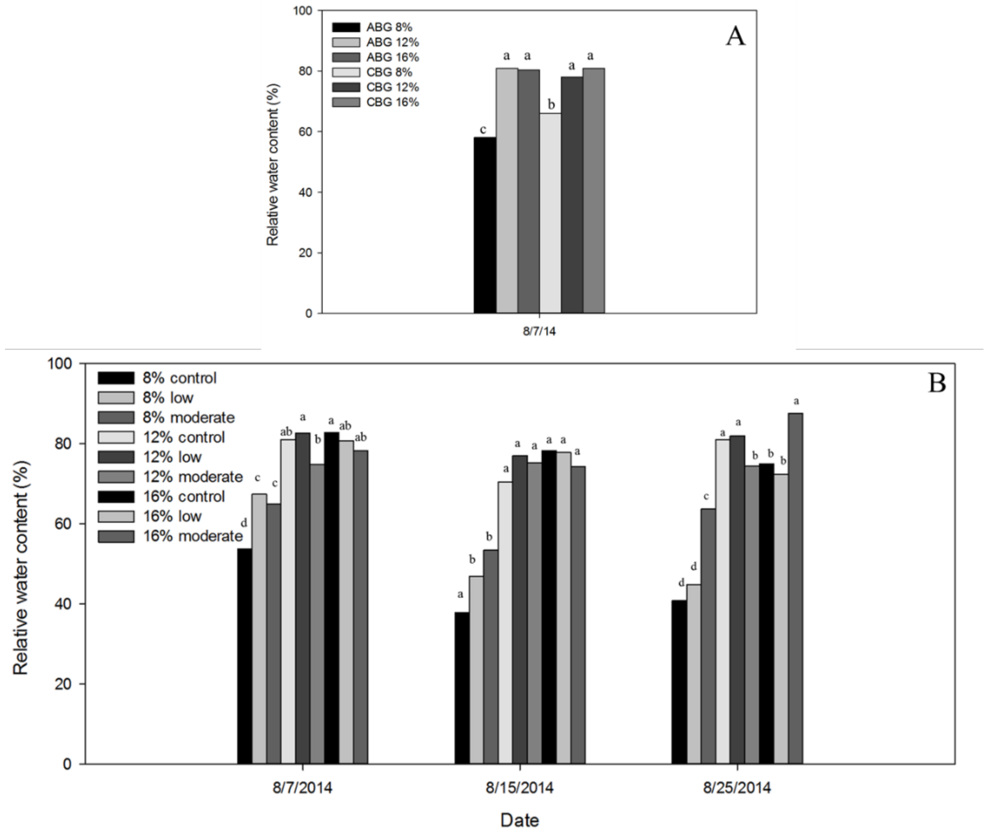

Figure 5. Leaf relative water content (RWC) of (A) species x irrigation interaction in 2014, results obtained 7 August. East Lansing, MI and (B) irrigation x traffic interaction in 2014, results obtained 7 August, 15 August, and 25 August. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

NDVI

A species x irrigation interaction occurred on three dates in 2013 and on three dates in 2014 (Figure 6A and B). CBG at the 8, 12 and 16% irrigation treatments had higher NDVI than ABG at 8, 12 and 16% irrigation treatments in 2013 and 2014. On one date (30 June, 2014), there was a species x traffic interaction. CBG and ABG had higher NDVI values under the non-trafficked control treatment when compared to the moderate traffic treatment (Figure 7). In 2013 and 2014, CBG had higher NDVI values when compared with ABG on all dates data were significant (Table 7 and 8). Irrigation treatments were significant on six dates in 2013 and one date in 2014. The 16% irrigation treatment had higher NDVI when compared with the 8% irrigation treatment in 2013 and 2014 (Table 7 and 8). Traffic treatments had a significant effect on six dates in 2013 with the moderate traffic treatment having lower NDVI values when compared to the non-trafficked. NDVI measurements are highly correlated to visual shoot density, quality, and color of seashore paspalum (*Paspalum vaginatum* Swartz) and hybrid bermudagrass (*Cynodon dactylon*) (Trenholm et al., 1999). However, there is limited research on comparing NDVI values of ABG to CBG under irrigation and traffic treatments. The results from the current research show that traffic treatments and irrigating to an 8% irrigation treatment on a USGA sand based putting green decrease NDVI values, which could be a result from decreased shoot density.

Table 7. Effects of species (S), irrigation (I), and traffic (T) treatments on normalized difference vegetation index (NDVI) East Lansing, MI 2013.

2013 Treatment		NDVI (0.000-1.000)											
		24-Jun	1-Jul	8-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	3-Sep	10-Sep	16-Sep
Species (S)	ABG	0.677 b[u]	0.663 b	0.677 b	0.596 b	0.660 b	0.665 b	0.674 b	0.681 b	0.679 b	0.743 b	0.754 b	0.754 b
	CBG	0.706 a	0.683 a	0.701 a	0.636 a	0.708 a	0.720 a	0.710 a	0.706 a	0.703 a	0.755 a	0.761 a	0.771 a
LSD (P=0.05)[x]		0.009	0.010	0.012	0.029	0.008	0.011	0.009	0.008	0.010	0.007	0.007	0.007
Irrigation (I)	8	0.686	0.669	0.688	0.614	0.680	0.686	0.692	0.686	0.688	0.746	0.752 b	0.761
	12	0.691	0.675	0.686	0.615	0.686	0.695	0.691	0.699	0.696	0.752	0.759 ab	0.760
	16	0.698	0.675	0.693	0.617	0.686	0.697	0.694	0.695	0.689	0.749	0.761 a	0.767
LSD (P=0.05)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.007	NS
S x I		NS	NS	NS	NS	NS	NS	*	NS	NS	*	NS	*
Traffic (T)	Low	0.691	0.671 ab	0.686	0.622	0.687 a	0.697 a	0.694 b	0.693	0.694 a	0.756 a	0.760	0.763 ab
	Moderate	0.683	0.669 b	0.685	0.612	0.665 b	0.675 b	0.677 c	0.685	0.673 b	0.733 b	0.744	0.750 b
	Control	0.700	0.679 a	0.696	0.613	0.700 a	0.705 a	0.706 a	0.703	0.706 a	0.758 a	0.769	0.774 a
LSD (P=0.05)		NS	0.003	NS	NS	0.015	0.008	0.007	NS	0.019	0.016	NS	0.013
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at P $\leq$0.05.

Table 8. Effects of species (S) irrigation (I), and traffic (T) treatments on normalized difference vegetation index (NDVI) East Lansing, MI 2014.

2014 Treatment		NDVI (0.000-1.000)										
		5-Jun	16-Jun	25-Jun	30-Jun	7-Jul	21-Jul	28-Jul	11-Aug	18-Aug	25-Aug	4-Sep
Species (S)	ABG	0.699	0.741	0.760 b[u]	0.769	0.751 b	0.727	0.726 b	0.715 b	0.723	0.731	0.724
	CBG	0.703	0.740	0.772 a	0.772	0.768 a	0.708	0.739 a	0.733 a	0.739	0.747	0.725
LSD (P=0.05)[x]		NS	NS	0.007	NS	0.013	NS	0.009	0.016	NS	NS	NS
Irrigation (I)	8	0.699	0.739	0.763	0.763 b	0.753	0.680	0.711 b	0.692 b	0.698 b	0.723 b	0.721 ab
	12	0.703	0.739	0.768	0.773 a	0.758	0.740	0.738 ab	0.740 a	0.746 a	0.748 a	0.705 b
	16	0.701	0.742	0.768	0.776 a	0.767	0.733	0.747 a	0.740 a	0.750 a	0.747 a	0.748 a
LSD (P=0.05)		NS	NS	NS	0.007	NS	NS	0.028	0.034	0.037	0.017	0.026
S x I		NS	*	NS	NS	*	NS	*	NS	NS	NS	NS
Traffic (T)	Low	0.704	0.742	0.769	0.766 b	0.762	0.734	0.733	0.732	0.727	0.738	0.724
	Moderate	0.704	0.738	0.766	0.768 b	0.757	0.692	0.737	0.722	0.731	0.739	0.730
	Control	0.695	0.740	0.764	0.778 a	0.761	0.727	0.728	0.718	0.736	0.741	0.720
LSD (P=0.05)		NS	NS	NS	0.005	NS	NS	NS	NS	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively

[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at P ≤0.05.

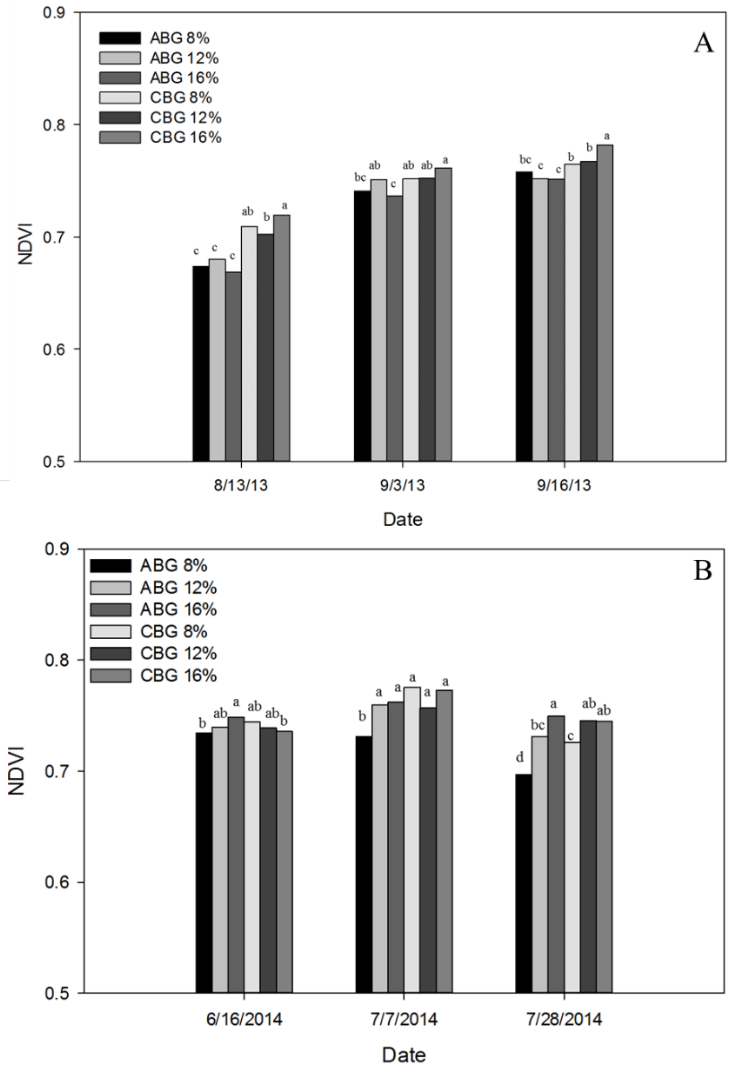

Figure 6. Normalized difference vegetation index (NDVI) of species x irrigation interaction in (A) 2013, results obtained 13 August, 3 September, and 16 September. East Lansing, MI. and (B) 2014, results obtained 16 June, 7 July, and 28 July. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

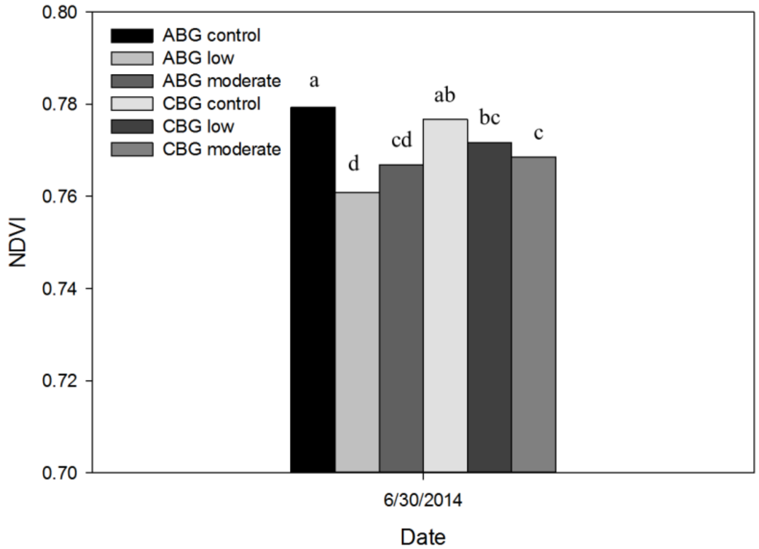

Figure 7. Normalized difference vegetation index (NDVI) of species x traffic interaction in 2014, results obtained 30 June. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Chlorophyll content

In 2013 and 2014, canopy chlorophyll content was significantly different between species. CBG had higher chlorophyll content than ABG on all dates when significant differences were detected (Figure 8A and B). Significant differences were not detected among irrigation and traffic treatments. No interactions existed among treatments. These results are supported by previous research showing that CBG has naturally higher chlorophyll content when compared to ABG grown in 5:3:1, v/v/v (sandy loam:sand:peat moss) soil under greenhouse conditions (Gaussoin et al., 1997). The results from the current research show that CBG has greater chlorophyll content when compared to ABG under traffic and irrigation treatments on a USGA sand based putting green.

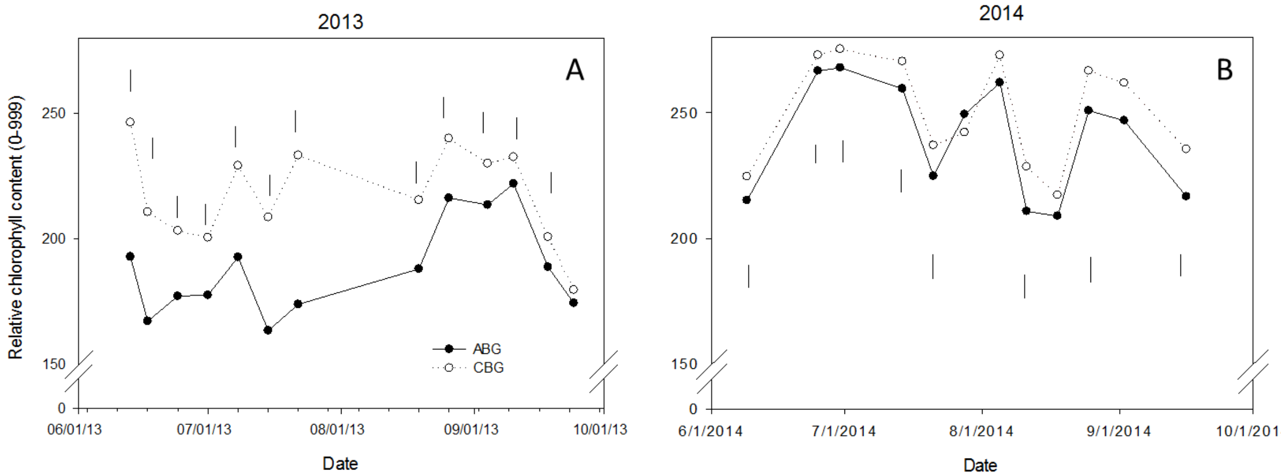

Figure 8. Relative chlorophyll content of annual bluegrass (ABG) and creeping bentgrass (CBG) in (A) 2013 and (B) 2014. East Lansing, MI. Vertical least significant difference (LSD) bars represent Fisher's least significant difference values ($P \leq 0.05$) for irrigation treatment comparison at a given day.

Electrolyte leakage

No significant differences were found between species, irrigation, or traffic treatments in 2013. Four dates in 2014 had a significant species x irrigation interaction. ABG had higher EL at the 8% irrigation treatment when compared with CBG at the 8% irrigation treatment (Figure 9). Yang et al. (2014) shows that annual grass species (annual ryegrass and ABG) are more susceptible to abiotic stresses, such as heat stress, and have increased EL when compared with perennial grass species (perennial ryegrass and rough bluegrass). The results from the current research show that ABG has lower membrane stability (higher EL) compared to CBG under an 8% irrigation treatment in a USGA sand based putting green, which simulates a water deficit situation.

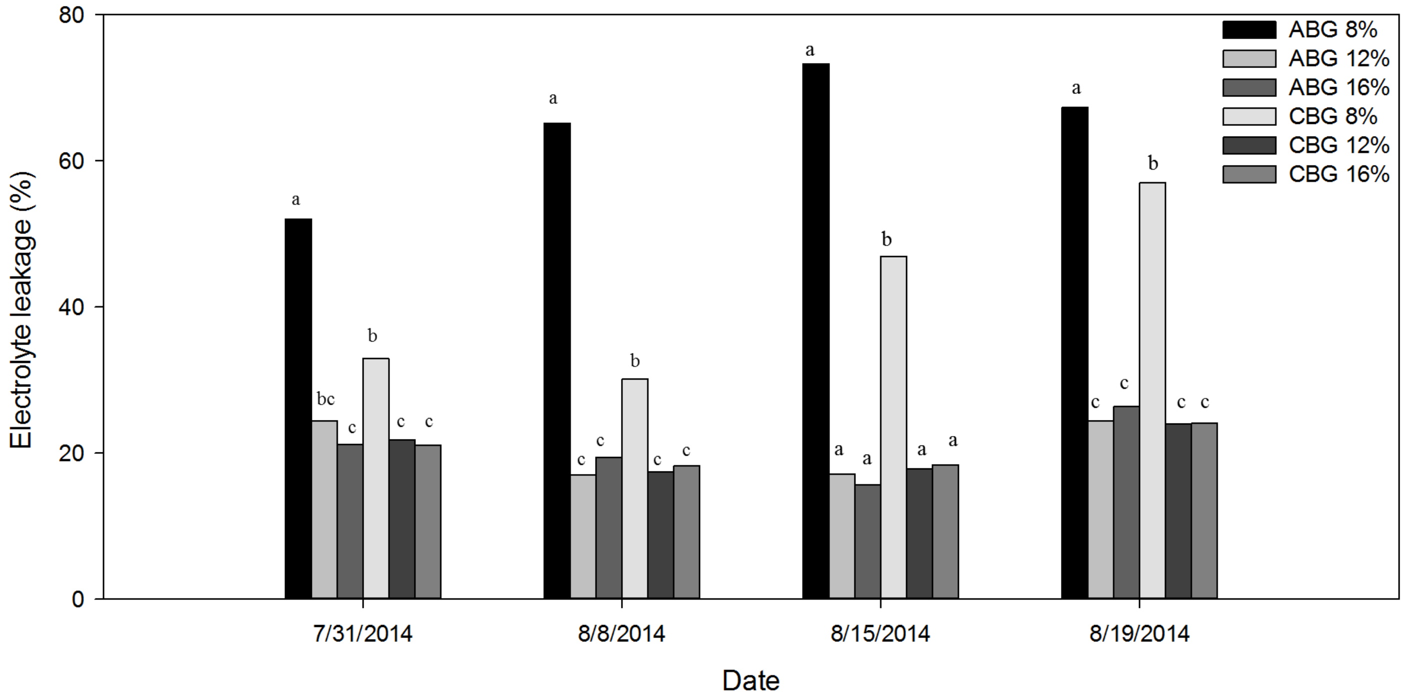

Figure 9. Electrolyte leakage (EL) of species x irrigation interaction in 2014, results obtained 31 July, 8 August, 15 August, and 19 August. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Turfgrass quality

Significant species x irrigation interaction occurred on one date in 2013, which shows that as the irrigation treatment increases (8% < 12% < 16%), ABG turfgrass quality decreases. CBG turfgrass quality was not affected by irrigation treatments. (Figure 10A). In 2014, there was a significant species x irrigation interaction on one date. On 7 July, CBG at 12 and 16% irrigation treatments had higher turfgrass quality than ABG at the 12 and 16% irrigation treatments respectively (Figure 10B). Species treatments were significant on ten dates in 2013 (Table 9) and on six dates in 2014 (Table 10) in which CBG had higher turfgrass quality than ABG. This is consistent with previous research showing that wear from mechanical stress and foot traffic decreased turfgrass quality in CBG cultivars on a USGA sand based putting green (Young et al., 2015). On two dates, an irrigation x traffic interaction occurred. On these dates, as the amount of traffic applied at each irrigation treatment increased, turfgrass quality deceased. (Figure 11). Irrigation treatment had a significant effect on turfgrass quality which shows that the 12 and 16% irrigation treatments had greater turfgrass quality than the 8% irrigation treatment (Table 9 and 10). Traffic treatment effects were significant on thirteen dates in 2013, in which the control and low traffic treatment had higher turfgrass quality than the moderate traffic treatment (Table 9 and 10). Previous research support this since traffic to a bermudagrass fairway decreased turfgrass quality at 0.6, 0.45, 0.3, and 0.0 × ET replacement irrigation treatments on a fine sandy loam soil (Hejl et al., 2016). Results from the current research show that higher turfgrass quality can be associated with increased membrane stability (lower EL) and higher water retention in leaf tissue (RWC) which were all characteristics of CBG when compared to ABG on a USGA sand based putting green.

Table 9. Effects of species (S), irrigation (I), and traffic (T) treatments on turfgrass quality. East Lansing, MI 2013.

2013 treatment		Turfgrass Quality (1-9)													
		24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	5-Sep	11-Sep	16-Sep	24-Sep
Species (S)	ABG	6	6.7	6.6	6.1 b[u]	4.9 b	5 b	5.4 b	5.7 b	6.1 b	6.1 b	6.8	6 b	6 b	6.2
	CBG	6.3	6.7	6.9	6.6 a	7.1 a	6.8 a	6.9 a	6.9 a	7.1 a	6.9 a	7.2	6.7 a	6.8 a	6.3
LSD (P=0.05)[x]		NS	NS	NS	0.5	0.6	0.5	0.4	0.4	0.4	0.4	NS	0.4	0.3	NS
Irrigation (I)	8	5.9	6.6	6.6	6.2	5.9	6	6.2	6.1	6.5	6.3	7	5.9 b	6.2 b	6.1
	12	6.3	6.7	6.6	6.3	6.1	5.9	6.2	6.4	6.7	6.7	7.1	6.8 a	6.6 a	6.4
	16	6.3	6.9	6.9	6.6	6	5.7	6	6.3	6.7	6.6	6.9	6.3 ab	6.4 ab	6.3
LSD (P=0.05)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.5	0.3	NS
S x I		NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	6.1	6.7 b	7 a	6.1	6.2 a	6.1 a	6.3 a	6.6 b	6.9 a	6.9 b	7.3 a	6.8 a	6.7 a	6.6 a
	Moderate	5.8	6.1 c	5.9 b	6.4	5.4 b	5.1 b	5.2 b	4.9 c	5.7 b	5.2 c	5.9 b	5.1 b	5.1 b	5.3 b
	Control	6.7	7.4 a	7.2 a	6.6	6.5 a	6.5 a	6.9 a	7.3 a	7.3 a	7.4 a	7.8 a	7.2 a	7.4 a	6.9 a
LSD (P=0.05)		NS	0.3	0.4	NS	0.4	0.4	0.9	0.6	0.4	1.1	1.2	0.7	0.6	0.6
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively

[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at P ≤ 0.05.

Table 10. Effects of species (S), irrigation (I), and traffic (T) treatments on turfgrass quality. East Lansing, MI 2014.

2014 treatment		Turfgrass Quality (1-9)										
		6-Jun	10-Jun	25-Jun	30-Jun	7-Jul	14-Jul	22-Jul	28-Jul	5-Aug	19-Aug	27-Aug
Species (S)	ABG	6.5	6.1	7	7.1 b[u]	6.9 b	6.9	6.2 b	5.9 b	5.6 b	5.6	5.8
	CBG	7.1	5.8	7.4	7.6 a	7.4 a	7.3	7.1 a	6.8 a	6.3 a	5.6	5.6
LSD (P=0.05)[x]		0.5	NS	NS	0.3	0.4	NS	0.4	0.6	0.6	NS	NS
Irrigation (I)	8	6.6	5.9	7.1 b	7.3	7.1	6.7 b	5.8 b	5.3 b	4.8 b	4.5 b	4.7 b
	12	6.7	5.9	7.1 b	7.3	7.1	7 ab	6.9 a	6.7 a	6.3 a	5.9 a	6.2 a
	16	7.1	6.1	7.6 a	7.4	7.2	7.6 a	7.1 a	7 a	6.8 a	6.4 a	6.1 a
LSD (P=0.05)		NS	NS	0.3	NS	NS	0.6	0.7	1.3	1	0.9	0.9
S x I		NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	6.8	5.8 b	7.3 a	7.4	7.3	7.2	6.7	6.4	5.9	5.9	6.2
	Moderate	6.9	6.6 a	7.6 a	6.9	6.7	6.8	6.3	6.2	6.1	5.2	5.1
	Control	6.6	5.5 b	6.8 b	7.7	7.3	7.2	6.8	6.4	5.8	5.8	5.8
LSD (P=0.05)		NS	0.4	0.4	NS	NS	NS	NS	NS	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at P ≤0.05.

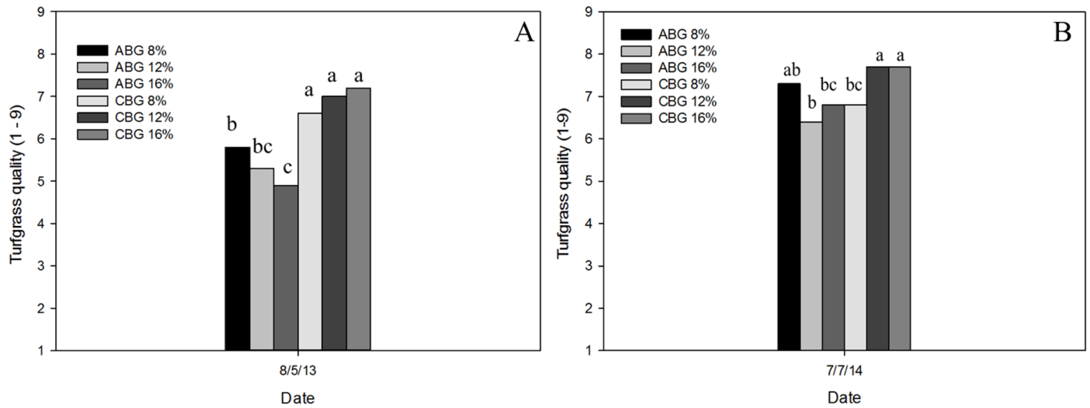

Figure 10. Turfgrass quality of species x irrigation interaction in (A) 2013, results obtained 5 August. East Lansing, MI. and (B) 2014, results obtained 7 July. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

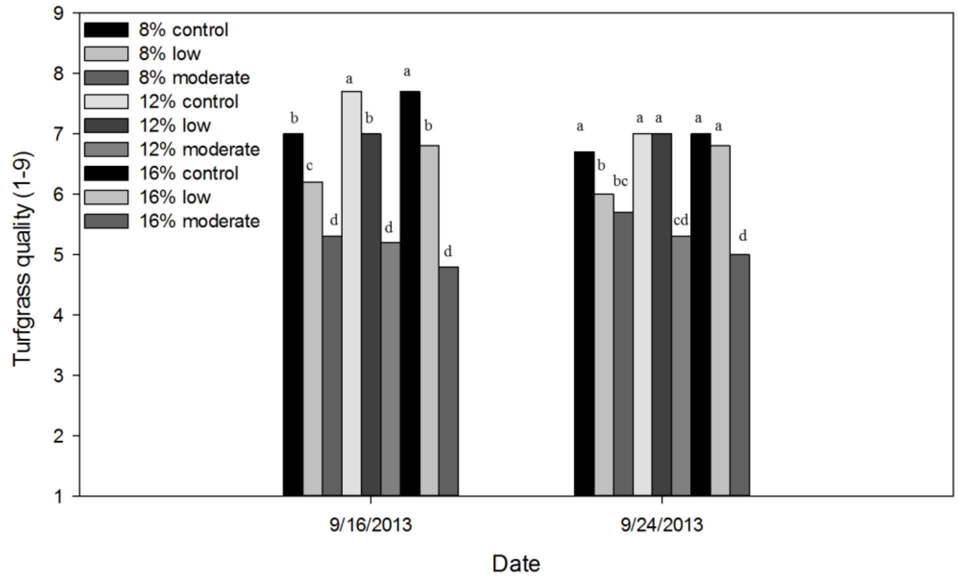

Figure 11. Turfgrass quality of irrigation x traffic interactions in 2013, results obtained 16 September and 24 September. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Ethylene gas evolution

There was a significant species x irrigation interaction on one date in 2013. ABG had greater ethylene production at the 8 and 16% irrigation treatment when compared to the 12% irrigation treatment (Figure 12A). Other species (alfalfa and rice) produce more ethylene under drought and partially submerged conditions (Irigoyen et al., 1992, Metraux and Kende, 1983). There were two dates a species x traffic interaction occurred. ABG produced more ethylene on the non-trafficked plot when compared to CBG on the non-trafficked plot in 2013 (Figure 12B) and ABG under moderate traffic produced greater ethylene than CBG under moderate traffic in 2014 (Figure 13). Other stress experiments observed ethylene production in CBG to increase under abiotic stress (salinity) when compared with non-stressed plants (Krishnan and Merewitz, 2015). Exogenous application of ethylene gas to CBG resulted in no quality or density differences when compared to non-ethylene treated plants (Strunk, 2015; Karcher 2011). Our results show that an abiotic stress, such as simulated traffic, can increase ethylene gas production in ABG on a USGA sand based putting green.

In 2013, species had a significant effect on one date with ABG producing more ethylene when compared to CBG (Table 11). Irrigation treatments were significant on two dates in 2013 and on one date in 2014. On both dates in 2013 the 16% irrigation treatment had greater ethylene production when compared to 8% irrigation treatment (Table 11). However, in 2014 the 8% irrigation treatment had greater ethylene production than the 16% irrigation treatment (Figure 13). Ethylene is known as a stress response hormone. Research has shown that under abiotic stress conditions (drought and flooding) ethylene gas production can be elevated. Banga et al. (1996) describes that completely submerged *R. acetosella* plants have lower ethylene release than non-submerged plants. Metraux and Kende (1983) found that partially submerging a plant (rice) increases ethylene released. Research on alfalfa leaves describe that under slight drought stress, ethylene evolution is highly stimulated while under severe drought stress ethylene evolution was inhibited (Irigoyen et al., 1992). Traffic treatment effects were significant on one date in 2014, with the moderate traffic treatment having greater ethylene production than the low and control treatments in 2014 (Table 12). There is limited to no research showing ethylene production in ABG and CBG. Our results are some of the first to report measuring ethylene gas production from these species under traffic and irrigation treatments on a USGA sand based putting green. Results show that ABG produces more ethylene than CBG under 8 and 16% irrigation treatments. Ethylene gas production increased as the amount of traffic applied to ABG plot areas increased. This shows that abiotic stress from irrigation and traffic treatments increases ethylene production in ABG when compared to CBG. Ethylene evolution may be a viable and informative method to evaluate stress levels on putting greens and in other turfgrass systems.

Table 11. Effects of species (S), irrigation (I), and traffic (T) treatments on ethylene production. East Lansing, MI 2013.

2013 treatment		Ethylene Production (ppb/min)										
		20-Jun	11-Jul	1-Aug	9-Aug	15-Aug	21-Aug	29-Aug	5-Sep	11-Sep	18-Sep	25-Sep
Species (S)	ABG	11.3	9.1	1.4	2	3.2	4.7	11.4	3.8	7.1	5.1 a	5.4
	CBG	7.5	6.2	1.3	1.7	3.5	4.1	11.2	4.1	6.2	3.1 b	4.6
LSD (P=0.05)[x]		NS	NS	NS	NS	NS	NS	NS	NS	NS	1.7	NS
Irrigation (I)	8	9.5	8.3	0.9	1.3	2.8	4.2	9.6	3.1 b	5.8	3.6	4.3 b[u]
	12	5.2	7.6	2.1	2.2	2.3	4.3	13.7	4.3 a	7.3	2.6	5 a
	16	13.6	7	1.1	2	4.9	4.8	10.7	4.4 a	6.9	6.2	5.7 a
LSD (P=0.05)		NS	NS	NS	NS	NS	NS	NS	1.2	NS	NS	1.3
S x I		*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	9.7	8.4	1.7	2.4	4.2	4.9	11.3	6.3	9.1	3.9	4.4
	Moderate	8.4	8.1	1.7	2.2	2.7	5.6	13.1	1.3	5.9	5.2	6.8
	Control	10.2	6.5	0.7	0.9	3.2	2.8	9.5	4.2	5	3.3	3.8
LSD (P=0.05)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T		*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at $P \leq 0.05$.

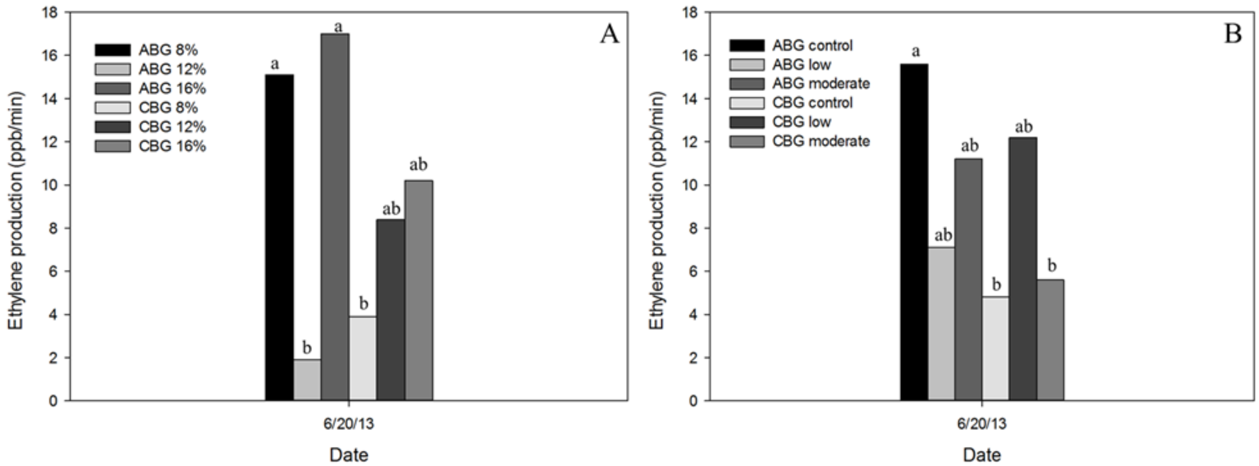

Figure 12. Ethylene gas production of (A) species x irrigation interaction in 2013, results obtained 20 June. East Lansing, MI. and (B) species x traffic interaction in 2013, results obtained 20 June. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher’s least significant difference at $P \leq 0.05$.

Table 12. Effects of species (S), irrigation (I), and traffic (T) treatments on ethylene production. East Lansing, MI 2014.

2014 treatment		Ethylene production (ppb/min)					
		19-Jun	10-Jul	22-Jul	6-Aug	28-Aug	18-Sep
Species (S)							
	ABG	6	10.6	11.3	14.5	11.1	9.7
	CBG	7.8	7.9	8	13.5	9.6	10.7
LSD (P=0.05)[x]		NS	NS	NS	NS	NS	NS
Irrigation (I)	8	8.4 a[u]	13.9	12.3	14.9	12.6	7.6
	12	7.4 a	7.6	6.8	12.9	7.8	7.6
	16	4.8 b	5.9	9.9	14.1	10.7	15.3
LSD (P=0.05)		2.8	NS	NS	NS	NS	NS
S x I		NS	NS	NS	NS	NS	NS
Traffic (T)	Low	6.9	8.5	8.1 b	12.5	10.8	10.3
	Moderate	7.3	7.9	13 a	17.8	11.6	12.9
	Control	6.4	11.5	7.8 b	11.6	8.7	7.3
LSD (P=0.05)		NS	NS	4.3	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	*	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different; Fisher's least significant difference at P ≤ 0.05.

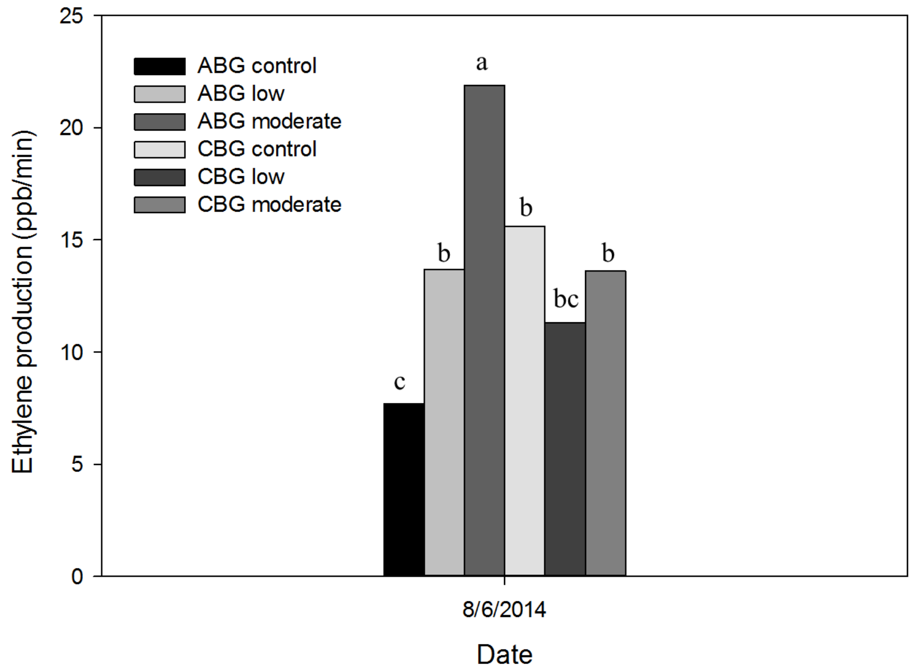

Figure 13. Ethylene gas production of species x traffic interaction in 2014, results obtained 6 August. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Root length

There was significant traffic x irrigation interaction on four dates in 2013. Low trafficked plots under a 12% irrigation treatment had longer roots when compared to the control traffic treatment at the 12% irrigation treatment. The low traffic at 8% irrigation treatment had longer roots on one date when compared to low traffic at 12 and 16% irrigation treatments (Figure 14A and 14B). Through the use of a brinkman traffic simulator, root length of *L. perenne* cultivars was increased under traffic conditions when compared to non-trafficked plots (Glab and Szewczyk, 2015). Qian and Fry (1996) found that zoysiagrass (*Zoysia japonica* Steud) watered everyday (100% ET replacement) had shorter root lengths when compared with turf watered after onset of leaf rolling (infrequently watered to 100% cumulative daily ET). Root lengths under low traffic treatments at an 8 and 12% irrigation treatment were greater when compared with other traffic and irrigation treatments.

In 2013, effects of species on root length were significantly different on all dates. CBG had longer roots than ABG (Table 13). This is consistent with previous research showing CBG had longer roots than ABG under fairway conditions in a loamy sand soil (Murphy et al., 1994). Irrigation treatments had a significant effect on root length on two dates in 2013 and one date in 2014. The 8% irrigation treatment had longer roots than the 16% irrigation treatment (Table 13 and 14). Traffic treatments were significantly different on five dates in 2013. This shows that moderately trafficked plots had shorter root lengths when compared with control plots while the low traffic treatment was no different from the control (Table 13). There is limited research pertaining to rooting lengths comparing ABG to CBG under traffic treatments in a USGA sand based soil. Our results indicate that traffic treatments at a moderate rate, negatively affect rooting length in a USGA sand based soil while low traffic treatments increased root length when compared to a non-trafficked control. Future research may investigate the role of sand content and distribution in a soil on rooting length of ABG and CBG.

Table 13. Effects of species (S), irrigation (I), and traffic (T) treatments on root length. East Lansing, MI 2013.

2013 Treatment		Rootlength (cm.)											
		14-Jun	18-Jun	27-Jun	4-Jul	11-Jul	17-Jul	25-Jul	1-Aug	9-Aug	15-Aug	21-Aug	29-Aug
Species (S)	ABG	3.8 b[u]	5 b	6 b	6.7 b	7.1 b	7.8 b	9.1 b	9.6 b	10.5 b	11 b	11.8 b	12.4 b
	CBG	11.1 a	11.7 a	13.7 a	14.1 a	14.8 a	15.1 a	15.2 a	15.5 a	15.6 a	15.4 a	15.7 a	15.6 a
LSD (P=0.05)[x]		2.7	2.7	2.6	2	2.2	1.9	1.9	2	2	1.8	1.6	1.8
Irrigation (I)	8	8.9 a	9.2	11.1 a	11.8	12	12.4	12.7	13.3	13.8	13.6	14.3	14
	12	7.3 ab	8.2	9.2 b	9.8	10.1	10.5	11.7	11.5	11.6	12.1	12.9	13.4
	16	6.1 b	7.7	9.3 b	9.5	10.8	11.5	12	13	13.8	13.9	14	14.6
LSD (P=0.05)		2	NS	1.6	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	7.3	8.4	10.4	11.8 a	11.5	12.2	13.4	13.5 a	14.1 a	14.1	15.2 a	15.4 a
	Moderate	7.7	8.8	10.1	9.7 b	10.5	11.1	11.6	11.6 c	12.2 b	12.6	12.5 b	12.4 b
	Control	7.3	8	9.1	9.7 b	10.8	11.1	11.4	12.6 b	12.9 b	12.9	13.5 b	14.2 a
LSD (P=0.05)		NS	NS	NS	1.5	NS	NS	NS	0.8	0.9	NS	1.8	1.4
S x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	*	NS	NS	NS	NS	*	*	NS	NS	*	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively

[u] Within columns, means followed by the same letter not significantly different;
Fisher's least significant difference at $P \leq 0.05$.

Table 14. Effects of species (S), irrigation (I), and traffic (T) treatments on root length. East Lansing, MI 2014.

2014 Treatment		Rootlength (cm.)							
		26-Jun	9-Jul	15-Jul	21-Jul	29-Jul	6-Aug	14-Aug	20-Aug
Species (S)	ABG	13.5	13.4	13	12.5	13	13	13	12.9
	CBG	13.2	13.3	13.3	11	13	13	13.5	13.5
LSD (P=0.05)[x]		NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	8	12.5	13.6	13	12.3 ab[u]	13.4	12.8	13.1	13.2
	12	13.2	13.9	13.8	13.6 a	13.7	13.7	14.2	13.8
	16	14.4	12.5	12.6	9.4 b	11.9	12.5	12.5	12.6
LSD (P=0.05)		NS	NS	NS	1.9	NS	NS	NS	NS
S x I		NS	NS	NS	NS	NS	NS	NS	NS
Traffic (T)	Low	12.5	13.7	13.7 a	12	13.8	13.7	13.7	13.7
	Moderate	13.5	13	13.4 a	12.2	12.5	13	13.4	13.1
	Control	14	13.3	12.4 b	11.1	12.8	12.3	12.6	12.9
LSD (P=0.05)		NS	NS	0.3	NS	NS	NS	NS	NS
S x T		NS	NS	NS	NS	NS	NS	NS	NS
I x T		NS	NS	NS	NS	NS	NS	NS	NS
S x I x T		NS	NS	NS	NS	NS	NS	NS	NS

[x] * and NS indicate significant and not significant at the 0.05 level of probability, respectively
[u] Within columns, means followed by the same letter not significantly different; Fisher's least significant difference at $P \leq 0.05$.

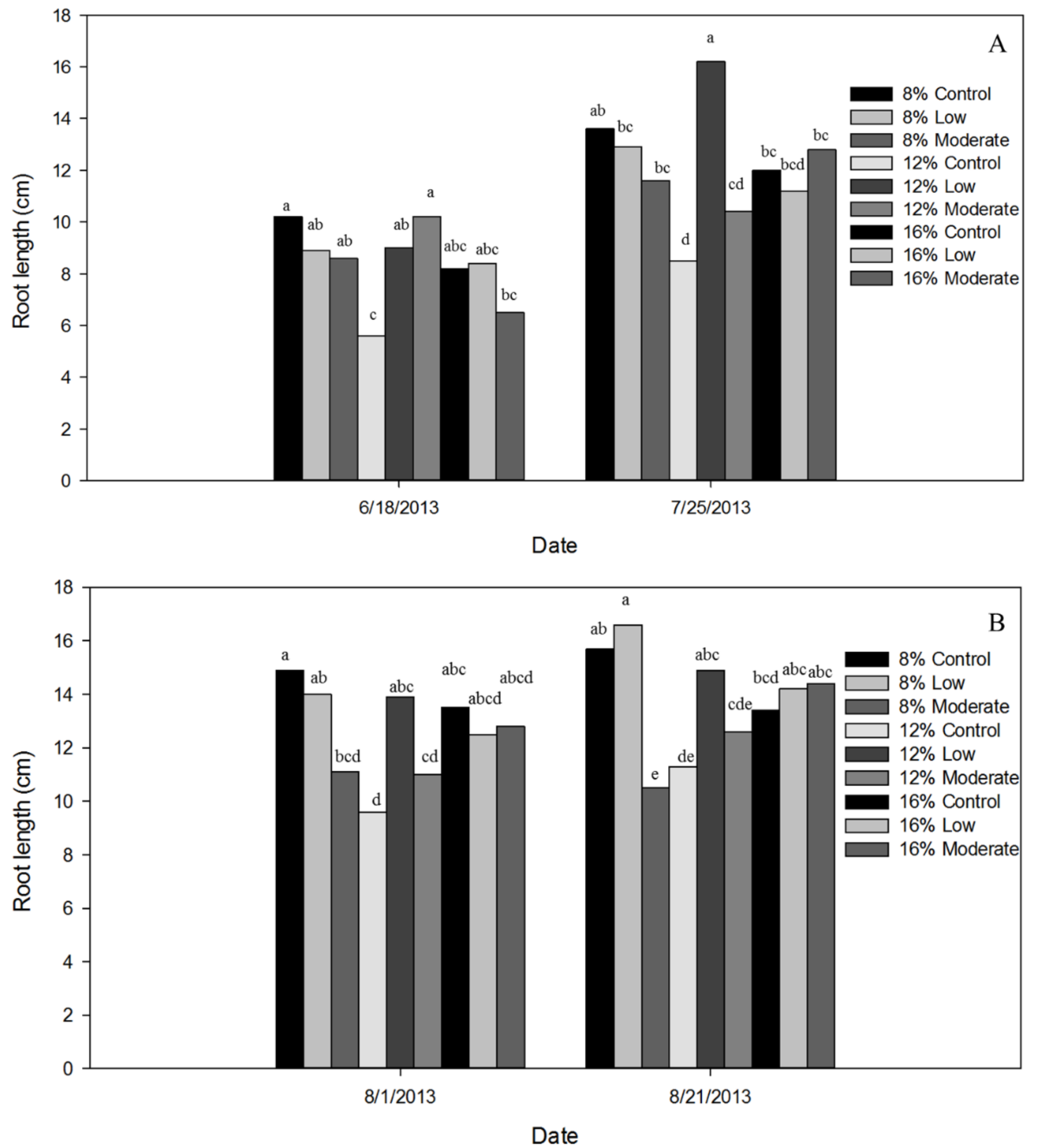

Figure 14. Root lengths of irrigation x traffic interactions in 2013, results obtained (A) 18 June and 25 July and (B) 1 August and 21 August. East Lansing, MI. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Root mass

During the summer of 2013, species had a significant effect on root biomass. CBG had significantly higher root biomass compared to ABG (Figure 15A). This agrees with Lyons et al., (2011) which found that CBG had greater root biomasses than that of ABG in a two-year experiment. Our results indicate that ABG had less total root biomass when compared to CBG in a USGA sand based root zone.

In 2014, two dates had a significant species x irrigation interaction. On June 8, ABG at 8% irrigation target had greater root biomass than CBG at the 8% irrigation target. On June 25, ABG had greater root biomass at the 12% irrigation target when compared to CBG at the 12% irrigation target (Figure 15B). Wilkinson and Duff (1972) determined ABG has comparable rooting habits to that of CBG. The current research shows that under certain conditions (8 and 12% irrigation treatments), ABG can have greater root biomasses when compared to CBG in a USGA sand based root zone. Future experiments may further investigate rooting attributes of CBG and ABG in different soil types to determine optimal soil characteristic for greatest root biomass between species.

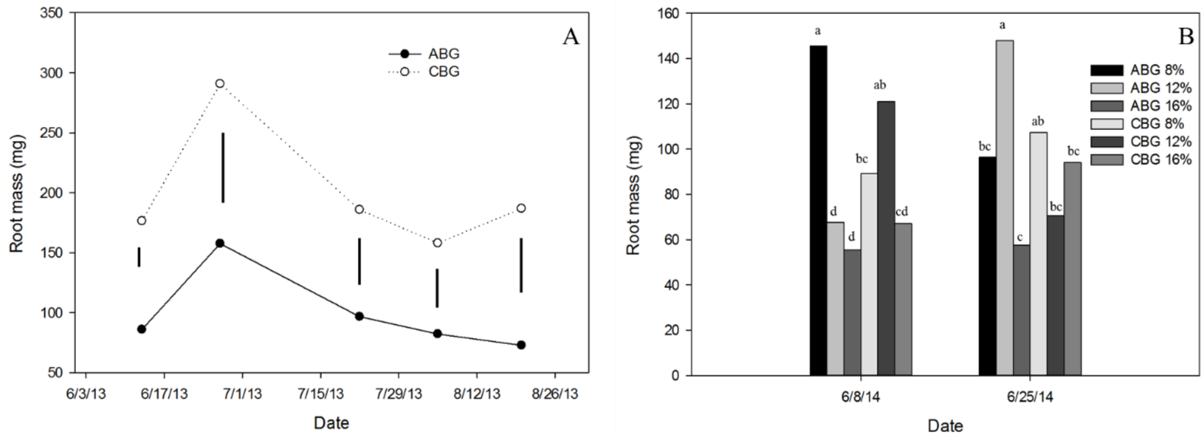

Figure 15. Root masses of (A) annual bluegrass (ABG) and creeping bentgrass in 2013. East Lansing, MI. Vertical least significant difference (LSD) bars represent Fisher's least significant difference values ($P \leq 0.05$) for irrigation comparison at a given day and (B) species x irrigation interaction, results obtained 8 June and 25 June, 2014. Different letters indicate significant differences among irrigation treatments within a given day; Fisher's least significant difference at $P \leq 0.05$.

Annual bluegrass invasion

In 2013 and 2014, moderate and low traffic treated CBG plots had higher ABG invasion when compared to the control. The low traffic treatment also had significantly greater ABG than the control (Table 15). On one date in 2013, the 12% irrigation CBG plots had more ABG than the CBG plots irrigated to 16%. In 2014, the 8% treatment irrigation had greater ABG invasion within CBG plot areas when compared to the 12 and 16% treatment irrigation treatments (Table 2). This is contrary to previous research. Using automated irrigation with a tensiometer had less ABG invasion into bermudagrass plots when compared to manually scheduling irrigation in a sandy loam soil (Youngner et al., 1981).

ABG invasion was likely to occur when CBG is under stress (irrigation of traffic), which is associated with significant thinning of the turf canopy. For instance, CBG could not maintain adequate shoot density under moderate traffic treatments (measured through NDVI). This could result in light penetrating through the thinning CBG canopy and to allow for ABG seed germination. The results from the current research show that irrigation treatments did not affect ABG invasion into CBG plots; however, increasing traffic treatments strongly correlated to increasing ABG invasion into CBG plots within a USGA sand based putting green.

Table 15. Effects of irrigation (I) and traffic (T) treatments on annual bluegrass invasion into creeping bentgrass plots. East Lansing, MI 2013 and 2014.

	Treatment Level	Percent annual bluegrass invasion[x] (0-100%)					
		6/13/13	7/22/13	8/20/13	5/28/14	7/23/14	8/19/14
Irrigation (I)	8%	17.5	19.7 b[u]	43.8	35.6 a	39.5	49.2
	12%	20.6	23.6 a	43.5	27.4 c	38.8	44.9
	16%	15.0	17.7 b	41.7	32.4 b	40.1	48.8
LSD (P=0.05)		NS	2.1	NS	2.3	NS	NS
Traffic (T)	Control	17.5	15.9 c	31.3 c	22.7 c	25.4 c	32.0 c
	Low	18.6	20.0 b	37.6 b	29.9 b	34.7 b	38.5 b
	Moderate	17.0	24.9 a	40.1 a	42.6 a	48.3 a	52.3 a
LSD (P=0.05)		NS	2.2	4.6	3.4	3.1	2.7
I x T		NS	NS	NS	NS	NS	NS

* and NS indicate significant and not significant at the 0.05 level of probability, respectively

[u] Within columns, means followed by the same letter not significantly different; Fisher's least significant difference at P ≤0.05.

[x] Number of annual bluegrass plants found per 441 line-intersections.

CONCLUSIONS

In both 2013 and 2014, irrigation and traffic treatments had a significant impact on ABG and CBG physiological characteristics. The 12% irrigation treatment produced adequate turfgrass quality and leached significantly less water through the root zone when compared to the 16% irrigation treatment. This could help conserve fresh water which has become increasingly limited around the world. VWC measurements from the surface to a 3.8 and 12.2 cm depth revealed that CBG had higher VWC when compared to ABG. This could be associated with the finding that CBG had greater root biomass and longer root lengths when compared to ABG. As expected, the 16% irrigation treatment caused plots to have greater VWC than the 8% irrigation treatment. Traffic also had an effect on VWC since moderate traffic treatment had higher VWC in both 2013 and 2014 when compared to the control. This could be due to compaction from simulated foot traffic reducing pore spaces within the USGA sand based root zone; however, further research that quantified compaction from simulated foot traffic would be required.

Turfgrass quality was observed to be greater in CBG when compared to ABG under irrigation and traffic treatments. This can be correlated to CBG having greater membrane stability, higher leaf internal water status, greater chlorophyll content, and a higher NDVI when compared to ABG. Moderately trafficked plot areas had lower NDVI when compared to non-trafficked plots. These results indicate that traffic treatments can decrease shoot density resulting in lower NDVI. This could result in an increase in ABG invasion in CBG plot areas by allowing light to penetrate through the thinning CBG canopy and allow for ABG seed germination.

Ethylene gas production varied under irrigation and traffic treatments in ABG and CBG. Results show that ABG produces greater amounts of ethylene under an 8% and 16% irrigation treatment when compared to CBG. Moderate traffic treatments increased ethylene gas production. Deficit irrigation, excessive irrigation, and traffic increased ethylene gas production. The direct in-field measurement of ethylene gas production method used in this study may be a viable method to quantify ethylene gas evolution from turfgrass canopies. Measurement of ethylene in the field may be a way to detect turfgrass stress incidence and could be a good indicator of turfgrass stress levels on putting greens. A more in depth analysis of ethylene gas production under other abiotic stress conditions may be warranted to investigate the role of ethylene gas within CBG and ABG.   Future studies would be needed to further investigate the utility of ethylene measurement in various turfgrass systems.

APPENDIX

APPENDIX

Table 16. Analysis of variance (AOV) table for water leachate volumes of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

2013 treatment	df	Sampling date										
		6/21	6/28	7/4	7/11	7/18	7/25	8/1	8/7	8/21	9/5	9/12
rep	2											
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	*	*	*	*	*	*	*	*	*	*	*
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10											
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24											
Total	53											

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 17. Analysis of variance (AOV) table for water leachate volumes of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	10-Jun	16-Jun	3-Jun	7-Jul	14-Jul	22-Jul	28-Jul	5-Aug	11-Aug	18-Aug	25-Aug
		Sampling date										
rep	2											
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	*	*	*	*	*	*	*	*	*	*	*
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10											
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24											
Total	53											

*and NS indicate significance at $P \leq 0.05$, and not significant at $P \leq 0.05$, respectively

Table 18. Analysis of variance (AOV) table for volumetric water content (VWC) to a 3.8 cm depth within species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	11-Jun	17-Jun	24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	3-Sep	10-Sep
rep	2														
Species (S)	1	*	*	*	NS	*	NS	*	*	*	*	NS	NS	NS	NS
Irrigation (I)	2	NS	*	*	*	*	*	*	*	*	*	*	*	*	*
S x I	2	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
W.P. error	10														
Traffic (T)	2	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24														
Total	53														

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 19. Analysis of variance (AOV) table for volumetric water content (VWC) to a 3.8 cm depth of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date															
		5-Jun	9-Jun	16-Jun	23-Jun	30-Jun	7-Jul	14-Jul	21-Jul	28-Jul	4-Aug	11-Aug	18-Aug	25-Aug	2-Sep	11-Sep	15-Sep
rep	2																
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
S x I	2	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10																
Traffic (T)	2	*	*	NS	NS	*	*	*	*	NS	*	NS	NS	*	*	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24																
Total	53																

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 20. Analysis of variance (AOV) table for volumetric water content (VWC) to a 12.2 cm depth of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date													
		11-Jun	17-Jun	24-Jun	1-Jul	8-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	3-Sep	10-Sep	16-Sep
rep	2														
Species (S)	1	*	*	*	*	*	*	*	*	*	NS	*	NS	NS	*
Irrigation (I)	2	NS	NS	*	*	*	*	*	*	*	*	*	*	*	*
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
W.P. error	10														
Traffic (T)	2	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	*	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24														
Total	53														

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 21. Analysis of variance (AOV) table for volumetric water content (VWC) to a 12.2 cm depth of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date														
		28-May	5-Jun	9-Jun	16-Jun	23-Jun	30-Jun	7-Jul	14-Jul	21-Jul	28-Jul	4-Aug	11-Aug	18-Aug	25-Aug	2-Sep
rep	2															
Species (S)	1	*	*	*	NS	*	NS	*	*	NS	*	NS	*	NS	*	*
Irrigation (I)	2	NS	NS	NS	*	*	*	*	*	*	*	*	*	*	*	*
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10															
Traffic (T)	2	*	*	NS	NS	NS	NS	NS	*	NS	NS	*	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24															
Total	53															

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 22. Analysis of variance (AOV) table for normalized difference vegetation index (NDVI) of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date											
		24-Jun	1-Jul	8-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	3-Sep	10-Sep	16-Sep
rep	2												
Species (S)	1	*	*	*	*	*	*	*	*	*	*	*	*
Irrigation (I)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS	*	NS	NS	*	NS	*
W.P. error	10												
Traffic (T)	2	NS	*	NS	NS	*	*	*	NS	*	*	NS	*
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24												
Total	53												

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 23. Analysis of variance (AOV) table for normalized difference vegetation index (NDVI) of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date										
		5-Jun	16-Jun	25-Jun	30-Jun	7-Jul	21-Jul	28-Jul	11-Aug	18-Aug	25-Aug	4-Sep
rep	2											
Species (S)	1	NS	NS	*	NS	*	NS	*	*	NS	NS	NS
Irrigation (I)	2	NS	NS	NS	*	NS	NS	*	*	*	*	*
S x I	2	NS	*	NS	NS	*	NS	*	NS	NS	NS	NS
W.P. error	10											
Traffic (T)	2	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24											
Total	53											

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 24. Analysis of variance (AOV) table for relative chlorophyll content of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date											
		9-Jun	25-Jun	30-Jun	14-Jul	21-Jul	28-Jul	5-Aug	11-Aug	18-Aug	25-Aug	2-Sep	16-Sep
rep	2												
Species (S)	1	*	*	*	*	*	*	*	*	*	*	*	NS
Irrigation (I)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10												
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24												

*and NS indicate significance at $P \leq 0.05$, and not significant at $P \leq 0.05$, respectively

Table 25. Analysis of variance (AOV) table for relative chlorophyll content of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date											
		9-Jun	25-Jun	30-Jun	14-Jul	21-Jul	28-Jul	5-Aug	11-Aug	18-Aug	25-Aug	2-Sep	16-Sep
rep	2												
Species (S)	1	*	*	*	*	*	NS	NS	*	NS	*	NS	*
Irrigation (I)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10												
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24												
Total	53												

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 26. Analysis of variance (AOV) table for turfgrass quality of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date													
		24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	29-Jul	5-Aug	13-Aug	19-Aug	26-Aug	5-Sep	11-Sep	16-Sep	24-Sep
rep	2														
Species (S)	1	*	NS	NS	NS	*	*	*	*	*	*	NS	*	*	NS
Irrigation (I)	2	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*	NS
S x I	2	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
W.P. error	10														
Traffic (T)	2	*	NS	*	*	NS	*	*	*	*	*	*	*	*	*
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24														
Total	53														

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 27. Analysis of variance (AOV) table for turfgrass quality of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date											
		29-May	6-Jun	10-Jun	25-Jun	30-Jun	7-Jul	14-Jul	22-Jul	28-Jul	5-Aug	19-Aug	27-Aug
rep	2												
Species (S)	1	NS	*	NS	NS	*	*	NS	*	*	*	NS	NS
Irrigation (I)	2	*	NS	NS	*	NS	NS	*	*	*	*	*	*
S x I	2	*	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
W.P. error	10												
Traffic (T)	2	*	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24												

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 28. Analysis of variance (AOV) table for electrolyte leakage of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date											
		19-Jun	26-Jun	2-Jul	9-Jul	16-Jul	23-Jul	30-Jul	6-Aug	19-Aug	27-Aug	4-Sep	11-Sep
rep	2												
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10												
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24												
Total	53												

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 29. Analysis of variance (AOV) table for electrolyte leakage of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date									
		16-Jun	26-Jun	2-Jul	10-Jul	16-Jul	31-Jul	8-Aug	15-Aug	19-Aug	29-Aug
rep	2										
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	*	*
Irrigation (I)	2	NS	NS	NS	NS	NS	*	*	*	*	*
S x I	2	NS	NS	NS	NS	NS	*	*	*	*	NS
W.P. error	10										
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24										
Total	53										

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 30. Analysis of variance (AOV) table for leaf relative water content of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date									
		7-Jun	18-Jun	2-Jul	9-Jul	16-Jul	23-Jul	30-Jul	6-Aug	20-Aug	3-Sep
rep	2										
Species (S)	1	NS	NS	NS	*	*	*	NS	NS	NS	NS
Irrigation (I)	2	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10										
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	*	*
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24										
Total	53										

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 31. Analysis of variance (AOV) table for leaf relative water content of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	2-Jul	16-Jul	23-Jul	1-Aug	8-Aug	15-Aug	25-Aug
		Sampling date						
rep	2							
Species (S)	1	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	NS	NS	NS	NS	*	*	*
S x I	2	NS	NS	NS	NS	*	NS	NS
W.P. error	10							
Traffic (T)	2	NS	NS	NS	NS	NS	*	*
S x T	2	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	*	*	*
S x I x T	4	NS	NS	NS	NS	NS	NS	NS
S. P Error	24							
Total	53							

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 32. Analysis of variance (AOV) table for ethylene gas production of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date										
		17-Jul	25-Jul	1-Aug	9-Aug	15-Aug	21-Aug	29-Aug	5-Sep	11-Sep	18-Sep	25-Sep
rep	2											
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
Irrigation (I)	2	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	*
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10											
Traffic (T)	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24											
Total	53											

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 33. Analysis of variance (AOV) table for ethylene gas production of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date					
		19-Jun	10-Jul	22-Jul	6-Aug	28-Aug	18-Sep
rep	2						
Species (S)	1	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	*	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS
W.P. error	10						
Traffic (T)	2	NS	NS	*	NS	NS	NS
S x T	2	NS	NS	NS	*	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS
S. P Error	24						
Total	53						

*and NS indicate significance at $P \leq 0.05$, and not significant at $P \leq 0.05$, respectively

Table 34. Analysis of variance (AOV) table for root length of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date											
		14-Jun	18-Jun	27-Jun	4-Jul	11-Jul	17-Jul	25-Jul	1-Aug	9-Aug	15-Aug	21-Aug	29-Aug
rep	2												
Species (S)	1	*	*	*	*	*	*	*	*	*	*	*	NS
Irrigation (I)	2	*	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10												
Traffic (T)	2	NS	NS	NS	*	NS	NS	NS	*	*	NS	*	*
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	*	NS	NS	NS	NS	*	*	NS	NS	*	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24												

*and NS indicate significance at $P \leq 0.05$, and not significant at $P \leq 0.05$, respectively

Table 35. Analysis of variance (AOV) table for root length of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date							
		26-Jun	9-Jul	15-Jul	21-Jul	29-Jul	6-Aug	14-Aug	20-Aug
rep	2								
Species (S)	1	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation (I)	2	NS	NS	NS	*	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS	NS	NS	NS
W.P. error	10								
Traffic (T)	2	NS	NS	*	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS	NS	NS	NS
S. P Error	24								

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 36. Analysis of variance (AOV) table for root mass of species (S), irrigation (I), and traffic (T) treatments in 2013, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date				
		13-Jun	27-Jun	22-Jul	5-Aug	20-Aug
rep	2					
Species (S)	1	*	*	*	*	*
Irrigation (I)	2	NS	NS	NS	NS	NS
S x I	2	NS	NS	NS	NS	NS
W.P. error	10					
Traffic (T)	2	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS
S. P Error	24					

*and NS indicate significance at P≤0.05, and not significant at P≤0.05, respectively

Table 37. Analysis of variance (AOV) table for root mass of species (S), irrigation (I), and traffic (T) treatments in 2014, results obtained at HTRC, East Lansing, MI.

Source of variation	df	Sampling date				
		8-Jun	25-Jun	9-Jul	5-Aug	18-Aug
rep	2					
Species (S)	1	NS	NS	NS	NS	NS
Irrigation (I)	2	NS	NS	NS	NS	NS
S x I	2	*	*	NS	NS	NS
W.P. error	10					
Traffic (T)	2	NS	NS	NS	NS	NS
S x T	2	NS	NS	NS	NS	NS
I x T	4	NS	NS	NS	NS	NS
S x I x T	4	NS	NS	NS	NS	NS
S. P Error	24					

*and NS indicate significance at $P \leq 0.05$, and not significant at $P \leq 0.05$, respectively

REFERENCES

REFERENCES

Abeles, F. B., Morgan, P. W., and Saltveit, M. E. 1. 1992. Ethylene in plant biology (Second edition.). San Diego: Academic Press. P. 85-87.

Agnew, M. L., and R. N. Carrow. 1985. Soil compaction and moisture stress preconditioning in Kentucky bluegrass. I. Soil aeration, water use, and root responses. Agron. J. 77(6):872-878.

Apelbaum, A., and Yang, S. F. 1981. Biosynthesis of stress ethylene induced by water deficit. Plant Physiol. 68:594–596.

Aronson, L. J., A. J. Gold, R. J. Hull, and J. L. Cisar. 1987. Evapotranspiration of cool-season turfgrasses in the humid northeast. Agron J 79:901–904.

Baghzouz, M., D.A. Devitt, and R.L. Morris. 2007. Assessing canopy spectral reflectance of hybrid bermudagrass under various combinations of nitrogen and water treatments. App. Eng. Agric. 23:763-774. DOI: 10.13031/2013.24055

Banga M, Slaa EJ, Blom CWPM, Voesenek LACJ. 1996. Ethylene biosynthesis and accumulation under drained and submerged conditions: a comparative study of two Rumex species. Plant Physiol. 112:229–37

Barrs, H.D., and Weatherley, P.E. 1962. A re-examination of the relative turgidity techniques for estimating water deficits in leaves. Aust. J. Biol. Sci. 15:413–428.

Beard J. B. 1970. An ecological study of annual bluegrass. USGA Green Section Record. 8(2): 13-18.

Beard, J.B. 1973. Turfgrass: Science and culture. Englewood Cliffs, N.J.: Prentice Hall, Inc.

Beard, J.B., P.E. Rieke, AJ. Turgeon, and JM. Vargas Jr. 1978. Annual bluegrass (*Poa annua* L) description, adaptation, culture and control. Res. Rpt. 352. Michigan State Univ. Agric. Exp. Sta., East Lansing, MI.

Beltrano, J., Ronco, M. G., & Montaldi, E. R. (1999). Drought stress syndrome in wheat is provoked by ethylene evolution imbalance and reversed by rewatering, aminoethoxyvinylglycine, or sodium benzoate. Journal of Plant Growth Regulation, 18(2):59-64.

Bigelow, C. A., and W. T. Jr. Tudor. 2012. Economic analysis of creeping bentgrass and annual bluegrass greens maintenance. Golf Course Manage. 80(10): 76-78, 80, 82, 84, 86, 88, 90-93.

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

Blankenship, T. M. 2011. Water use characteristics of ten newly established cool-season turfgrass species. M.S. Thesis: Oregon State University

Blom, C. W. 1999. Adaptations to flooding stress: from plant community to molecule. Plant Biology. P. 261-273. DOI: 10.1111/j.1438-8677. 1999.tb00252.x

Blum, A., and A. Ebercon, 1981. Cell membrane stability as a measure of drought and heat tolerance in wheat. Crop Sci. 21:43–47. DOI:10.2135/cropsci1981.0011183X0021000100

Carrow, R., and Johnson, B. 1996. Turfgrass wear stress: Effects of golf car and tire design Hortscience 31:968–971

Carrow, R.N. and A.M. Petrovic. 1992. Effects of traffic on turfgrass, p. 285–330. In: D.V. Waddington, R.N. Carrow, and R.C. Shearman (ed.). Turfgrass. Amer. Soc. Agron., Crop Sci. Soc. Amer., Soil Sci. Soc. Amer., Madison, Wis.

Carrow, R.N. and G. Wiecko. 1989. Soil compaction and wear stresses on turfgrasses: Future Research Directions. Proceedings of the 6th International Turfgrass Research Conf., Tokyo. 31 July-5 August, pp. 37-42.

DaCosta, M., and B. Huang. 2006a. Minimum water requirements for creeping, colonial and velvet bentgrasses under fairway conditions. Crop Sci. 46(1):81-89. DOI: 10.2135/cropsci2005.0118

DaCosta, M., and B. Huang. 2006b. Deficit irrigation effects on water use characteristics of bentgrass species. Crop Sci. 46(4):1779-1786. DOI: 10.2135/cropsci2006.01-0043

DaCosta, M., and Huang, B. 2006c. Osmotic adjustment associated with variation in bentgrass tolerance to drought stress. J. Amer. Soc. Hort. Sci. 131:338–344.

Erickson, J.E., J.L. Cisar, G.H. Snyder, J.C. Volin, and D. M. Park. 2005. Phosphorus and potassium leaching under contrasting residential landscape models established on a sandy soil. Crop Sci. 45:546-552. DOI: 10.2135/cropsci2005.0546

Fiorani, F., Bögemann G., Visser E.J., Lambers H., and Laurentius A., Voesenek CJ. 2002. Ethylene emission and responsiveness to applied ethylene vary among Poa species that inherently differ in leaf elongation rates. Annu Rev Plant Physiol 129:1382-90. DOI:10.1104/pp.001198

Frank, K., Bryan, J., and Laskowski, K. 2012. Using soil moisture sensors for irrigation management on a creeping bentgrass and *Poa annua* putting green. Michigan Golf Course Turfgrass Field Day Report. p. 17-19.

Fry, J. D., and J. D. Butler. 1989. Annual bluegrass and creeping bentgrass evapotranspiration rates. HortScience. 24:269-271.

Gaussoin, R. E., and B. E. Branham. 1989. Influence of cultural factors on species dominance in a mixed stand of annual bluegrass/creeping bentgrass. Crop Sci. 29(2):480-484.

Gaussoin, R. E., B. E. Branham, and J. A. Flore. 1997. Carbon dioxide exchange rate and chlorophyll content of turfgrasses treated with flurprimidol or mefluidide. J. Plant Growth Regul. 16(2):73-78. DOI: 10.1007/PL00006981

Głab, T., and W. Szewczyk. 2015. The effect of traffic on turfgrass root morphological features. Scientia Horticulturae. 197:542-554. DOI: 10.1016/j.scienta.2015.10.014

Gibeault, V.A., V.B. Younger, and W.H. Bengeyfield. 1983. Golf shoe study II. USGA Green Section Record 21: 1-7.

Guertal, E. A. 2007. Phosphorus leaching from sand-based putting greens. USGA Turfgrass Environ. Res. Online. 6:1-6.

Han, L.-B., G.-L. Song, and X. Zhang. 2008. Preliminary observations on physiological responses of three turfgrass species to traffic stress. HortTechnology. 18(1):39-143.

Hathaway, A. D., and Nikolai, T.A. 2005. A putting green traffic methodology for research applications established by in situ modeling. International Turfgrass Society Annexe - Technical Papers 2005. 10:69-70.

Hathaway, A. D. 2006. Effect of four creeping bentgrass cultivars and quantified foot traffic on the invasion of annual bluegrass into a putting green. M.S. Thesis: Michigan State University, East Lansing

Hejl, R. W., B. G. Wherley, R. H. White, J. C. Thomas, and C. H. Fontanier. 2016. Deficit Irrigation and Simulated Traffic on 'Tifway' Bermudagrass Summer Performance and Autumn Recovery. Crop Sci. 56:809-817. doi:10.2135/cropsci2015.03.0197

Hudak, P.F. 2000. Regional trends in nitrate content of Texas groundwater. Journal of Hydrology 228:37-47. DOI: 10.1016/S0022-1694(99)00206-1

Isgrigg, J., III, and F.H. Yelverton. 1999. New approaches to management of annual bluegrass in bentgrass putting greens. Proc. Southern Weed Sci. Soc. 52:72.

Irigoyen, J.J., D.W. Emerich, and M. Sanchez-Diaz. 1992. Alfalfa leaf senescence induced by drought stress: photosynthesis hydrogen peroxide metabolism, lipid peroxidation and ethylene evolution. Physiol. Plant. 84:67-72. DOI: 10.1111/j.1399-3054.1992.tb08766.x

Johnson, B.J., and T.R. Murphy. 1995. Effect of paclobutrazol and fluprimidol on suppression of *Poa annua* spp *reptans* in creeping bentgrass (*Agrositis stolonifera*) greens. Weed Technol. 10:705–709.

Kaminski, J., and T. Hsiang. 2007. Attacking anthracnose: A five-year research initiative takes aim at annual bluegrass pests. GreenMaster. 42(2): 22-23.

Karcher, D., M. D. Richardson, and W.D Strunk. 2011. Improving turf quality during tournament preparation through ethylene inhibition. USGA Turfgrass Environ. Res. Summ. p. 45.

Kende, H. 1993. Ethylene biosynthesis. Annu. Rev. Plant Physiol. Plant Mol. Biol. 44: 283-307

Krishnan, S., K. Laskowski, V. Shukla, and E. B. Merewitz. 2013. Mitigation of drought stress damage by exogenous application of a non-protein amino acid γ- aminobutyric acid on perennial ryegrass. J. Am. Soc. Hortic. Sci. 138:358-366.

Krishnan, S., and E. B. Merewitz. 2015. Phytohormone responses and cell viability during salinity stress in two creeping bentgrass cultivars differing in salt tolerance. J. Am. Soc. Hortic. Sci. 140:346-355.

Kruse, J., N. Christians, and M. Chapin. 2006. Remote sensing of nitrogen stress in creeping bentgrass. Agron J. 98:1640-1645. DOI: 10.2134/agronj2006.0022

La Mantia, J.M., and D.R. Huff. 2011. Instability of the greens-type phenotype in *Poa annua*. Crop Sci. 51:1784–1792. DOI: 10.2135/cropsci2010.10.0580.

Law, R.A., D. Bradshaw and P.D. Putwain. 1977. Life history and variation in *Poa annua*. Evolution 31:233-246.

Liu, L., H. D, K. Wang, B. Huang, and Z. Wang. 2011. Differential photosynthetic responses to salinity stress between two perennial grass species contrasting in salinity tolerance. HortScience. 46:311-316.

Lu N. C. S., B. Wilske, J. Chen, S. Chen, G. Sun. 2011 Effects of land use practices on ET-soil water relationships in semi-arid Inner Mongolia. J Plant Ecol. 4:49–60.

Lyons, E. M., P. J. Landschoot, and D. R. Huff. 2011. Root distribution and tiller densities of creeping bentgrass cultivars and greens-type annual bluegrass cultivars in a putting green. HortScience. 46:1411-1417.

Mahdi, Z., and V.T. Stoutmeyer. 1953. A method of measurement of populations in dense turf Agron. J. 45: 514-515. DOI: 10.2134/agronj1953.00021962004500010001

Metraux J. P, Kende H. 1983. The role of ethylene in the growth response of deepwater rice. Plant Physiology 72: 441-446.

Matin, M.A., J.H. Brown, and H. Ferguson. 1989. Leaf water potential, RWC, and diffusive resistance as screening techniques for drought resistance in barley. Agron. J. 81:100–105. DOI: 10.2134/agronj1989.00021962008100010001

McCann, S.E., and Huang, B. 2008. Evaluation of drought tolerance and avoidance traits for six creeping bentgrass cultivars. HortScience 43:519-524.

McCarty, B. 1999. Controlling Poa annua in bentgrass greens. Grounds Maintenance 34 (1):17-18, 20.

McCullough, P.E., S.E. Hart, and D.W. Lycan. 2005. Plant growth regulator regimens reduce *Poa annua* populations in creeping bentgrass. Appl. Turfgrass Sci. doi:10.1094/ATS-2005-0304-01-RS

McCullough, P. E., H. Liu, L. B. McCarty, and J. E. Toler. 2006. Ethephon and trinexapac-ethyl influence creeping bentgrass growth, quality, and putting green performance. Applied Turfgrass Science, 3: 1-7. DOI: 10.1094/ATS-2006-0324-01-RS

Mojid, M. A., and H. Cho. 2004 Evaluation of the time-domain reflectometry (TDR)-measured composite dielectric constant of root-mixed soils for estimating soil-water content and root density. Journal of Hydrology 295.1: 263-275.

Morenz, M., Van Til1, R., and Luukkonen C. Water Use for Irrigation in Michigan, 2001. USGS Fact Sheet FS 2005-3079 September 2005

Murphy, J. A., M. G. Hendricks, P. E. Rieke, A. J. M. Smucker, and B. E. Branham. 1994. Turfgrass root systems evaluated using the minirhizotron and video recording methods. Agron. J. 86:247-250. DOI: 10.2134/agronj1994.00021962008600020000

National Turfgrass Evaluation Program. 2015. A guide to NTEP turfgrass ratings. National Turfgrass Evaluation Program, Beltsville, MD. http://www.ntep.org/reports/ratings.htm#quality (verified 9 Dec. 2016).

Nilsen, T.E. and D.M. Orcutt. 1996. Physiology of plants under stress. New York: Wiley.

Pelz, D., and N. Mastroni. 1989. "The Battle of the 'Lumpy Doughnut.'" p. 24-38. In Putt Like the Pros. Harper Collins Pub., New York, NY.

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

Renney, A.J. 1964. Preventing Poa annua infestations. In Proceedings of the 18th Annual Northwest Turfgrass Conference. Gleneden Beach, Oregon, pp. 3-5

Reicher, Z., M. Sousek, A. Patton, D. Weisenberger, A. Hathaway, and R. Calhoun. 2015. Annual bluegrass control on putting greens from three or four years of season-long applications of herbicides or plant growth regulators in three states. Crop, Forage and Turfgrass Management. 1(1):1-7.

Rutledge, James Marable 2010. Physiology and growth response of roughstalk bluegrass and creeping bentgrass to high temperature stress. Ph.D. Dissertation: Purdue University.

Samaranayake, H., T. J. Lawson, and J. A. Murphy. (2008) Traffic stress effects on bentgrass putting green and fairway turf. Crop Sci. 48: 1193-202. DOI:10.2135/cropsci2006.09.0613

Schuerger, A.C., G.A. Capeele, J.A. DiBenedetto, C. Mao, C.N. Thai, M.D. Evans, F.T. Richards, T.A. Blank, and E.C. Styrjewski. 2003. Comparison of two hyperspectral imaging and two laser-induced fluorescence instruments for the detection of zinc stress and chlorophyll concentration in bahiagrass (*Paspalum notatum Flugge*). Remote Sens. Environ. 84: 572-588. DOI: 10.1016/S0034-4257(02)00181-5

Shaddox, T. W., Unruh, J. B., & Trenholm, L. E. 2016. Nitrate leaching from soluble nitrogen applied to ‘Floratam’ St. Augustinegrass and common centipedegrass during dormancy. Crop Sci., 56: 837-844. DOI: 10.2135/cropsci2015.02.0104

Shearman, R. C. and J. B. Beard. 1973. Environmental and cultural pre-conditioning effects on the water use rate of *Agrostis palustris Huds*., cultivar Penncross. Crop Sci 13:424–427.

Shukla, V., Y. Ma, and E. Merewitz. 2015. Creeping bentgrass response to drought stress and polyamine application. J. Am. Soc. Hortic. Sci. 140:94-101.

Stevens, M., Megerian, C., & Morin, M. (2015, May 05). Emergency 25% cut in California cities' water use approved. Retrieved March 9, 2016, from http://www.latimes.com/local/lanow/la-me-ln-water-regulations-20150504-story.html

Strunk, William 2015. Investigations of ethylene and ethylene inhibition, ball lie, and synthetic turf color. Ph.D. Dissertation: University of Arkansas. Fayetteville.

Taiz, L., and E. Zeiger. (2006). Ethylene: The gaseous hormone. Fourth Edition. Sinauer Associates, Inc. Chapter, 22, p. 571-591.

Trenholm, L. E., R. N. Carrow, and R. R. Duncan. 1999. Relationship of multispectral radiometry data to qualitative data in turfgrass research. Crop Sci. 39(3): 763-769.

Turgeon, A.J. 2008. Turfgrass management. 8th ed. Pearson Prentice Hall, Upper Saddle River, NJ. Chapter, 1, P. 3-11.

Vargas, J. M., and A. J. Turgeon. 2003. *Poa annua*: physiology, culture, and control of annual bluegrass. J. H Wiley and Sons. Hoboken, N. J. Jersey

Volaire, F. 2003. Seedling survival under drought differs between an annual (*Hordeum vulgare*) and a perennial grass (*Dactylis glomerata*). New Phytologist 160.3: 501-510.

Wang, K., and Y. Jiang. 2013. The effects of short-term excessive irrigation on growth and physiology of creeping bentgrass on sand and soil greens. Int. Turfgrass Soc. Res. J. 12:517-521.

Watschke, T. L. and R.E. Schmidt. 1992. Ecological aspects of turf communities. Turfgrass, 129-174.

Wilkinson, J. F. and D. T. Duff. 1972. Rooting of *Poa annua* L. *Poa pratensis* L., and *Agrastis palustris Huds*. at three soil bulk densities. Agron. J.64:66-68.

Woosley, P.B., D.W. Williams, and A.J. Powell. 2003. Postemergence control of annual bluegrass (*Poa annua* spp. *reptans*) in creeping bentgrass (*Agrostis stolonifera*) turf. Weed Technol. 17:770–776. doi:10.1614/WT02-153

Xu, Z., and C. F. Mancino. 2001. Annual bluegrass and creeping bentgrass response to varying levels of iron. HortScience. 36:371-373.

Yang, Z., Y. Miao, J. Yu, J. Liu, and B. Huang. 2014. Differential growth and physiological responses to heat stress between two annual and two perennial cool-season turfgrasses. Scientia Horticulturae. 170:75-81.

Young, J., M. Richardson, and D. Karcher. 2015. Creeping bentgrass putting green response to combined mowing, rolling, and foot traffic under environmental stress. Agron. J. 107(6):1959-1966. DOI:10.2134/agronj15.0087

Youngner, V. G. 1959. Ecological studies on *Poa annua* in turfgrasses. Jour. of the British Grassland Soc. 14(4):233-247.

Youngner, V. B., A. W. Marsh, R. A. Strohman, V. A. Gibeault, and S. Spaulding. 1981. Water use and turf quality of warm-season and cool-season turfgrasses. Int. Turfgrass Soc. Res. J. 4:51-257.

Yu, C., Zielen, A.J., Cheng, J.-J., Lepoire, D.J., Gnasapragasam, E., Kamboj, S., Arnish, J., Wallo, A., Williams, III, W.A., and Peterson, H., 2001. User's Manual for RESRAD Version 6, ANL/EAD-4, Argonne National Laboratory, Argonne, IL.

Zoroya, G. 2015. Texas hit with heavy rains, heightened flood threat. Verified March 9, 2016, from http://www.usatoday.com/story/news/nation-now/2015/10/24/texas-hit-heavy-rains-heightened-flood-threat/74523670/