Environmental and management impacts in turfgrass systems: Nitrous oxide emissions, carbon sequestration, and drought and traffic stress

by

Ross Charles Braun

B.S., North Dakota State University, 2011
M.S., Kansas State University, 2014

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture and Natural Resources
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Abstract

Turfgrasses sequester and emit carbon dioxide, and emit nitrous oxide (N_2O) when fertilized with nitrogen and irrigated. Future water availability is a serious issue and drought restrictions may be imposed on turf managers while turf areas are subjected to traffic stress. My objectives in Chapter 2 were to: 1) quantify the magnitude and patterns of N_2O emissions and carbon (C) sequestration in zoysiagrass *(Zoysia japonica* Steud.); and 2) determine how irrigation (66% and 33% reference evapotranspiration [ET_o] replacement) and fertilization (polymer-coated urea, urea, and unfertilized) management may reduce N_2O emissions and enhance carbon sequestration. My objectives in Chapters 3 and 4 were to evaluate above- and below-ground responses of cool-season (C3) [Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.)] and warm-season (C4) grasses {buffalograss [*Buchloe dactyloides* (Nutt.) Engelm] and zoysiagrass] at golf course-related mowing heights [1.6-cm (fairway) and 6.4-cm (rough)], with and without traffic during a simulated drought and subsequent recovery period (without traffic).

In Chapter 2, N_2O emissions increased by 6.3% with more irrigation during summers and increased from 4.06 kg ha^{-1} in unfertilized turf to 4.50, and 5.62 kg ha^{-1} in polymer-coated urea and urea treated turf, respectively, during the 2-year study. There was no difference in C sequestration rates between a high vs. low input management schedule. The C sequestration rate was 0.952 Mg C ha^{-1} yr^{-1} for zoysiagrass when averaged across management schedules and depths. The use of a controlled-release fertilizer such as PCU compared to the use of a quick-release fertilizer and/or lower irrigation will reduce N_2O emissions in turfgrass. In Chapters 3 and 4, the better drought tolerance of C4 grasses led to more differences between traffic treatments within C4 than C3 grasses, but C4 grasses maintained the highest quality and green cover. Quality at rough- compared to fairway-height was more impacted by traffic. Decreasing soil moisture due to drought led to a minimal impact from traffic on soil bulk density, soil penetration resistance (SPR), and root measurements. During drought, SPR at deeper soil depths and fairway plots increased and exceeded the critical value of 2.0 MPa. Both C4 grasses and perennial ryegrass had larger root diameters, which may have led to better soil compaction resistance. Traffic during drought will have a negative and accelerated impacts above-ground, but minimal impact below-ground, which will vary with turf species and mowing height.

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Dale Bremer

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Dedication

I dedicate this work to my loving wife, Amanda, and our son, Louis.

Chapter 1 - Review of Literature: Nitrous Oxide Emissions in Turfgrass

Abstract

Nitrous oxide (N_2O) is a natural and anthropogenic by-product associated with global climate change and is potentially the most ozone-depleting gas. Nitrous oxide is 310 times more effective at trapping longwave radiation in the atmosphere than carbon dioxide. Turfgrass is typically fertilized and irrigated and has the potential to emit N_2O at similar rates as other agricultural soils and thus, may contribute significantly to atmospheric N_2O budgets. Turfgrass systems have comparable cumulative annual N_2O emissions as other agricultural systems. However, only a few turfgrass studies exist in which fluxes were intensively measured for a duration long enough to be able to calculate accurate annual emissions. Because N_2O production is determined by complex interactions among soil physical, biological and chemical properties (e.g., moisture, temperature, ammonium and nitrate content, pH, clay fraction), direct correlations between N_2O fluxes and any one of these variables are typically low. The effects of N fertilizer sources on emissions have been investigated in other agricultural systems but minimal research has been conducted in turfgrass systems, especially pertaining to controlled-released N fertilizers. Further N_2O research is required in turfgrass to develop management practices (e.g., irrigation and fertilization regimes) that may reduce emissions of N_2O in turfgrass. Continuation of direct N_2O measurements over the long-term to calculate total inventory can be expensive and time consuming. Therefore, the use of model simulations (i.e., DAYCENT and DNDC) should be further developed for turfgrass systems to predict long-term impacts of different management practices on carbon and nitrogen cycling in turfgrass.

Nitrous Oxide Emissions

The greenhouse gas (GHG) nitrous oxide (N_2O) is a natural and anthropogenic by-product associated with global climate change (IPCC, 2007). Nitrous oxide has been labeled as potentially the most ozone-depleting gas and has also been reported to be 310 times more effective at trapping longwave radiation in the atmosphere than carbon dioxide (CO_2) (IPCC, 2007; Ravishankara et al., 2009). Agricultural activities (soil and animal manure management) are estimated to account for up to 60% of N_2O emissions, which have increased by about 17% from 1990 to 2005 (Smith et al., 2007; IPCC, 2007). Agricultural soils, which include turfgrass soils, are not likely to be sinks for N_2O due to high N availability/input from fertilization (Syakila et al., 2011). Human activities of fertilizing agricultural land with nitrogen (N), including in turfgrass systems, are responsible for a significant amount of total N_2O emissions into the atmosphere each year (Bremer, 2006; Horgan et al., 2002; Kaye et al., 2004; Lewis and Bremer, 2013; Maggiotto et al., 2000; Mosier et al., 1998; Ryden, 1981).

Turfgrass Industry

Urban expansion has resulted in irrigated turfgrass covering an estimated 16 to 20 million hectares in the United States (Milesi et al, 2005). Furthermore, population growth will continue to increase the amount of developed land area; urbanization in the United States is projected to increase by 79% by 2025 (Alig et al., 2004). The turfgrass industry consists of home lawns, commercial properties, golf courses, parks, athletic fields, and roadsides in the United States. It is estimated to be worth $40 billion, which is a significant part in the U.S. economy and generates more income than any other agricultural commodity in many states (National Turfgrass Federation, 2009). Besides economic benefits, turfgrass provides a variety of environmental and human health benefits that improve the quality of life (Beard and Green, 1994; Erickson et. al., 2001; Gross et. al., 1990; Maas et al., 2009; Miltner et al., 1996; Taylor et al., 1998). However, turfgrass is increasingly being questioned in regards to its possible effects on climate change (Town-Small and Czimczik, 2010). Land coverage by turfgrass includes an estimated 2.56 million hectares of intensively-managed turfgrass on golf courses worldwide (Bartlett and James, 2011). Golf courses, home and commercial lawns, athletic fields, and other turfgrass areas are commonly irrigated and receive nitrogen fertilizer and thus, turfgrass may have a significant role in the global GHG budget. In 2005, it was estimated that turfgrass represented the largest irrigated crop in the USA, with three times more acreage than irrigated corn (*Zea mays* L.)

(Milesi et al., 2005). Therefore, turfgrass has the potential to emit similar amounts of N_2O as other agricultural lands and N_2O budgets should include contributions from turfgrass soils (Townsend-Small et al., 2011).

Soil Properties

Soil Water Content

Nitrous oxide emissions typically increase after fertilizer applications, precipitation or irrigation events (Bremer, 2006; Denmead et al., 1979; Kaiser et al., 1996; Sextone et al., 1985). In the desert climate of Phoenix, Arizona, N_2O fluxes, mainly from bermudagrass (*Cynodon dactylon* L. Pers.) lawns, were significantly larger than managed xeric landscapes and remnant desert sites within the urban area after a precipitation event (Hall et al., 2008).

Higher soil water content, also referred to as "water-filled pore space" (WFPS), during or after fertilization, may be a key driver in amplified N_2O fluxes. Soil water content greatly influences the processes of nitrification and denitrification in the soil, which can result in N_2O fluxes (Christensen, 1983; Davidson, 1991; Firestone and Davidson, 1989; Ryden, 1981). Nitrification is the microbial process of converting ammonium (NH_4^+) to nitrate (NO_3^-); this process is dependent on aerobic conditions, typically 30 to 60% WFPS, and a supply of NH_4^+ in soil. Denitrification is the conversion of NO_3^-, to gaseous forms of N including nitrite (NO_2^-), nitric oxide (NO), N_2O, and dinitrogen gas (N_2), which occurs during high WFPS (>60%) and anaerobic conditions where oxygen (O_2) is restricted and denitrifying microorganisms are present.

Higher N_2O fluxes in agricultural systems have been associated with higher soil moisture (Clayton et al., 1997; Denmead et al., 1979; Dobbie et al., 1999; Linn and Doran, 1984; Mosier and Hutchinson, 1981; Sehy et al., 2003; Thorton and Valente, 2001). Similarly, this relationship has been observed in turfgrass systems (Bijoor et al., 2008; Bremer, 2006; Lewis, 2010; Lewis and Bremer, 2013; Lu et al., 2015). Conversely, others have reported that higher WFPS did not always enhance N_2O production in turfgrass systems (Li et al., 2013; Townsend-Small et al., 2011). Further N_2O research on the effects of irrigation quantity or frequency is required.

These inconsistencies in the relationship between soil water content and N_2O emissions could possibly be due the soil N level, type of fertilizer (ammonium- or nitrate-based) and the soil water content status at the time of application. Beauchamp (1997) summarized practices to possibly minimize N_2O emissions in agricultural systems by selecting nitrate- or ammonium-based fertilizers depending on the soil water content. To potentially help reduce N_2O emissions, it has been recommended that nitrate-based fertilizers [e.g. ammonium nitrate (NH_4NO_3), and calcium nitrate ($Ca(NO_3)_2$)] are used when nitrification is expected during low WFPS and aerobic conditions, and ammonium-based fertilizers [e.g. urea and ammonium sulfate ($(NH_4)_2SO_4$)] are used when denitrification is expected during high WFPS and anaerobic conditions (Beauchamp, 1997; Breitenbeck and Bremner, 1986; Byrnes et al., 1990). Past agronomic research has indicated similar results. For example, Tenuta and Beauchamp (2003) reported urea fertilizer produced higher N_2O emissions than other ammonium-based fertilizers (ammonium sulfate) and nitrate-based fertilizers (ammonium nitrate and calcium nitrate) in barley (*Hordeum vulgare* L.) under aerobic conditions in Guelph, Ontario, Canada. Maggiotto et al. (2000) observed a nitrate-based fertilizer (ammonium nitrate) produced higher N_2O emissions during wetter soil periods and the ammonium-based fertilizer (urea) produced higher emissions during drier soil periods in a perennial ryegrass (*Lolium perenne* L.) turf stand in Guelph, Ontario, Canada.

Soil water content can have an impact on the magnitude of N_2O emitted. The previous research indicates an opportunity to possibly reduce N_2O emissions by proper selection of either ammonium- or nitrate-based fertilizer depending on expected soil water content levels. Under these expectations, if soil water content levels were to be reduced by deficit irrigation practices, a watering strategy that reduces water inputs while maintaining adequate turf health with no or minimal reduction in turf quality, then ammonium-based fertilizers should be avoided or at the very least the amount of available N in the soil should be released slowly with a slow- or controlled-release fertilizer. However, there has been mixed results in both agronomic and turfgrass systems, where application of ammonium- and/or nitrate-based fertilizer produced emissions contrary to what was expected based on WFPS. Past turfgrass research has shown that an ammonium-based fertilizer (urea) still produced high N_2O emissions under high WFPS due to irrigation and/or significant rainfall, although no nitrate-based fertilizer was compared (Bremer, 2006; Lewis, 2010). Controlled-release fertilizers could possibly reduce the impact that WFPS has on emissions, however, minimal research in turfgrass systems has been conducted investigating the effects of controlled-release N fertilizers, such as polymer-coated urea (PCU) or sulfur-coated urea (SCU) on N_2O emissions under various soil water content conditions. A reduction in irrigation quantity or frequency could have the potential to reduce N_2O emissions when properly combined with the correct fertilizer. Further research should be conducted to investigate not only different irrigation techniques and timings, such as deficit irrigation and irrigation timing after application of fertilizer, but also comparing ammonium- and nitrate-based fertilizers as well as controlled- and slow-release N fertilizers under various aerobic and anaerobic soil conditions to attain a better understanding of the impact soil water content and nitrogen fertilizers have on N_2O emissions in a turfgrass system.

It is possible to have significant spatial variability in soil physical, biological and chemical properties (e.g., moisture, temperature, ammonium and nitrate content, pH, clay fraction) across a single turfgrass or agricultural system, which could lead to differences in N_2O production. There may be other soil factors which limit or intensify N_2O production despite the soil having a high soil water content, which was discussed above (Li et al., 2013).

Soil Temperature

Turfgrass environments under high soil water content and soil temperatures of 30 °C or higher are more likely to experience denitrification losses from applied fertilizers (Mancino et al., 1988). Bijoor et al. (2008) noticed N-fertilized tall fescue (*Festuca arundinacea* Schreb. Syn *Schedonorus arundinaceus* Schreb.) consistently produced greater N_2O fluxes when artificially heated compared to unheated control plots. Turfgrass plots that were fertilized during warmer summer conditions emitted more N_2O than plots fertilized during cooler conditions in spring or fall (Lewis and Bremer, 2013). Similarly, larger N_2O fluxes were the result of higher soil temperatures in an unfertilized grass sward of perennial ryegrass and dallisgrass (*Paspalum dilatatum* Poir.) (Denmead et al., 1979). However, other researchers have reported there was no relationship between soil temperature and N_2O fluxes in both turfgrass and agricultural soils (Townsend-Small and Czimczik, 2010; Wagner-Riddle and Thurtell, 1998). Soil temperature is just one of the many factors that plays a complex uncertain role in N_2O emissions (Christensen, 1983; Goodroad & Keeney, 1984).

Soil Nitrogen

Nitrous oxide fluxes have also been reported to have inconsistent results relating to soil NH_4^+ and NO_3^- content in both turfgrass and agricultural systems (Bergstrom et al., 2001; Bremer, 2006; Denmead et al., 1979; Lewis and Bremer, 2013; Li et al., 2013; Tenuta and Beauchamp, 2003; Thorton and Valente, 2001). Due to low correlation between emissions and soil NH_4^+ and NO_3^- contents, it has been suggested soil N turnover rates possibly play a larger role in N_2O production (Schimel et al., 1989; Matson and Vitousek 1990; Mosier et al., 1997). The reported inconsistencies of the significance of soil NH_4^+ and NO_3^- influence on N_2O production could be determined by the water and oxygen content of the soil at the time N_2O fluxes are measured (Freney et al., 1979). Under high WFPS and low O_2 contents (anaerobic conditions) N_2O production may likely be more influenced by soil NO_3^- content than soil NH_4^+ content due to denitrification and vice versa under aerobic conditions (Freney et al., 1979).

Other Soil Factors

There have been differences in N_2O emissions as they relate to other soil factors such as soil pH, organic carbon, and clay content (Bremer, 2006; Lu et al., 2015; Li et al., 2013). Li et al. (2013) reported N_2O production was negatively correlated to soil pH at higher WFPS. Whereas, Lu et al. (2015) reported soil pH did not influence N_2O production. Different results were also reported for the effect of the clay content of the soil on N_2O production. Lu et al. (2015) reported percent clay content had no effect on N_2O production, however, Li et al. (2013) reported positive a correlation for clay content at 60% WFPS.

Organic carbon that is readily available in soil is an important component of the denitrification process, which can be influenced by biomass production, such as clippings. Impacts of biomass production in a turfgrass systems has also been investigated (Bremer, 2006; Li et al., 2013). Bremer (2006) found that urea fertilizer applied at a low rate resulted in significantly less clippings returned among N fertilization treatments on fourteen of fifteen measurement days, however N_2O fluxes from this same low rate urea treatment were only significantly lower for three of the fifteen days. Therefore, less clippings did not always translate to less N_2O fluxes. The addition of bermudagrass clippings enhanced N_2O production at 60% WFPS, but had negligible influence at 90% WFPS. The addition of wheat straw resulted N_2O production that was comparable to or lower than control (no addition of wheat straw) plots at 60% and 90% WFPS (Li et al., 2013).

An increase in N_2O fluxes has been reported in the winter during snow melting events and spring/thaw events. In Ontario, Canada, N_2O emissions increased substantially during winter and spring thaw in bare agricultural soils, but emissions were minimal in plots with presence of vegetation [alfalfa (*Medicago sativa* L.) or Kentucky bluegrass (*Poa pratensis* L.)] during thaw (Wagner-Riddle and Thurtell, 1998). The lowest total N_2O emissions over four winter and spring thaw periods were recorded in an established 20-year stand of Kentucky bluegrass compared to agricultural fields of bare soil, barley, soybean [*Glycine max* (L.) Merr.], canola (*Brassica napus*), alfalfa, and corn subjected to various management practices (manure and nitrogen fertilizer addition, alfalfa ploughing, and fallowing) (Wagner-Riddle and Thurtell, 1998). Similarly, 60% of the annual N_2O fluxes occurred outside the growing season from October to April due to winter and spring freeze/thaw events in plots of perennial silage grass, barley, and fallow after potato (*Solanum tuberosum* L.) harvest in Jokioinen, Finland (Syväsalo et al., 2004). Lewis and Bremer (2013) reported increases in N_2O fluxes in turfgrass plots in one of two years during snow melt in the winter. Regardless of vegetation, it may be crucial to measure emissions throughout the winter and during freeze/thaw events to have a more accurate representation of the annual N_2O emitted.

Since N_2O production is determined by complex interactions among soil physical, biological and chemical properties (e.g., moisture, temperature, ammonium and nitrate content, pH, clay fraction), direct correlations between N_2O fluxes and any one of these variables are typically low. However, regardless of turfgrass or agricultural systems, future research on N_2O emissions should include these variables to study possible correlations and improve mechanistic models.

Fertilization Impact

An increase in N_2O fluxes has been reported immediately following nitrogen fertilization. Nitrous oxide fluxes in perennial ryegrass were amplified by as much as 15 times within 3 days of the fertilization event, with increases tending to be greater when substantial precipitation occurred (Bremer, 2006). In the previous study, fluxes decreased to background levels after 14 to 21 days (Bremer, 2006). Similarly, Bergstrom et al. (2001) found that N_2O emissions generally returned to background levels within 16 days of fertilizer application in a Kentucky bluegrass. Thirty percent of the total annual N_2O lost occurred during the two weeks immediately following an N-fertilizer application in a corn field in northern Colorado (Mosier and Hutchinson, 1981).

Turfgrass researchers measuring N_2O emissions have concentrated on quick-release fertilizer types, such as ammonium nitrate, ammonium sulfate, calcium nitrate, urea, and others. In Kentucky bluegrass, there were no significant differences in N_2O emissions among plots fertilized with ammonium sulfate, calcium nitrate, and urea at 100 kg N ha^{-1} yr^{-1}, although emissions in all fertilized treatments were statistically greater than the unfertilized check (Bergstrom et al., 2001). Urea fertilizer applied at 250 kg N ha^{-1} yr^{-1} to perennial ryegrass increased annual N_2O emissions 63% compared to urea at 50 kg N ha^{-1} yr^{-1}, but there were no significant differences between urea and ammonium sulfate applied at the same (higher) rate (Bremer, 2006).

Little investigation has been done on the influence of controlled-release (slow-release) N fertilizers on N_2O emissions in agricultural systems, and even less in turfgrass systems (Snyder et al., 2009). Nitrous oxide emissions may be reduced with the use of controlled-release N fertilizers (PCU, SCU, and others) by reducing the amount of N in the soil that is available to denitrify. The many different examples of PCU and SCU fertilizers not only differ in coating material type and layers, but also the coating thickness, all of which allow water to move inside and urea nitrogen inside to dissolve. The N diffusion rate is affected by coating thickness, soil temperature, soil moisture and soil N concentration gradient, which also governs plant growth.

Generally, controlled-release fertilizers have reduced N_2O emissions in various agronomic systems compared to quick-release fertilizers. Nitrous oxide production immediately after fertilization was initially lower in barley plots treated with PCU compared to those treated with urea with or without the nitrification inhibitor dicyandiamide on a clayey soil in Colorado (Delgado and Mosier, 1996). However, 60 to 80 days after fertilization total N_2O emissions were higher in the PCU-treated plots compared to urea alone (Delgado and Mosier, 1996). Halvorson et al. (2008) also recorded greater spikes in N_2O emissions with application of urea than with PCU fertilizers in irrigated corn in Colorado. Similarly, Shoji et al. (2001) reported PCU applied to irrigated barley in Colorado reduced N_2O emissions by 35% compared to urea. Merchan-Paniaqua (2006) reported reduced N_2O emissions in corn crop in Missouri with use of PCU compared to urea in 2004, but not in 2005, the latter received less than half the rainfall than the former year. Hyatt et al. (2010) reported reduced N_2O emissions in irrigated potato fields in Minnesota with use of PCU compared to conventional split applications of urea and ammonium nitrate over three-year study.

Controlled-release fertilizers have been shown to possibly reduce N_2O emissions in turfgrass systems. However, the results have not been as evident as seen in agronomic systems and very few studies exist. Maggiotto et al. (2000) found that both SCU and urea resulted in lower N_2O emissions than ammonium nitrate, all applied at a rate of 200 kg N ha^{-1} yr^{-1} in perennial ryegrass. In a study with slow-release vs. quick-release N fertilizers, Lewis (2010) reported PCU did not reduce N_2O emissions compared to urea in bermudagrass (*Cynodon* *dactylon* x *C. transvaalensis* Burtt-Davy) fertilized at 200 kg N ha^{-1} yr^{-1}. Conversely, Lemonte et al. (2016) reported lower N_2O emissions over a 45-day sampling period from PCU compared to urea, when both were applied at 200 kg N ha^{-1} yr^{-1} to a mixed stand of Kentucky bluegrass and perennial ryegrass. The high rate of 200 kg N ha^{-1} yr^{-1} applied as urea may have influenced the results from this study since it is well above the recommended rate to apply at one time. Also, in their study, N_2O emissions were only measured for 45 days, which may not have been enough time for the PCU fertilizer to reach full nutrient release. However, in the above studies by Lewis (2010) and Lemonte et al. (2016) estimates of annual N_2O emissions were not possible because measurements were only collected during the growing season or a short-designated period.

Over a one-year period, Gillette et al. (2016) evaluated the effects on N_2O emissions of three different slow- and controlled-release fertilizers [(urea with nitrification and urease inhibitors, which inhibit microbial and enzyme activity), a controlled release; PCU, and a reactive slow-release; (methylene urea, which is influenced by microbial activity)]. All three of these fertilizers were each applied in three applications for a total of 150 kg N ha^{-1} yr^{-1} on two different golf course mowing heights (fairway and rough). Polymer-coated urea at fairway height, and methylene urea and PCU at the higher rough mowing height emitted the lowest N_2O (Gillette et al., 2016). Furthermore, all three slow and controlled-release forms of N fertilizer had higher N_2O emissions than unfertilized turf. No quick-release fertilizer was included for comparison in Gillette et al. (2016) since the urea treatment contained nitrification and urease inhibitors and the methylene urea was a reactive slow-release form. Results from this previously mentioned study and along with other past research, including a meta-analysis of published field experiments, all concluded that urease inhibitors are ineffective in reducing N_2O emissions in agricultural soils (Dobbie and Smith, 2003; Gillette et al., 2016; Hiroko et al., 2010). In the study by Gillette et al. (2016), the controlled-release PCU along with the two slow-release nitrogen forms were applied at three fertilization timings in June, July, and September. Furthermore, application timing and frequencies of PCU in the study is questionable due to the product longevity (average number of days for nutrient release) is not mentioned. Controlled and slow-release forms of N fertilizer are more expensive but are utilized in the turf industry for the advantage of providing temperature-driven nutrient release; thus, fewer applications may be necessary. These controlled- and slow-release forms N fertilizer, especially the PCU would most likely be applied in a single application once a year, not three timings over a 120-day period.

Overall, relatively little work has been done to investigate effects of controlled-release fertilizers compared to quick-release fertilizers on N_2O emissions in turfgrass systems. These controlled-release forms of nitrogen may slow the processes of nitrification and denitrification, thus reducing emissions of N_2O.

Typically, a relatively small percentage of the applied N fertilizer is lost as N_2O through denitrification. Past studies have reported 0.4 to 4.8% of various applied quick- and controlled-release N fertilizer sources were lost as N_2O in turfgrass systems (Gillette et al., 2016; Horgan et al., 2002; Kaye et al., 2004; Lewis, 2010; Lewis and Bremer, 2013; Maggiotto et al., 2000). These previous findings are similar to the reported percentages lost as N_2O from applied fertilizer on different agricultural lands (Bouwman, 1994; Bouwman et al., 1995; Clayton et al., 1997; Mosier and Hutchinson, 1981; Mosier et al., 1986; Syväsalo et al., 2004; Wagner-Riddle et al., 1997; Webb et al., 2004). Future research should investigate more effective N fertilizer sources, such as controlled-release N fertilizers combined with improved irrigation techniques and timing to minimize the loss as N_2O and maximize plant uptake.

Long-term Cumulative Nitrous Oxide Emissions

There have only been a few studies in turfgrass that have measured N_2O emissions over an entire year or multiple years to calculate annual N_2O emissions (Bremer, 2006; Gillette et al., 2016; Groffman et al., 2009; Kaye et al., 2004; Lewis and Bremer, 2013; Townsend-Small et al., 2011). Studies that have only been conducted over a relatively short time period cannot accurately calculate estimates of annual N_2O emissions. To account for seasonal and interannual climatic variability, a sampling frequency of continuous daily measurements or at least constant periodic measurements over at least one year or multiple years is required. Annual N_2O emissions in three N-fertilized turfgrass species fluctuated between years based on changes in soil moisture and temperature due to interannual climatic variability (Lewis and Bremer, 2013).

Lewis and Bremer (2013) also found clear intra-annual differences in N_2O emissions between warm- and cool-season turfgrasses due to recommended differences in seasonal fertilization timings. Regardless, there were no significant differences in cumulative emissions in that study, which ranged from 2.38 to 3.36 kg N_2O-N ha^{-1} yr^{-1} in bermudagrass, perennial ryegrass, and zoysiagrass (*Zoysia japonica* Steud.) (Lewis and Bremer, 2013). Cumulative annual N_2O emissions ranged from 1.01 to 1.65 kg N_2O-N ha^{-1} yr^{-1} in a perennial ryegrass stand fertilized with different N sources and amounts (Bremer, 2006). In a perennial ryegrass fairway

(1.9-cm mowing height), Gillette et al. (2016) reported cumulative annual N_2O emissions of 2.3 kg N_2O-N ha^{-1} yr^{-1} from PCU, which was significantly lower than both urea with nitrification and urease inhibitors and methylene urea, 6.5 and 7.6 kg N_2O-N ha^{-1} yr^{-1}, respectively. However, when the same treatments were investigated at the same time in a Kentucky bluegrass stand at 6.35-cm height, Gillette et al. (2016) reported cumulative annual N_2O emissions of 2.4, 1.50, and 1.49 kg N_2O-N ha^{-1} yr^{-1} for urea with nitrification and urease inhibitors, PCU, and methylene urea, respectively.

Cumulative N_2O emissions were comparable between turfgrass and agricultural ecosystems according in several studies (Kaye et al., 2004; Townsend et al., 2011). Kaye et al. (2004) reported urban Kentucky bluegrass lawns, which occupied 6.4% of the studied 1578 km^2 in Colorado, contributed up to almost 30% of the total regional N_2O emissions. In their 1-year experiment, turfgrass N_2O emissions were comparable to irrigated corn at 2.4 kg N_2O-N ha^{-1} yr^{-1}. However, turfgrass annual N_2O emissions (kg N_2O-N ha^{-1} yr^{-1}) were 10 times higher than native grassland and wheat-fallow soils (Kaye et al., 2004). In a study in California, annual N_2O emissions were 1.8 to 2.3 kg N_2O-N ha^{-1} yr^{-1} across multiple turfgrass lawns and athletic fields comprised of mixtures of tall fescue, perennial ryegrass, and bermudagrass irrigated daily; 2.2 kg N_2O-N ha^{-1} yr^{-1} for multiple corn fields irrigated weekly; and 1.2 kg N_2O-N ha^{-1} yr^{-1} for a field of five rotated row crops all fertilized and irrigated identically by drip irrigation [celery (*Apium* L.), tomatoes (*Solanum lycopersicum* L.), carrots (*Daucus carota* L.), beans (*Phaseolus vulgaris* L.), and alfalfa] (Townsend et al., 2011). The previous study reported similar annual N_2O emissions among turfgrass, corn, and row crop sites although different fertilizer types, application methods, and rates were implemented at each site (Townsend et al., 2011). In another study comparing land cover types, Groffman et al. (2009) reported minimal differences in annual emissions between urban grasslands and neighboring forest sites in Maryland. The annual emissions for the urban grasslands consisting of Kentucky bluegrass, tall fescue, fine fescue (*Fesctuca spp.*) and white clover (*Trifolium repens*) and neighboring forest sites ranged from 0.5 to 3 kg N_2O-N ha^{-1} yr^{-1} (Groffman et al., 2009).

Annual N_2O emissions in turfgrass systems mentioned above generally ranged from 1 to 3.5 kg N_2O-N ha^{-1} yr^{-1} across various turfgrass species and under different fertilization regimes (Bremer, 2006; Gillette et al., 2016; Groffman et al., 2009; Kaye et al., 2004; Lewis and Bremer, 2013; Townsend-Small et al., 2011). However, annual N_2O emissions have also been reported up to 7.6 kg N_2O-N ha^{-1} yr^{-1} in a perennial ryegrass fairway in Colorado, which the researcher speculated was due to environmental conditions of warm surface soil temperatures and high WFPS after fertilization that were favorable for a rapid release of N_2O (Gillette et al., 2016). The annual N_2O emissions in turfgrass systems reported herein are similar to or lower than other agricultural land [e.g. fertilized pastures, barley, alfalfa, canola, corn] (Duxbury et al., 1982; Sehy et al., 2003; Syväsalo et al., 2004; Tilsner et al., 2003; Wagner-Riddle et al., 1997). More specifically, over a 2-year period, Clayton et al. (1997) reported annual emissions of 0.69 to 5.2 kg N_2O-N ha^{-1} yr^{-1} in silage cut perennial ryegrass grasslands in Scotland receiving three fertilizer applications per year of either ammonium sulfate, urea, calcium nitrate, or ammonium nitrate for a total of 360 kg N ha^{-1} yr^{-1}. The following year at the same site as Clayton et al. (1997), Smith et al. (1998) recorded emissions of 1.0 kg N_2O-N ha^{-1} yr^{-1} in silage cut perennial ryegrass grasslands fertilized with ammonium nitrate at 360 kg N ha^{-1} yr^{-1}. Therefore, the 3-year mean for the grassland fertilized with ammonium nitrate was 2.24 kg N_2O-N ha^{-1} yr^{-1} and reported differences were attributed interannual climatic variability (Smith et al., 1998). Dobbie et al. (1999) reported annual N_2O emissions over a 3-year period at the same site studied by Clayton et al. (1997) and Smith et al. (1998) ranged from 1.9 to 18.4 kg N_2O-N ha^{-1} yr^{-1} in cut ryegrass fields receiving ammonium nitrate at 220 to 320 kg N ha^{-1} yr^{-1}; however, significant seasonal flux variations resulted due to wet and dry periods of weather. In the previous two studies, annual emissions of N_2O from arable crops were recorded at 1.2 to 4.7 kg N_2O-N ha^{-1} yr^{-1} for potato, 1.2 kg N_2O-N ha^{-1} yr^{-1} for oilseed rape (*Brassica napus* L.), 9.1 to 12.1 kg N_2O-N ha^{-1} yr^{-1} for broccoli (*Brassica oleracea* L.), and less than 1 kg N_2O-N ha^{-1} yr^{-1} for spring barley and winter wheat (*Triticum aestivum* L.) (Dobbie et al., 1999; Smith et al., 1998). In a 6-year study in the United Kingdom, emissions of N_2O were reported below 2 kg N_2O-N ha^{-1} yr^{-1} for several cereal crops, sugar beet (*Beta vulgaris* L.), potato, and linseed (*Linum usitatissimum*) (Webb et al., 2004).

Turfgrass systems covering a substantial area of land has comparable cumulative annual N_2O emissions with agricultural systems. However, only a few turfgrass studies exist in which fluxes were intensively measured over the entire year for at least one or multiple years to be able to calculate accurate annual N_2O emissions among species and management regimes, which may vary widely. Therefore, it is essential to continue research and analyze how turfgrass systems contribute to the overall global GHG budget and investigate methods to reduce N_2O emissions.

Modeling Nitrous Oxide Emissions

Continuation of direct N_2O measurements (e.g. bi-weekly or weekly) over the long-term to calculate total inventory can be expensive and time consuming. Therefore, the use of model simulations developed from past agricultural and turfgrass studies have been investigated as another way to predict total inventory of trace gas emissions, carbon and nutrient cycling, and other plant production factors.

Model simulations of carbon and nitrogen cycling (sequestration and decomposition) in plant ecosystems can provide predictions of plant growth, soil carbon dynamics, nitrogen leaching, and trace gas [N_2O, NO, N_2, ammonia (NH_3), methane (CH_4), CO_2] emissions. These model simulations are based on several recorded input variables for a given time, which can be broadly grouped into the four parameters of climate, soil, crop (plant), and management.

Few studies have estimated carbon cycling in turfgrass systems by using model simulations, such as the CENTURY model and the CranTurfC model (Bandaranayake et al., 2003; Bartlett and James, 2011; Qian et al., 2003; Zirkle et al., 2011), and even fewer studies have simulated potential N_2O and other trace gas fluxes in turfgrass systems by using model simulations, such as the DAYCENT model and the DNDC (i.e., DeNitrification DeComposition) model (Gu et al., 2015; Zhang et al., 2013a, 2013b).

The CENTURY model (Parton et al., 1987) is a biogeochemical model that has been used in agricultural systems to simulate long-term changes in soil organic carbon and nitrogen, nutrient cycling, and plant production. The CENTURY model operates on a monthly time-step, which is useful in agricultural systems, but can be a limitation in successfully simulating turfgrass management practices that are conducted on a weekly or daily basis, such as mowing and irrigation (Zhang et al., 2013a). The DAYCENT model is a variation of the CENTURY model, although data input and output is scheduled on a daily time-step, which is a finer time scale than the CENTURY model (Del Grosso et al., 2001; Parton et al., 1994, 1998, 2001).

The DAYCENT model is a process-based model that has been successfully utilized in a variety of ecosystems, including turfgrass (Del Grosso et al., 2005, 2006; Li et al., 2006; Parton et al., 2001; Pepper et al., 2005; Zhang et al., 2013a, 2013b). Zhang et al. (2013a, 2013b) applied the DAYCENT model to past research of observed N_2O emissions from Bremer (2006) and Kaye et al. (2004). The DAYCENT model initially overestimated N_2O emissions by about 200%, but once adjustments were made for biological nitrification inhibition in the root exudate of perennial ryegrass then estimated N_2O emissions were within 8% of the observed values (Zhang et al., 2013b). The DAYCENT model simulated annual cumulative N_2O emissions in Kentucky bluegrass within 16% of the observed values of Kaye et al. (2004) (Zhang et al., 2013b).

The DNDC (DeNitrification DeComposition) is a process-based model that has been widely used. It is capable of simulating N_2O and CH_4, and CO_2 fluxes, along with carbon cycling, NH_3 volatilization, NO_3^- leaching and other crop production factors (Li et al., 1992, 1996, 2001). The DNDC model has only been implemented in one turfgrass study (Gu et al., 2015). The predicted N_2O emissions from the DNDC model at three sites generally matched the observed N_2O fluxes and predicted long-term 75-year average ranged from 0.75 to 3.57 kg N_2O-N ha^{-1} yr^{-1} depending on turfgrass age and lawn care practices of either minimal, moderate, or intensive management archetypes generated from a survey sample in Nashville, TN (Gu et al., 2015). Gu et al. (2015) reported the DNDC model simulated more N_2O peaks than were observed in the field, likely due to low field sampling frequency.

Both of these biogeochemical models (i.e., DAYCENT and DNDC) require the same soil and environmental inputs, and will both generate output of N gas emissions (N_2O NO, NH_3), CH_4, CO_2, soil organic matter change, crop production, N leaching, and runoff. However, each model differently describes soil water routing, nitrogen cycling, and plant growth utilizing different model algorithms for estimating carbon and N dynamics and trace gas emissions. For further information, Grant et al. (2016) presented an excellent review of the model specifications comparing the DNDC and DAYCENT models. Several past studies have evaluated these two models side-by-side in agronomic systems (Abdalla et al., 2010; Grant et al., 2016; Smith et al., 2008). Abdalla et al. (2010) reported both models overestimated N_2O fluxes, although the cumulative emissions and flux patterns simulated by DAYCENT were more similar to observed values than equivalent estimates from the DNDC model. These models, specifically the DAYCENT and DNDC should each be further tested and possibly compared side-by-side in turfgrass systems where direct measurements of N_2O and other trace gas fluxes have been recorded to predict long-term impacts of different management practices (irrigation and fertilization) on carbon and nitrogen cycling in turfgrass systems.

Summary

Turfgrass systems are typically fertilized and irrigated, therefore they have the potential to emit N_2O at similar rates as other agricultural soils and thus, play an important role in atmospheric N_2O budgets. Past research has shown soil water content can greatly impact the magnitude of N_2O emitted. Therefore, further research should be conducted investigating different irrigation techniques and timings, such as deficit irrigation and timing after application of fertilizer, to investigate their potential to reduce N_2O emissions. Annual N_2O emissions measured in managed turfgrass systems have generally ranged from 1 to 3.5 kg N_2O-N ha^{-1} yr^{-1} across various turfgrass species under different fertilization regimes. Relatively little work has been done to investigate effects of controlled-release forms of N-fertilizers on N_2O emissions in turfgrass systems. These controlled-release forms of nitrogen may slow the processes of nitrification and denitrification, thus reducing emissions of N_2O.

Further N_2O research is required in turfgrass to develop management practices (e.g., irrigation and fertilization regimes) that may reduce emissions of N_2O in turfgrass systems. Future research should be directed towards long-term investigations of controlled-release N fertilizers combined with improved irrigation techniques such as deficit irrigation to minimize N_2O emissions and maximize plant nutrient uptake.

Lastly, biogeochemical simulation models that estimate trace gas fluxes and simulate long-term emissions such as the DAYCENT and DNDC models have been widely used in various agronomic systems, but little investigation has been conducted in turfgrass systems. There is a need to further develop and test these models in turfgrass systems where direct measurements of N_2O and other trace gas fluxes have been recorded to predict long-term impacts of different management practices (e.g., irrigation and fertilization) on carbon and nitrogen cycling in turfgrass systems.

Therefore, in Chapter 2, the effects of irrigation levels and N fertilizer types (controlled-release vs. quick-release) on N_2O emissions in turfgrass are investigated to 1) quantify the magnitude and patterns of N_2O emissions in turfgrass; and 2) determine how irrigation and N fertilization may be managed to reduce N_2O emissions.

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Chapter 2 - Nitrous Oxide Emissions and Carbon Sequestration in Turfgrass: Effects of Irrigation and N Fertilization

Abstract

Nitrous oxide (N_2O) and carbon dioxide (CO_2) are important greenhouse gases associated with global climate change. Turfgrasses sequester and emit CO_2, and emit N_2O when fertilized with nitrogen (N) and irrigated. The development of management practices such as use of controlled-release N fertilizers and/or deficit irrigation may reduce N_2O emissions, but also affect carbon (C) sequestration in turf soils. My objectives were to: 1) quantify the magnitude and patterns of N_2O emissions and C sequestration in turfgrass; and 2) determine how irrigation and N fertilization may be managed to reduce N_2O fluxes and enhance carbon sequestration. N_2O emissions were measured for two-years in 'Meyer' zoysiagrass (*Zoysia japonica* Steud.) under an automated rainout shelter in Manhattan, KS using static chambers. Two irrigation levels [66% reference evapotranspiration (ET_o) replacement and 33% ET_o replacement] and three N-fertilization treatments [urea, polymer-coated urea (PCU), both applied at a rate of 98 kg N ha^{-1} yr^{-1} and an unfertilized no-N (UF)] were included. Soil organic carbon (SOC) and C sequestration rate were also measured. During two summers, N_2O emissions were 6.3% higher with 66% ET_o (2.88 kg ha^{-1}) than with 33% ET_o (2.71 kg ha^{-1}). Over the two years, cumulative N_2O emissions averaged 4.06 kg ha^{-1} in UF turf, 4.5 kg ha^{-1} in PCU-treated turf, and 5.62 kg ha^{-1} in urea-treated turf, each statistically different from one another ($P \leq 0.01$). A higher input management schedule (urea + 66% ET_o irrigation treatment) did not increase C sequestration compared with a low input management schedule (no fertilizer + 33% ET_o irrigation treatment), and the C sequestration rate was 0.952 Mg C ha^{-1} yr^{-1} for zoysiagrass when averaged across management schedules and depths. Results from this study indicate the use of a controlled-release fertilizer, such as PCU, and/or lower irrigation reduces N_2O emissions in turfgrass.

Introduction

Nitrous oxide (N_2O) and carbon dioxide (CO_2) are important greenhouse gases (GHG) associated with global climate change. Nitrous oxide has been labeled as potentially the most ozone-depleting gas and has also been reported to be 310 times more effective at trapping longwave radiation in the atmosphere than CO_2 (IPCC, 2007; Ravishankara et al., 2009). These greenhouse gases are natural and anthropogenic by-products. Agricultural activities (soil and animal manure management) account for up to 60% of N_2O emissions and have increased by 17% from 1990 to 2005 (Smith et al., 2007; IPCC, 2007). Humans fertilizing agricultural land with nitrogen (N) are responsible for significant amounts of the N_2O emitted into the atmosphere each year (Mosier et al., 1998), including in turfgrass systems (Bremer, 2006; Horgan et al., 2002; Kaye et al., 2004; Lewis and Bremer, 2013; Maggiotto et al., 2000, Ryden, 1981).

Urban expansion has resulted in irrigated turfgrass covering an estimated 16 to 20 million hectares in the United States (Milesi et al, 2005). The turfgrass industry consists of home lawns, commercial properties, golf courses, parks, athletic fields, and roadsides in the United States. There is an estimated 2.56 million hectares of intensively-managed turfgrass on golf courses worldwide (Bartlett and James, 2011). Golf courses, home and commercial lawns, athletic fields, and other turfgrass areas are commonly irrigated and receive nitrogen fertilizer and thus, may contribute significantly to the global GHG budget.

Higher soil water content, also referred to as “water-filled pore space” (WFPS), during or after fertilization may be a key driver in amplified N_2O fluxes. Soil water content greatly influences the processes of nitrification and denitrification in the soil, which can result in N_2O fluxes (Christensen, 1983; Davidson, 1991; Firestone and Davidson, 1989; Ryden, 1981). Past N_2O research in turfgrass has shown N_2O emissions typically increase after N fertilizer applications and precipitation or irrigation (Bijoor et al., 2008; Bremer, 2006; Lewis, 2010; Lewis and Bremer, 2013; Lu et al., 2015). Conversely, others have reported that higher WFPS did not always enhance N_2O production in turfgrass systems (Li et al., 2013; Townsend-Small et al., 2011). Further research on the effects of irrigation quantity or frequency on N_2O fluxes in turfgrass is required.

Increased N_2O fluxes have been reported immediately after nitrogen fertilization (Bergstrom et al., 2001; Bremer, 2006). The majority of turfgrass studies measuring N_2O emissions have concentrated on quick-release fertilizers such as ammonium nitrate, ammonium sulfate, calcium nitrate, and urea. Little research has been done on the influence of controlled-release (slow-release) N-fertilizers on N_2O emissions in agricultural systems, and even less in turfgrass systems (Snyder et al., 2009). Nitrous oxide emissions may be reduced with the use of controlled-release N fertilizers [polymer-coated urea (PCU), and sulfur-coated urea (SCU), and others] by reducing the amount of N in the soil that is available to denitrify. The N diffusion rate in coated fertilizer is affected by coating thickness, soil temperature, soil moisture and soil N concentration gradient, which also governs plant growth. Generally, controlled-release fertilizers have reduced N_2O emissions in various agronomic systems compared to quick-release fertilizers (Delgado and Mosier, 1996; Halvorson et al., 2008; Hyatt et al., 2010; Merchan-Paniaqua, 2006; Shoji et al., 2001).

In turfgrass systems, the little research that has been conducted regarding the effects of controlled-release fertilizers on N_2O fluxes has indicated mixed results. Lewis (2010) reported PCU did not reduce N_2O emissions compared to urea in bermudagrass (*Cynodon dactylon* x *C. transvaalensis* Burtt-Davy) fertilized at 200 kg N ha^{-1} yr^{-1}. Conversely, Lemonte et al. (2016) reported lower N_2O emissions by PCU compared to urea, when both were applied at 200 kg N ha^{-1} yr^{-1} to a mixed stand of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.), and sampled over 45-days. In the above studies by Lewis (2010) and Lemonte et al. (2016), estimates of annual N_2O emissions were not possible because measurements were only collected during the growing season or a short-designated period. Maggiotto et al. (2000) found that both SCU and urea resulted in lower N_2O emissions than ammonium nitrate applied at rates up to 200 kg N ha^{-1} yr^{-1} in perennial ryegrass. Over a one-year period, Gillette et al. (2016) evaluated the effects on N_2O emissions of three different slow- and controlled-release fertilizers [(urea with nitrification and urease inhibitors, which inhibit microbial and enzyme activity), a controlled release; PCU, and a reactive slow-release; (methylene urea, which is influenced by microbial activity)]. All three of these fertilizers were each applied in three applications for a total of 150 kg N ha^{-1} yr^{-1} on two different golf course mowing heights [fairway (1.6-cm) and rough (6.35-cm)]. Polymer-coated urea at fairway height, and methylene urea and PCU at the higher rough mowing height emitted the lowest N_2O (Gillette et al., 2016). Furthermore, all three slow and controlled-release forms of N fertilizer had higher N_2O emissions than unfertilized turf. No quick-release fertilizer was included for comparison in Gillette et al. (2016) since the urea treatment contained nitrification and urease inhibitors and the methylene urea was a reactive slow-release form.

There have only been a few studies in turfgrass that have measured N_2O emissions over an entire year or multiple years, which allows calculation of annual N_2O emissions (Bremer, 2006; Gillette et al., 2016; Groffman et al., 2009; Kaye et al., 2004; Lewis and Bremer, 2013; Townsend-Small et al., 2011). Studies conducted over periods of less than one-year (e.g., only during the growing season) cannot provide accurate estimates of annual N_2O emissions. To obtain the latter, continuous, daily, or at least frequent, periodic measurements over one year is required. Furthermore, multiple years may be important to account for seasonal and interannual climatic variability when calculating cumulative annual N_2O emissions in turfgrass systems. Annual N_2O emissions in three N-fertilized turfgrass species fluctuated between years based on changes in soil moisture and temperature due to interannual climatic variability (Lewis and Bremer, 2013).

Cumulative N_2O emissions are similar between some turfgrass species and agricultural ecosystems (Kaye et al., 2004; Townsend et al., 2011). Annual N_2O emissions in turfgrass systems have generally ranged from 1 to 3.5 kg N_2O-N ha^{-1} yr^{-1} across various turfgrass species and under different fertilization regimes (Bremer, 2006; Gillette et al., 2016; Groffman et al., 2009; Kaye et al., 2004; Lewis and Bremer, 2013; Townsend-Small et al., 2011). However, annual N_2O emissions up to 7.6 kg N_2O-N ha^{-1} yr^{-1} occurred in a perennial ryegrass fairway in Colorado, which the researcher speculated was due to environmental conditions of warm surface soil temperatures and high WFPS after fertilization that were favorable for a rapid release of N_2O emissions (Gillette et al., 2016). The annual emissions in turfgrass systems reported herein are similar to or lower than other agricultural land [e.g. fertilized pastures, barley (*Hordeum vulgare* L.), alfalfa (*Medicago sativa* L.), canola (*Brassica napus*), corn (*Zea mays* L.)] (Duxbury et al., 1982; Sehy et al., 2003; Syväsalo et al., 2004; Tilsner et al., 2003; Wagner-Riddle et al., 1997).

Research by others has indicated that turfgrass may sequester atmospheric carbon (C) (Qian et al., 2010), including that on golf courses (Qian and Follett, 2002). The ability of turfgrass to sequester carbon is significant because the removal of atmospheric CO_2 by millions of hectares of turf may help to mitigate climate change. Carbon sequestration results when more CO_2 is removed from the atmosphere via photosynthesis than is returned to the atmosphere via respiration; the “surplus” C is sequestered in the soil. Nitrogen fertilization, as well as irrigation applied to turfgrass during dry periods, affects photosynthesis and respiration, which likely impacts C sequestration. In semi-arid Colorado, C sequestration was greater in irrigated than in non-irrigated fine fescue (*Fesctuca* spp.) (Qian et al., 2010). Little research has been conducted to document specific effects of irrigation levels or N-fertilization types on C sequestration in turfgrass, or that identify potentially optimal irrigation and N regimes for sequestering C in turf.

Contributions of N_2O and CO_2 fluxes from turfgrass should be considered because they may have significant impacts on global GHG atmospheric inventories. Therefore, it is essential to investigate how turfgrass systems contribute to the overall global GHG budget and investigate methods to reduce N_2O emissions and enhance C sequestration. Turfgrass management practices such as using controlled-release fertilizers combined with improved irrigation techniques (e.g., deficit irrigation) may reduce N_2O emissions and maximize plant CO_2 uptake. The development of management practices that reduce N_2O emissions from turfgrass and enhance C sequestration in turf soils may help mitigate climate change and atmospheric ozone destruction.

Therefore, objectives of this study were to: 1) quantify the magnitude and patterns of N_2O emissions and C sequestration in turfgrass; and 2) determine how irrigation and N fertilization may be managed to reduce N_2O fluxes and enhance C sequestration.

Materials and Methods

Study Site

This field experiment was conducted from 22 Aug. 2013 to 19 Oct. 2016 under an automated rainout shelter (12 by 12 m) at the Rocky Ford Turfgrass Research Center in Manhattan, Kansas USA (39° 13’ 53” N, 96° 34’51” 6 W). The soil type was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls). The rainout shelter was stationed north of the experimental area and upon detection of 0.254 mm of precipitation, would deploy and cover the experimental area in less than one-minute and then retract 1 hour after cessation of rainfall.

‘Meyer’ zoysiagrass (*Zoysia japonica* Steud.) was sodded on 4 June 2013 with the north and south ends of the plot area bordered with metal edging (10 cm depth). Thirty-six plots measuring 1.14 by 1.23 m were established 5 Aug. 2013 and were maintained at a 2.54 cm mowing height with a walk-behind non-motorized reel mower.

Fungicide applications for preventing and controlling *Rhizoctonia* large patch (*Rhizoctonia solani* Kühn Anastomosis Group (AG)-2-2 LP) included flutolanil, N-[3-(1-

methylethoxy) phenyl]-2-(trifluoromethyl)benzamide (Prostar 70WG, Bayer Environmental Science, Research Triangle Park, NC) at 4.69 kg a.i. ha^{-1} on 14 Sept. 2014, 19 Sept. 2015, and 8 Sept. 2016 and propiconazole, 1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1*H*-1,2,4-triazole (Lesco Spectator Ultra 1.3, Lesco, Inc., Cleveland, OH) at 1.78 kg a.i. ha^{-1} on 17 Apr. 2015.

Insecticide applications for controlling billbug grubs (*Sphenophorus* spp.) and white grubs (*Phyllophaga* ssp.) and (*Cyclocephala lurida* Bland) included imidacloprid, 1-[(6-Chloro-3-pyridinyl)methyl]-*N*-nitro-2-imidazolidinimine (Merit 0.5 G, Bayer Environmental Science, Research Triangle Park, NC) at 0.37 kg a.i. ha^{-1} on 13 July 2015 and 22 May 2016 .

Treatments

Two deficit irrigation treatments, replicated 6 times each, were applied to plots in a randomized complete-block design. The two deficit irrigation treatments were a medium, 72% reference evapotranspiration (ET_o) replacement and a low, 54% ET_o replacement. In 2014, researchers observed minimal drought stress at the two deficit irrigation levels. Therefore, in 2015 the medium and low deficit irrigation levels were reduced to 68% ET_o and 45% ET_o replacement, respectively from 1 June to July 19 and then to 66% ET_o and 33% ET_o replacement, respectively from 20 July to 1 Sept. In 2016, irrigation levels remained at 66% and 33% ET_o.

The automated rainout shelter was activated during the summer from 1 June to at least 31 Aug. Irrigation amounts were calculated from daily ET rates using the American Society of Civil Engineers (ASCE) standardized reference evapotranspiration equation (Walter et al., 2001) and data from an on-site weather station (available at: http://www.ksre.ksu.edu/wdl). Irrigation was applied by hand with a watering wand attached to a hose and meter (Model 03N31, GPI, Inc., Wichita, KS) twice a week from 1 June to 11 Sept. 2014 (106 d) and 1 June to 1 Sept. 2015 (92 d). For better precision of the effects of irrigation on N_2O emissions, irrigation was applied separately to the base collar within each plot with a graduated bottle from 1 June to 2 Sept. 2016 (93 d). The plots then all received adequate irrigation and any occurring precipitation from September through May, when the rainout shelter was not activated.

Three fertilizer treatments, replicated 6 times each, were applied to plots in a randomized complete-block design. The three nitrogen fertilizer treatments included: 1) polymer-coated urea (PCU) (41-0-0; 90-day release, POLYON SGN 150, Koch Agronomic Services, LLC, Wichita, KS) applied once at the beginning of summer for a total of 98 kg N ha^{-1} yr^{-1}; 2) urea (46-0-0;

Thrive Branded Fertilizer, Mears Fertilizer Inc. El Dorado, KS) applied at a rate of 49 kg N ha^{-1} at the beginning of summer and again at mid-summer for a total of 98 kg N ha^{-1} yr^{-1}; and 3) an unfertilized “control” (UF) receiving no N fertilizer. For precision, fertilizer amounts for the plot area and its respective base collar area were separately measured and applied by a hand-shaker jar. Fertilization dates were 1 June and 21 July in 2014; 2 June and 16 July in 2015; and 6 June and 20 July in 2016. After fertilization, plots were individually hand-watered as described above with respect to its corresponding irrigation treatment to incorporate fertilizer into the soil and reduce ammonia volatilization (Bowman et al., 1987). Irrigation amounts for the medium and low ET_o treatments immediately after fertilization were 15.7 mm and 11.7 mm in 2014; 12.7 mm and 8.6 mm in 2015, and 12.7 mm and 6.4 mm in 2016, respectively.

Nitrous Oxide Measurements

Fluxes of N_2O were measured from Oct. 2014 through Oct. 2016 using static, vented poly-vinyl chloride (PVC) chambers (7.5-cm high by 20-cm diameter) using the method described by Hutchinson and Mosier (1981; Mosier et al., 1991, 1997; Kaye et al., 2004). The static chambers used in this study were the same as used in previous studies (Bremer, 2006; Lewis and Bremer, 2013). Poly-vinyl chloride base collars (anchors) were installed randomly at one location within each plot on 2 Oct. 2014 for the first year of measurements and then reset on 6 Oct. 2015 for the second year of measurements. The PVC base collars were driven approximately 7 cm into the soil. Turfgrass within the base collars was maintained at the same height as the rest of the plot. Emissions of N_2O-N were measured at least once weekly during the growing season from May through September and once every 2-4 weeks during winter dormancy from October through April. Measurements occurred more frequently surrounding fertilization events in the summer, N_2O-N fluxes were measured at 1 day, 3 days, (also 5 days, 2016 only) and 7 days after N fertilization. On measurement days, gas samples were collected between 0700 to 1100 CST. On measurement days, chambers were installed on the base collar and an airtight seal was maintained with closed-cell weather stripping between the chamber and collar and with a tight rubber sleeve covering the outside perimeter of the junction between the chamber and collar. Immediately after a chamber was installed on the base collar, 25-mL gas samples were removed from inside each chamber with 30-mL polypropylene syringes after 0, 20, and 40 minutes and immediately injected into pre-evacuated 12-mL Labco Exetainer vials (Labco Limited, United Kingdom) with Labco grey butyl rubber septa. Gas samples were transported to the laboratory and N_2O concentrations were determined by gas chromatography (GC) using a Shimadzu Model 14B GC (Shimadzu Corporation, Japan) equipped with a Nickel 63 (^{63}Ni) electron capture detector and Porapak Q column (3.175 x 10^{-3} m diam. x 1 m, 80/100 mesh). Before samples were measured the GC was calibrated using analytical-grade standards containing 0.2, 2.15, 3.5, and 15.3 parts per million N_2O. Gas samples were analyzed generally within 2 to 48 h after each sampling campaign. Nitrous oxide flux data from each plot on each measurement day were evaluated to ensure the proper flux calculation method was selected and then flux rates were calculated using either a linear regression flux calculation method or the flux calculation method in equation 2.1 as described by Hutchinson and Mosier (1981) and Mosier et al. (1991):

$$N_2O\ flux = \frac{V(C_1 - C_0)^2}{[A \times t_1 \times (2C_1 - C_2 - C_0)]} \times \ln\left[\frac{(C_1 - C_0)}{(C_2 - C_1)}\right] \qquad [2.1]$$

where V is the volume of the enclosed air within chamber, A is the area of the soil covered, C_0, C_1, and C_2 are the chamber headspace concentrations at times t_0, t_1 (20 min), and t_2 (40 min). A linear regression flux calculation method was applied if a rejection criterion was met using equation 2.2 as described in Parkin et al. (2012) and Venterea et al. (2009):

$$0 \leq \left[\frac{C_1 - C_0}{C_2 - C_1}\right] \geq 1 \qquad [2.2]$$

where variables have been previously described above. Minimum positive and negative detection limits for each measurement date were determined using the method described by Parkin et al. (2012). Across all 69 measurements dates the minimum positive and negative detection limits for the Hutchinson and Mosier (1981) method ranged from 6.3 to 16.6 µg N_2O-N m^{-2} h^{-1} and -16.6 to -6.3 µg N_2O-N m^{-2} h^{-1}, respectively (Appendix Table A.1). The minimum positive and negative detection limits for the linear regression method ranged from 1.6 to 4.1 µg N_2O-N m^{-2} h^{-1} and -4.1 to -1.6 µg N_2O-N m^{-2} h^{-1}, respectively (Appendix Table A.1). Based on past research by Gilbert (1987), all measured flux values in this study were used even if it fell below the minimum detection limit (or within the detection limit band), which is the least biased course of action.

Cumulative annual emissions of N_2O-N were calculated as the sum of the outputs of flux rates on each measurement date and the number of days between adjacent measurement dates. Annual emissions were estimated by using interpolation between sampling points using equation 2.3 as described in McGowan (2015):

$$Cumulative\ N_2O\ (kg\ N\ ha^{-1}) = \sum_{i}^{n} \frac{(F_i + F_{i+1})}{2}\ (t_{i+1} - t_i) \qquad [2.3]$$

where F_i and F_{i+1} were the N_2O-N fluxes (kg ha^{-1} day^{-1}) at sampling points i and $i+1$; t_i and t_{i+1} were the sampling dates (day of year) at sampling points i and $i+1$; and n was the number of sampling points taken in a given year. Cumulative N_2O-N emissions were first calculated for each plot, and treatment means were then obtained by averaging the cumulative emissions from all plots within each treatment. Annual N_2O-N emissions were calculated from the estimated 365 days for the first calendar year from measurement dates of 29 Oct. 2014 to 5 Oct. 2015 and from the estimated 366 days for the second calendar year from measurement dates of 26 Oct. 2015 to 6 Oct. 2016. Overall cumulative N_2O-N emissions for the entire study were estimated by combining both sampling years (Oct. 2014 to Oct. 2016). For each year and the total of both years combined, cumulative summer N_2O-N emissions were calculated for the summer period from 2 June to 31 Aug. when the automated rainout shelter was activated and the irrigation and fertilizer treatments were applied. This was to evaluate the effects of irrigation on N_2O emissions. These cumulative N_2O-N emissions for the summer period is a better indication of the effect of irrigation treatment on N_2O emissions since this is the only time irrigation treatments are being applied during the study.

Ancillary Measurements

Weather data was collected from an on-site weather station positioned in full sun within 50 m of the study area. On each gas sampling date, volumetric soil water content, soil temperature, and soil NO_3^--N and NH_4^+-N were measured. Volumetric soil water content (θ) was measured and averaged over 5 locations per plot to a depth of 7.6 cm using a FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL). Water-filled pore space (WFPS) (v v^{-1}) was calculated from volumetric water content by equation 2.4 as described in Maggiotto et al. (2000):

$$WFPS = 100\frac{\theta}{\varepsilon} \qquad [2.4]$$

where ε is the total pore space (0.480 cm^3 cm^{-3}). To estimate ε, soil bulk density (ρ_b) was calculated from soil samples taken at random locations at 0 to 5 cm and 5 to 10 cm.

Soil temperature was measured once in each plot at a depth of 7.6 cm using digital soil thermometers (2015: Digital T-bar thermometer, Argus Realcold Property Ltd., Coopers Plains, Australia; 2016: DT310LAB Lab Digital Stem Thermometer, General Tools & Instruments LLC., New York, NY). One soil sample from 0 to 12.7 cm, with the grass and thatch removed, was collected from each plot and tested for NH_4^+, and NO_3^- concentration (Soil Testing Laboratory, Kansas State University).

Mowing frequency of each plot was recorded for the entire 2015 and 2016 growing season. Every 4 to 7 days, grass height was measured at four random locations within each plot. If the grass height was $\geq$ 3.8 cm in at least one of four locations within a plot, that plot was mowed on that day. A maximum height of 3.8 cm was established for the 2.54-cm mowing height due to general guidelines of not removing more than 1/3 of the turfgrass canopy (Hoyle, 2017; Law et al., 2016). Cumulative mowing frequency was summed separately for each plot and treatment means were then calculated. Irrigation frequency of each plot was also recorded.

Visual turf quality (VQ) of turfgrass plots was rated weekly from mid-May through mid-September on a 1 to 9 scale (1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality) according to color, texture, density, and uniformity (Morris and Shearman, 1999). Percent green cover (PGC) was measured by taking a digital photograph with a Nikon D5000 digital camera (Nikon Inc., Tokyo, Japan) of each plot weekly using a lighted camera box (51 cm x 61 cm x 56 cm) attached with a custom pink template border which provided an area of 48 cm x 25.4 cm of each plot. The camera was adjusted to manual settings of: f-stop of 5.6, 1/125 sec exposure time, and 800 ISO-speed. Images were analyzed with SigmaScan Pro 5.0 (ver. 5.0, SPSS Science Marketing Dept., Chicago, IL) using the "Turf Analysis" macro for batch analysis for three separate runs to account for template and green turf pixels (Karcher and Richardson, 2005). To determine green pixels, the macro threshold settings were adjusted to hue = 45 to 107 and saturation = 0 to 100 (Scan 1). For template pixels, the macro threshold settings were adjusted to hue = 0 to 32 (Scan 2), and again at hue = 108 to 255 (Scan 3), both at a saturation = 0 to 100. These threshold settings allowed for estimation of pixels, expressed as percentage of green turf color for each plot, calculated for each image by using equation 2.5:

$$Percent\ Green\ Cover\ (\%) = \frac{Scan\ 1\ pixels}{[Total\ Image\ Pixels - (Scan\ 2\ pixels + Scan\ 3\ pixels)]} \qquad [2.5]$$

where scan 1 pixels is the number of green pixels, total image pixels is the number of pixels for the entire image, and scans 2 and 3 are the total number of pink template pixels.

Soil Carbon Measurements

Soil carbon (C) was measured in plots from two management regimes: urea + 66% ET_o, designated as high management input schedule (HMI); and unfertilized + 33% ET_o, designated as low management input schedule (LMI). Soil C measurements were limited to two treatments to minimize disruption of the relatively small plots. On 22 Aug. 2013 (79 d after sodding) and 19 Oct. 2016 (1233 d after turf establishment) soil was sampled from four plots each (four replications) of HMI and LMI by first removing the plant material from the soil surface and then, using a flat-bladed shovel, undercutting and removing the soil from depths: 0-10, 10-20 and 20-30 cm by similar methodologies as Qian et al. (2010) and Follett et al. (2009). Soil bulk density (ρ_b) samples (volume of the soil core was 137.26 cm^3) were also collected from each soil depth zone mentioned above. Soil bulk density (g cm^{-3}) was determined by equation 2.6 in in accordance to (USDA-ARS and NRCS, 2001) methods:

$$Soil\ Bulk\ Density\ \left(\frac{g}{cm^3}\right) = \frac{Dry\ Weight\ of\ Soil\ Core\ (g)}{Volume\ of\ Soil\ Core\ (cm^3)} \qquad [2.6]$$

After ρ_b samples were collected they were dried in a forced-air oven for 48 h at 105 ºC and then weighed separately to determine dry weight. One soil core (2.54 cm diameter) was obtained at each depth from within each plot, for a total of three subsamples per plot. Samples were analyzed for total soil organic carbon (SOC) and total soil organic nitrogen (SON) (Soil Testing Laboratory, Kansas State University). Soil carbon/nitrogen ratio (C/N) was determined from SOC and SON. The annual change in SOC (ΔSOC) (Mg C ha^{-1} yr^{-1}) was calculated from the difference between the 2013 and 2016 samples.

Statistical Analysis

Differences in reported variables were evaluated by analysis of variance (ANOVA) using PROC GLIMMIX of SAS (SAS 9.4, SAS® Institute Inc., Cary, NC, USA). Analysis of variance of daily N_2O-N fluxes, cumulative N_2O-N emissions, WFPS, soil temperature, soil NO_3^--N, soil NH_4^+-N, VQ, PGC, and mowing frequency was conducted for each year, with fertilizer, irrigation, and fertilizer x irrigation as fixed effects and block as a random effect. Means were separated using Fisher's protected least significant difference test ($P \leq 0.05$). Soil organic carbon, SON, ρ_b, C/N, ΔSOC were analyzed using three-way ANOVA with management schedule, year, and depth as a fixed effects and block as a random effect. After analysis of type III tests for fixed effects for SOC, SON, ρ_b, C/N, ΔSOC, the F test for slice effects and the t test for slice differences were conducted utilizing a conservative Bonferroni adjustment test for multiple comparisons. Tests for slice effects were conducted to analyze the following: management schedules within each depth x year, years within each management schedule x depth, management schedules averaged across all depths within each year, years within each management schedule averaged across all depths, depths within each year, and years within each depth. Residual normality was tested with the *w* statistic of the Shapiro-Wilk test using the UNIVARIATE procedure of SAS 9.4 (Shapiro and Wilk, 1965). Correlations between WFPS, soil temperature, and NO_3^--N and NH_4^+-N in the soil and N_2O-N fluxes were conducted with the correlation procedure (Spearman) of SAS 9.4.

Results and Discussion

In both years, there were more significant differences in daily N_2O fluxes, WFPS, and other measured variables due to the fertilizer and irrigation main effects than due to the fertilizer x irrigation treatment interaction (Appendix Tables A.2 to A.18). Therefore, the two main effects will be discussed separately.

Daily Fluxes

The fertilizer x irrigation treatment interaction was significant on only 3 of 32 measurement dates in year 1, and 3 of 37 dates in year 2 (Appendix Tables A.2 and A.3). While the fertilizer main effect was significant on 8 of 32 dates in year 1 and on 16 of 37 dates in year 2 and the irrigation main effect was significant on only 5 of 32 dates in year 1 and 8 of 37 dates in year 2 (Figs. 2.1A, 2.2A, 2.3A, 2.4A). Therefore, the two main effects will be discussed separately.

Fertilizer Main Effect

Most differences in daily N_2O fluxes were due to higher N_2O fluxes in urea than in PCU and/or UF. Furthermore, most differences among fertilizer treatments occurred during the summer when the automatic rainout shelter was activated and fertilizer and irrigation treatments were applied (Figs. 2.5 and 2.6). In both years, significant spikes in N_2O fluxes after fertilization were observed only for urea, the quick-release fertilizer. This resulted in significantly higher fluxes in urea than in both PCU and UF immediately (1 day) and for up to 3 to 7 days after fertilization in both years (Figs. 2.5 and 2.6). Consistently, the highest fluxes from urea fertilization occurred 1 day after fertilization, peaking at 498 and 882 μg N_2O-N m^{-2} h^{-1}, respectively, for year 1; and 318 and 301 μg N_2O-N m^{-2} h^{-1}, respectively, for year 2 (Figs. 2.1A, 2.2A, 2.5, and 2.6). After the initial spikes, fluxes declined by day 3 and then leveled off after 7 to 14 days (Figs. 2.5 and 2.6). The range (μg N_2O-N m^{-2} h^{-1}) in the spikes of N_2O fluxes and number of days to decline to background levels are comparable with other N_2O research in turfgrass involving urea and other quick-release fertilizers (Bremer, 2006; Lewis and Bremer, 2013; Bergstrom et al., 2001).

Contrary to the quick-release fertilizer urea, N_2O fluxes in the controlled-release fertilizer (PCU) did not spike dramatically after N fertilization but rather were similar or slightly higher than in UF (Figs. 2.5 and 2.6). Gillette et al. (2016) also reported PCU-treated plots were more resistant to rapid fluxes after fertilization and credited it to the slower and more controlled N release of PCU even under high WFPS conditions during the summer. Overall, the controlled-release fertilizer resulted in lower N_2O fluxes on a daily basis compared to the quick-release fertilizer (Figs. 2.1A and 2.2A).

In year 1, fluxes from PCU peaked at 71 µg N_2O-N m^{-2} h^{-1} on 19 Aug. 2015 (78 days after PCU fertilizer application), while fluxes from UF peaked at 63 µg N_2O-N m^{-2} h^{-1} on 17 July 2015 (Figs. 2.1A and 2.5). In year 2, fluxes from PCU peaked at 80 µg N_2O-N m^{-2} h^{-1} on 23 July 2016 (47 days after PCU fertilizer application), while fluxes from UF peaked at 73 µg N_2O-N m^{-2} h^{-1} on 21 July and 26 July 2016 (Figs. 2.2A and 2.6). These peak fluxes for PCU and UF were considerably lower and less frequent than urea peak fluxes.

Of the eight dates in year one with differences in daily N_2O fluxes among fertilizer treatments, there were five when urea was higher than both PCU and UF, seven when urea was at least higher than UF, and only three when PCU was higher than UF. In year 1, the only date when N_2O fluxes from PCU were higher than urea was 15 July 2015, which was 43 days after urea and PCU fertilization. Of the 16 dates with differences in year two, there were 11 when urea was higher than both PCU and UF, 12 when urea was at least higher than PCU, 13 when urea was at least higher than UF, five when PCU was higher than UF, and no dates when PCU was higher than urea.

Irrigation Main Effect

The irrigation main effect was significant on only 5 of 32 measurement dates in year 1 and 8 of 37 dates in year 2 (Figs. 2.3A and 2.4A). The majority of these dates occurred during the summer when the automatic rainout shelter was activated and irrigation treatments were applied (Figs. 2.3A and 2.4A). Immediately after fertilization, there were consistently spikes in fluxes in both irrigation treatments. These spikes were likely the effects of urea fertilization, as described above, across both irrigation treatments. However, differences in N_2O fluxes between irrigation treatments were observed only once immediately after fertilization. On that date (7

June 2016), higher irrigation (66% ET_o) resulted in higher fluxes. Two of the five dates with differences in year one occurred during the summer when the rainout shelter was activated. The higher irrigation treatment resulted in higher N_2O fluxes on only one of the two dates. Five of the eight dates in year two occurred during the summer, when N_2O fluxes were higher in the higher irrigation treatment.

Cumulative Summer Nitrous Oxide Emissions

In both years, there were differences in cumulative summer N_2O-N emissions due to both the fertilizer and irrigation main effects (Table 2.1). Total cumulative summer N_2O-N emissions combined from both years resulted in significant differences not only from the irrigation and fertilizer main effects, but also the irrigation x fertilizer interaction.

In each respective summer, as well as in the two summers combined, N_2O emissions were higher in the higher (66% ET_o) than the lower irrigation (33% ET_o) (Table 2.1). Over two summers, total cumulative summer N_2O emissions 6.3% higher in the 66% ET_o treatment compared to the 33% ET_o treatment. This demonstrates that less irrigation reduces N_2O emissions. During each of the two summers, N_2O emissions were higher in urea than in both PCU and UF. Interestingly, N_2O emissions were more similar between PCU and UF than between either fertilized treatments. For example, compared to unfertilized turfgrass, PCU application increased N_2O emissions by only 11% over the two summers, while urea application increased emissions by 57.5%. There were no differences in N_2O emissions between PCU and UF during the summer of 2016, although fluxes were higher in PCU than UF in 2015 and when both summers were combined. These mixed results reveal that although N_2O emissions may be increased by PCU, such increases are much less than when urea is applied.

Cumulative N_2O-N emissions over the two summers were highest among treatments in urea x 66% ET_o, followed by urea x 33% ET_o (Table 2.1). In both fertilized treatments N_2O emissions were reduced by less irrigation. However, emissions were higher in urea with low irrigation than in PCU with high irrigation. Irrigation did not affect N_2O emissions in unfertilized plots. Over the two summers N_2O emissions were similar among UF (at both irrigation levels) and PCU at low (33% ET_o) irrigation. This indicates that fertilization with PCU and reducing irrigation could reduce N_2O emissions to similar levels as unfertilized turfgrass.

Cumulative Nitrous Oxide Emissions

For cumulative N_2O-N emissions, the fertilizer main effect was significant in both years and the entire 2-year period, while the irrigation main effect was not significant (Appendix Table A.4). The overall lack of irrigation main effect was contrary to cumulative summer N_2O emissions results. Like the fertilizer treatments, the irrigation treatments were only applied in the summer period. However, as mentioned above, not only did differences occur more often with the fertilizer main effect (24 of 69 measurement dates) than the irrigation main effect (13 of 69 dates), but also the differences between fertilizer treatments were more pronounced than irrigation treatments (Figs. 2.1A, 2.2A, 2.3A, 2.4A). Therefore, it is likely the absence of irrigation treatments during the remainder of either year (i.e., when all plots received identical irrigation and precipitation for 9 months of the year) diluted the overall effects of the irrigation treatments over the entire study. Perhaps related to this, there were no differences in annual or cumulative N_2O emissions over the 2-year period among any fertilizer x irrigation treatment interactions. This indicates that specific deficit irrigation x fertilizer treatment combinations did not affect cumulative N_2O emissions in this study.

Cumulative emissions of N_2O-N for the entire 2-year period were 38% higher in urea than in UF turf, and 25% greater in urea than PCU (Fig. 2.7). Cumulative emissions of N_2O-N over the 2-year period were 11% higher in PCU than in UF turf (Fig. 2.7). Annual emissions of N_2O-N for year 1 were 1.82 kg ha^{-1} yr^{-1} in UF turf, 2.09 kg ha^{-1} yr^{-1} in PCU-treated turf, and 2.77 kg ha^{-1} yr^{-1} in urea-treated turf, each statistically different from one another ($P \leq 0.01$). Annual emissions of N_2O-N for year 2 were 2.24 kg ha^{-1} yr^{-1} in UF turf, 2.41 kg ha^{-1} yr^{-1} in PCU-treated turf, and 2.85 kg ha^{-1} yr^{-1} in urea-treated turf, each statistically different from one another ($P \leq 0.01$). Cumulative emissions of N_2O-N for the entire 2-year period were 4.06 kg ha^{-1} in UF, 4.5 kg ha^{-1} in PCU, and 5.62 kg ha^{-1} in urea, each statistically different from one another ($P \leq 0.01$). These results indicate the use of a controlled-release fertilizer such as PCU should be encouraged because it will help reduce N_2O emissions in turfgrass compared to the use of a quick-release fertilizer.

A range of N_2O emissions similar to my results have been reported by Lewis and Bremer (2013), who reported cumulative emissions of 3.12 kg N_2O-N ha^{-1} yr^{-1} in zoysiagrass receiving urea at 100 kg N ha^{-1} yr^{-1}, and emissions of 3.36 and 3.35 kg N_2O-N ha^{-1} yr^{-1} in bermudagrass and perennial ryegrass, respectively, both fertilized with urea at 200 kg N ha^{-1} yr^{-1} during a 600-

day study. Kaye et al. (2004) reported annual emissions of 2.4 kg N_2O-N ha^{-1} yr^{-1} from Kentucky bluegrass lawns fertilized with urea at 110 kg N ha^{-1} yr^{-1} during a 1-year study. Cumulative N_2O emissions ranged from 1.01 to 1.65 kg N_2O-N ha^{-1} yr^{-1} in a perennial ryegrass stand fertilized with different N sources and amounts during a 1-year study (Bremer, 2006). In a 1-year study, N_2O emissions were 6.5, 2.3, and 7.6 kg N_2O-N ha^{-1} yr^{-1} for urea with nitrification and urease inhibitors, PCU, and methylene urea, respectively, in a perennial ryegrass golf course fairway, each applied in three applications for a total of 150 kg N ha^{-1} yr^{-1} (Gillette et al., 2016). In the latter study, N_2O emissions were 2.4, 1.50, and 1.49 kg N_2O-N ha^{-1} yr^{-1} for urea with nitrification and urease inhibitors, PCU, and methylene urea, respectively, in a Kentucky bluegrass golf course rough, each applied in three applications for a total of 150 kg N ha^{-1} yr^{-1}.

In my study, cumulative N_2O emissions were measured over a 2-year period and the annual emissions for each treatment were similar, but slightly higher in year two than year one. Annual N_2O emissions in N fertilized turfgrass species and agricultural systems have been found to fluctuate among years based on changes in soil moisture and temperature due to interannual climatic variability (Clayton et al., 1997; Lewis and Bremer, 2013; Smith et al., 1998). A strong correlation between daily N_2O fluxes and soil temperatures may have played a role in the interannual variability in annual N_2O emissions. Soil temperatures averaged slightly higher in year two than in year one across all treatments (Appendix Tables A.7 and A.8), including during the summer when fertilizer and irrigation treatments were applied.

Over each year, an equivalent of approximately 2.1 and 2.5% in PCU and 2.8 and 2.9% in urea of annually applied N was emitted into the atmosphere in year 1 and year 2, respectively. Therefore, an average of 2.3% in PCU and 2.9% in urea of the total applied N over the entire 2-year period was emitted as N_2O into the atmosphere, indicating that N from PCU fertilizer was possibly more efficiently used by the turf than urea fertilizer. These results are similar to those from previous turfgrass studies (Bremer, 2006; Lewis and Bremer, 2013; Gillette et al., 2016; Kaye et al., 2004). Bremer (2006) reported N losses of 0.65% from urea and 0.65% in ammonium sulfate, both applied at a rate of 250 kg N ha^{-1} yr^{-1}, and 2.02% in urea applied at a rate of 50 kg N ha^{-1} yr^{-1} to perennial ryegrass. Lewis and Bremer (2013) reported losses of 1.6 to 2.1% in a two-year study in zoysiagrass receiving urea applied at a rate of 100 kg N ha^{-1} yr^{-1}. In Kentucky bluegrass lawns in Colorado, 2.2% of urea fertilizer was emitted as N_2O into the atmosphere when applied at a rate of 110 kg N ha^{-1} yr^{-1} (Kaye et al., 2004). These findings in turfgrass are similar to losses as N_2O from applied fertilizer in different agricultural systems (Bouwman, 1994; Bouwman et al., 1995; Clayton et al., 1997; Mosier and Hutchinson, 1981; Mosier et al., 1986; Syväsalo et al., 2004; Wagner-Riddle et al., 1997; Webb et al., 2004).

General Trends

Soil properties of WFPS, soil temperature, soil NO_3^-, and soil NH_4^+ were measured to evaluate their relationships with N_2O emissions.

For WFPS, there were more dates in both years with a significant irrigation main effect (48 dates) than fertilizer main effect (30 dates) (Figs. 2.1B, 2.2B, 2.3B, and 2.4B) and (Appendix Tables A.5 and A.6). Most of the differences in WFPS resulting from the irrigation main effect (33 of 48 dates) were during the summer when irrigation treatments were applied (Figs. 2.3B and 2.4B). On significant dates, WFPS was typically higher in the 66% ET_o than the 33% ET_o treatment. This is expected because more water was applied to plots receiving the higher irrigation treatment.

Regarding the fertilizer main effect, in both years WFPS was typically higher in UF plots than in either PCU or urea plots (Figs. 2.1B and 2.2B). These differences occurred more often during the summer when fertilizer was applied and therefore, may have resulted from more active and aggressive growth in fertilized than in UF plots; thus, more soil water uptake occurred in fertilized plots.

Soil temperature, opposite of the WFPS results, had more significant dates for the fertilizer main effect (44 dates) than the irrigation main effect (18 dates) (Appendix Tables A.7 and A.8). Generally, soil temperatures were higher in PCU or urea than in UF plots, albeit some statistical differences were small (e.g. < 0.30 °C) and may have been biologically insignificant. The higher soil temperatures observed in PCU or urea plots may be due to their darker green turf color than unfertilized plots, resulting in more absorption of shortwave radiation.

When pooled over the entire 2-year study, correlations between daily N_2O-N fluxes and WFPS were weak, but significant ($r = 0.23$; $P < 0.001$; $n = 2484$), while a significant and strong correlation occurred between fluxes of N_2O-N and soil temperature ($r = 0.83$; $P < 0.001$; $n = 2484$) (Appendix Table A.9). Other studies have reported similar relationships between N_2O fluxes and soil temperatures (Bijoor et al., 2008; Bremer, 2006; Denmead et al., 1979; Lewis and Bremer, 2013; Mancino et al., 1988). In my study, fluxes of N_2O-N generally increased with soil temperatures, as similarly seen in previous studies. In past agricultural and turfgrass research, higher N_2O fluxes have been associated with higher soil water content (Bijoor et al., 2008; Bremer, 2006; Denmead et al, 1979; Lewis and Bremer, 2013, Lu et al., 2015; Mosier and Hutchinson 1981; Ryden, 1981). However, others have reported higher WFPS did not always enhance N_2O production in turfgrass systems (Li et al., 2013; Townsend-Small et al., 2011).

In both years, the majority of measurement dates with differences in soil NO_3^- among treatments was caused by fertilizer main effect rather than irrigation main effect (Figs. 2.8B, 2.9B, 2.10B, and 2.11B). Among treatments, urea generally had higher soil NO_3^- across dates, especially after fertilization. This is expected due to the soluble urea not having a polymer-coating like PCU and thus quickly undergoes enzymatic (urease) hydrolysis to ammonium carbonate [$(NH_4)_2CO_3$] and therefore more available to nitrify into to NO_3^- (Figs. 2.8B and 2.9B). Similar to the fertilizer main effect, the majority of differences due to irrigation main effect occurred during the summer in each year, with higher soil NO_3^- in plots receiving more irrigation (Figs. 2.10B and 2.11B). After fertilizations, urea may have been incorporated into the soil better by the higher than by the lower irrigation level. Higher WFPS up to a point also provides a greater potential to convert the urea to soil NO_3^-. There were very few significant dates for soil NH_4^+ for both the fertilizer main effect and even less for irrigation main effect (Figs. 2.8A, 2.9A, 2.10A, and 2.11A). Significant dates for the fertilizer main effect generally occurred during the summer, with higher soil NH_4^+ in fertilized (PCU and urea) than unfertilized plots (Figs. 2.8A and 2.9A). Differences in soil NH_4^+ between the two irrigation treatments were inconsistent and negligible in both years (Figs. 2.10A and 2.11A).

When pooled over the entire study, the correlation was weak, but significant between N_2O-N fluxes and soil NO_3^- ($r = 0.16$; $P < 0.001$; $n = 2484$), while correlation between fluxes of N_2O-N and soil NH_4^+ were not significant (Appendix Table A.9). Bremer (2006) reported similar results with both soil NH_4^+ and NO_3^- correlations to N_2O-N fluxes in perennial ryegrass plots. Overall, there have been inconsistent results relating soil NH_4^+ and NO_3^- to N_2O fluxes in both turfgrass and agricultural systems (Bergstrom et al., 2001; Bremer, 2006; Denmead et al., 1979; Lewis and Bremer, 2013; Li et al., 2013; Tenuta and Beauchamp, 2003).

Similar to past studies, soil temperature and WFPS tended to show a stronger relationship with N_2O fluxes than soil NH_4^+ or NO_3^- content. All of these variables, which play a role in N_2O production, involve complex interactions in the soil environment. Therefore, it is more important to consider all factors such as type of fertilizer (ammonium- or nitrate-based), WFPS, and soil temperature at the time of fertilization than just one factor alone. For instance, higher soil temperature and WFPS at and after fertilization may play a larger role in the soil N turnover rate, thus increasing N_2O production (Matson and Vitousek, 1990; Mosier et al., 1997; Schimel et al., 1989). Under anaerobic conditions during high WFPS, N_2O production is more influenced by soil NO_3^- than NH_4^+ due to denitrification (Freney et al., 1979).

Visual Turf Quality and Percent Green Cover

Visual turf quality was rated and PGC was measured in each turf plot to evaluate the effects of different N-fertilizers and deficit irrigation treatments on turfgrass performance.

For visual turf quality, the fertilizer main effect was significant for 12 of 17 measurement dates and the irrigation main effect was significant for 6 of 17 measurement dates in year 1 (Fig. 2.12). In year 2, the fertilizer main effect was significant for 16 of 19 measurement dates and the irrigation main effect was significant for 15 of 19 dates (Fig. 2.13). The fertilizer x irrigation treatment interaction was only significant once in year one and not significant in year two (Appendix Tables A.14 and A.15). Therefore, the two main effects will be discussed for VQ.

In year 1, differences in VQ were mainly due to the three fertilization levels, while in year two there were clear differences among both fertilizer and irrigation treatments (Figs. 2.12 and 2.13). In both years, VQ of urea plots increased immediately after the June fertilization and was higher than PCU and UF on the following measurement date (Figs. 2.12A and 2.13A). This is due to the quick-release of urea. In year 1, PCU generally required 11 to 25 days to reach similar VQ as urea, then PCU provided more stable, and occasionally higher VQ than urea. In year 2, PCU required 23 days to reach similar VQ ratings as urea, but again then provided more stable and at times, higher VQ ratings than urea. In both years, VQ in urea started to decline by 39 and 37 days, respectively, after the June fertilization, but quickly increased again after the second fertilization in mid-July (Figs. 2.12A and 2.13A). This up-and-down trend in VQ is expected with a quick-release fertilizer such as urea, which provides a quick response in turfgrass growth, but generally not a long-term one. While the turf receiving the controlled-release fertilizer, PCU had a slower initial response, it then sustained higher VQ over a longer duration during the summer. Both urea and PCU treatments provided higher VQ than UF throughout the majority of the summer in year 2 and up to mid-to-late August in year 1. Regardless, in both years the unfertilized plots were above acceptable VQ ratings (> 6 rating) throughout the summer.

In year 1, the irrigation main effect was not significant until August, at which point VQ increased in the higher irrigation treatment and decreased lower irrigation treatment (Fig. 2.12B). One possible reason for this late separation may have been the irrigation treatment adjustments from 68% ET_o (medium) and 45% ET_o (low) to the final 66% ET_o (medium) and 33% ET_o (low) on 20 July 2015 for reasons previously mentioned in materials and methods. In year 2, the separation in VQ between irrigation treatments was more evident, with consistently higher VQ with higher irrigation throughout the majority of the summer (Fig. 2.13B). However, both irrigation treatments were above acceptable VQ in both years, including zoysiagrass receiving only a 33% ET_o twice a week with all rainfall excluded for 92 days during the summer.

For PGC, the fertilizer main effect was significant for 14 of 17 measurement dates and the irrigation main effect for 7 of 17 dates in year 1 (Fig. 2.14). In year 2, the fertilizer and irrigation main effects were both significant for 15 of 19 measurement dates (Fig. 2.15). The fertilizer x irrigation treatment interaction was significant on only one date in year one and four dates in year two (Appendix Tables A.16 and A.17). Therefore, the two main effects will be discussed for PGC.

There were similar trends in PGC that were also observed in VQ already mentioned. In year 1, differences in PGC were mainly due to the fertilizer main effect, whereas in year two the differences were due to both fertilizer and irrigation main effects (Figs. 2.14 and 2.15). In year one, PGC increased rapidly in all plots during the summer and the onset of fertilizer and irrigation treatments. In year one, the rapid increase in VQ of only urea-treated plots after fertilization was not observed with PGC. Plots of PCU-treated turf, UF turf, and both irrigation treatments also increased on the same dates as urea after the June fertilization (Fig. 2.14). This may be due to overall warmer and more favorable temperatures for zoysiagrass growth and enhanced green color across all plots. In year 1, similar to VQ ratings, PCU resulted in more stable, and occasionally higher PGC than both urea and UF (Fig. 2.14A). In year 1, there were fewer differences in PGC between urea and UF than in VQ ratings. This may have been because VQ ratings included not only coverage and intensity green color, but also texture, density, and uniformity of the turf. While UF turf plots had fewer differences in PGC compared to urea-treated plots, the UF plots had slightly lower density and uniformity across the entire plot, which was detected by VQ ratings. In year 2, there was a more pronounced increase in PGC in urea plots compared to PCU and UF after the June fertilization, which resulted in higher PGC in urea than the other two fertilizer levels for 23 days (Fig. 2.15A); thereafter, PCU was not different from urea. In year 2 there was more separation in PGC between the two N fertilizer treatments and unfertilized than in year 1, with urea and PCU typically being higher than UF during the majority of the summer.

All fertilizer and irrigation treatments were higher than 74% green cover during the entire summer in both years (Figs. 2.14 and 2.15). In year 1, PGC in urea declined 32 days after the June fertilization but quickly increased again after the second fertilization in mid-July; this trend in urea was also observed in VQ ratings (Figs. 2.12A, 2.13A, and 2.14A). In year 2, this decline in PGC of urea was less pronounced despite a notable, corresponding decrease in VQ (Fig. 2.13A and 2.15A). The disparities in changes between VQ and PGC was likely a result of methodology. Visual quality ratings are subjective while PGC measurements are objective. Declines in VQ ratings were typically caused by corresponding decreases in the darkness of green turf color. However, this lighter green turf color still registered within the "green cover" hue settings established in SigmaScan. This resulted in a less pronounced decline in PGC than in VQ ratings. For the irrigation main effect, trends were similar between PGC and VQ ratings. When pooled across all fertilizer and irrigation treatments over the entire 2-year study, there was a moderate-to-strong correlation between VQ and PGC ($r = 0.64$; $P < 0.001$; $n = 1296$) (Appendix Table A.18).

Typically, after 30 to 40 days, zoysiagrass receiving urea started to decline in VQ and PGC until it received another N fertilization in mid-July, when it quickly increased again. Conversely, VQ and PGC in controlled-released fertilizer (PCU) plots initially responded slower after June fertilization but then sustained higher VQ and PGC over a longer period during the summer.

Cumulative Mowing Frequency

Turfgrass mowing is an energy-based input that has been labeled as a hidden carbon cost due to gasoline emissions (Zirkle et al., 2011). In 2015 and 2016, cumulative mowing frequency for each plot was calculated to quantify the effects of different N-fertilizers and deficit irrigation treatments on mowing frequency.

The fertilizer and irrigation main effects were significant for both years, while the fertilizer x irrigation treatment interaction was not significant for either year (Table 2.2). For both years, the higher irrigation treatment resulted in a higher mowing frequency, albeit generally only two to three more mowing events per year. Plots that received N fertilizer (PCU and urea) also had higher mowing frequencies than unfertilized plots in both years. In year 1 and year 2, an average of 7 and 9 more mowing events, respectively, were required in N-fertilized plots compared to unfertilized plots. While there were differences in mowing frequency between the quick-release and controlled-release fertilizers (within ±1.1 mowings yr^{-1}), the trend was not consistent across years. Thus, the results were inconclusive as to the relative effects of urea and PCU on mowing frequency.

There has been extensive research comparing effects of slow-release and quick-release nitrogen sources on turfgrass quality, visual color, shoot growth, clipping yield, and other characteristics. Clipping yields have generally been greater when fertilized with slow-release compared with quick-release N sources, although results have been mixed across studies (Cisar et al., 2005; Joo et al., 1997; Williams et al., 1997). In relating clipping yield to mowing frequency, one might assume greater clipping yield results in a higher mowing frequency. Regardless, in our study mowing frequencies were not consistently greater across years in plots fertilized with controlled-release than with quick-release N fertilizer.

Soil Carbon

The depth main effect was significant for all variables except C/N, and the year main effect was significant for SOC, SON, and C/N (Appendix Table A.19). Therefore, after analysis of type III tests for fixed effects for SOC, SON, ρ_b, C/N, ΔSOC, tests for slice effects were conducted to thoroughly investigate the following: i) management input schedules within each depth x year (Table 2.3); ii) years within each management schedule x depth (to compare year means; Table 2.3); iii) management schedules averaged across all depths within each year (Table 2.4); iv) years within each management schedule averaged across all depths (to compare year means; Table 2.4); v) depths within each year (Table 2.5); and vi) years within each depth (to compare year means; Table 2.5) (Appendix Table A.20).

Management schedule did not affect any measured soil carbon variable (SOC, SON, ρ_b, C/N, ΔSOC) within each depth (0-10, 10-20, and 20-30 cm) except C/N at 20-30 cm in 2016 (Table 2.3). In 2016, the carbon/nitrogen ratio was 95% higher in the HMI than in the LMI at 20-30 cm.

Between 2013 and 2016, SOC at 0-10 cm increased by 24% and 21% Mg C ha^{-1} for the HMI and LMI regimes, respectively, and C/N at 20-30 cm increased by 187% in the HMI (Table

2.3). Although the remaining SOC and C/N also increased numerically at each management schedule x depth, none were statistically significant. No statistical changes were observed in ρ_b, SON or ΔSOC at any management schedule x depth.

When averaged across all depths (0-30 cm), there were no differences between high and low management regimes for any of the measured soil carbon variables (SOC, SON, ρ_b, C/N, ΔSOC) in each year (Table 2.4). Similar to the year comparisons above, when averaged across all depths, SOC increased by 18% and 15% between 2013 and 2016 for both high and low input regimes, respectively, as did the C/N by 82% for high input only. This increase in soil organic carbon from 2013 to 2016 measured in both management schedules indicates a significant amount of carbon was sequestered by the zoysiagrass turf system.

When data were combined across depths (0-30 cm) and across both management input regimes (year main effect in Appendix Table A.19), the soil C/N ratio increased significantly from 10.1 in 2013 to 17.0 in 2016, SOC increased from 18.5 Mg C ha^{-1} in 2013 to 21.5 Mg C ha^{-1} in 2016, and ρ_b did not change (data not shown). The year main effect was also statistically significant for SON however differences were minimal.

When soil C was averaged across both management input regimes, differences were observed among depths within each year in all variables except soil C/N (Appendix Table A.20 and Table 2.5). The upper soil layer (0-10 cm) consistently had higher SOC and SON than the two lower depths in 2013 and 2016. The ΔSOC was also greater in the upper 0-10 cm than in the two lower depths. Lemus and Lal (2005) stated most changes in soil organic carbon tend to occur in the upper profile due to being more significantly influenced by climate, microbial biomass, and larger root biomass present. Qian et al. (2010) concluded that 2- to 5-year-old turfgrass systems likely favor soil carbon sequestration near the soil surface (0-10 cm) compared to 10-20 cm because an increase in soil C/N ratio was only observed in the upper depth after three years. In my study, increases in soil C/N ratio from 2013 to 2016 was observed in all three depths, although only significant increases occurred at the two lower depths (Table 2.5). This may possibly be attributed to the type of turfgrass species and rooting characteristics of the zoysiagrass. The zoysiagrass root system may have more dense and impacted N mineralization more at the two lower depths, although no root measurements were conducted. Root biomass and rooting capabilities vary among turfgrass species and even among cultivars within turfgrass species (Carrow, 1996; Ensign and Weiser, 1975; Huang, 1999; Lehman and Engelke, 1991;

Salaiz et al., 1991; Su et al., 2008; Qian et al., 1997). Lemus and Lal (2005) reported root biomass is possibly one of the most important factors affecting potential soil carbon sequestration. Regardless of the greater increase in C/N at the lower depths, the SOC content and ΔSOC in the upper profile (0-10 cm) were higher than in the two lower depths after three-years in zoysiagrass (Table 2.5). Qian et al. (2010) also reported increased SOC and C/N over a four-year period in three different turfgrass species. The annual ΔSOC values ranging from 0.24 to 1.77 Mg C ha^{-1} yr^{-1} in my study are similar to observed- or modeled- SOC sequestration rates in turfgrass reported by others (Bandaranayake et al., 2003; Qian and Follett, 2002; Qian et al., 2010; Wang et al., 2014; Zirkle et al., 2011). Also, these annual ΔSOC values measured in my study are similar to- or higher than SOC sequestration rates in managed and unmanaged grasslands, such as those in the Conservation Reserve Program (Follett et al., 2001; Gebhart et al., 1994; Post and Kwon, 2000).

Overall, most differences in SOC were due to depth in the soil profile, with greater C sequestration in the upper 0-10 cm. After a 3-year period, the HMI regime sequestered more C in the 0-10 and 10-20 cm depths than the LMI regime, but results were not statistically different. After a 3-year period, the zoysiagrass turf resulted in an average C sequestration rate of 0.952 Mg C ha^{-1} yr^{-1} averaged across both management input schedules and all three depths. Further research of direct SOC measurements over various turfgrass species and various management input schedules will increase understanding of total C budget and possibly lead to improved management practices to increase C sequestration in turfgrass systems.

Conclusions

There were weak, but significant correlations between N_2O fluxes and WFPS; and soil NO_3^- and N_2O fluxes. A strong and significant correlation was found between soil temperature and N_2O fluxes in turfgrass, N_2O fluxes generally increased with soil temperatures. Cumulative N_2O emissions during the summer increased 5 to 13% with irrigation (i.e., 33% to 66% ET_o), with the exception of UF plots. During two summers, N_2O emissions were 6.3% higher with 66% ET_o (2.88 kg ha^{-1}) than with 33% ET_o (2.71 kg ha^{-1}). Overall, the majority of the differences in daily and cumulative N_2O emissions over the entire study were due to the fertilizer main effect. The controlled-release fertilizer (PCU), which released N slowly over a longer duration resulted in no spikes in N_2O fluxes and lower daily N_2O fluxes than the quick-release, urea fertilizer. Thus, 2-year cumulative N_2O emissions were 25% higher for urea than PCU.

Cumulative N_2O emissions for the entire 2-year study were 4.06 kg ha^{-1} in UF turf, 4.5 kg ha^{-1} in PCU-treated turf, and 5.62 kg ha^{-1} in urea-treated turf, each statistically different from one another. Even though the VQ and PGC increased more slowly, PCU-treated plots generally sustained higher VQ and PGC than urea-treated plots over a longer period during the summer, but this did not result in consistently higher mowing frequencies than urea-treated plots. After a 3-year period, a higher input management schedule (urea + 66% ET_o irrigation treatment) in zoysiagrass did not increase C sequestration compared with a low input management schedule (no fertilizer + 33% ET_o irrigation treatment). A greater C sequestration rate occurred in the 0-10 cm soil layer compared to lower soil depths. Regardless of management input schedule or depth, after a 3-year period zoysiagrass exhibited enhanced SOC content and an average C sequestration rate of 0.952 Mg C ha^{-1} yr^{-1}, which may help mitigate climate change. Results from this study indicate the use of a controlled-release fertilizer such as PCU compared to the use of a quick-release fertilizer and/or less irrigation should be encouraged to reduce N_2O emissions in turfgrass. Further research should be conducted to investigate effects of other deficit irrigation levels and N fertilizer sources on N_2O emissions in turfgrass. Additional research of direct SOC measurements in various turfgrass species and management input schedules could lead to improved management practices that increase C sequestration in turfgrass systems.

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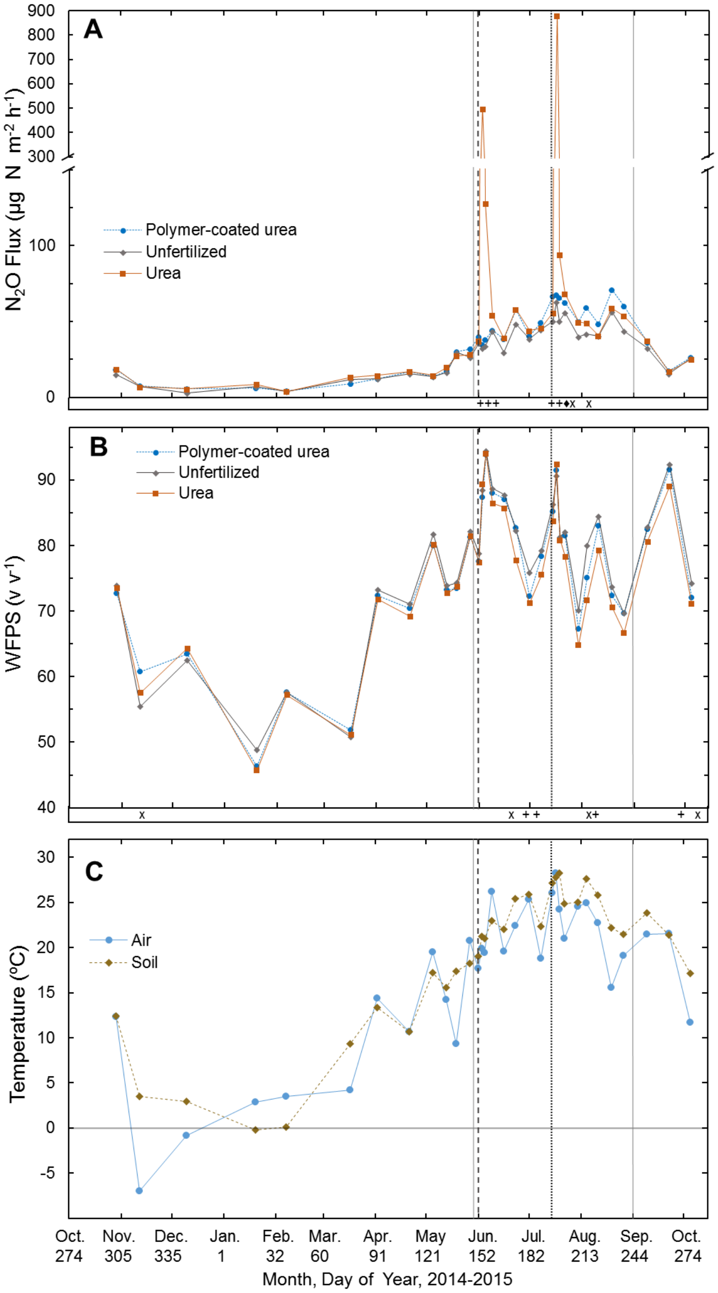

Figure 2.1. Year 1 of measurements from 29 Oct. 2014 (DOY 302) to 5 Oct. 2015 (278). (A) Fluxes of N2O-N from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. On measurement days, (B) Water-filled pore space (WFPS) at 7.6 cm (C). Temperatures of soil at 7.6 cm and air at 2 m. Solid vertical lines represent summer period when rainout shelter was activated. Dashed vertical line at 2 June represents fertilization (urea applied at 49 kg N ha-1 and polymer-coated urea applied at 98 kg N ha-1). Dotted vertical lines at 16 July represent 2nd urea application at 49 kg N ha-1. Symbols (X) along the abscissa indicate significant differences between at least 2 treatments, a plus (+) indicates significant differences between one and the other two treatments, and a diamond (♦) indicates differences among all three treatments on a given date according to Fisher’s Protected LSD (P ≤ 0.05).

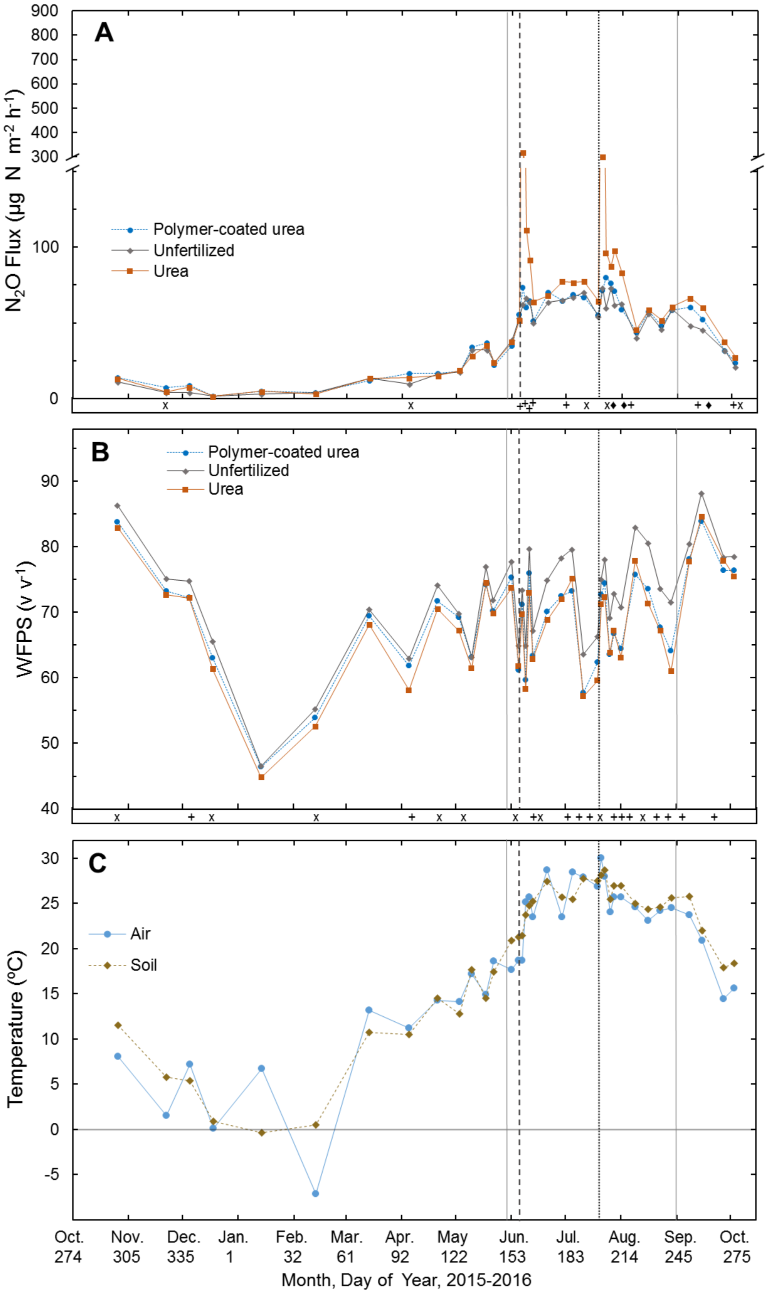

Figure 2.2. Year 2 of measurements from 26 Oct. 2015 (DOY 299) to 3 Oct. 2016 (277). (A) Fluxes of N_2O-N from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. On measurement days, (B) Water-filled pore space (WFPS) at 7.6 cm (C). Temperatures of soil at 7.6 cm and air at 2 m. Solid vertical lines represent summer period when rainout shelter was activated. Dashed vertical line at 6 June represents fertilization (urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}). Dotted vertical lines at 20 July represent 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between at least 2 treatments, a plus (+) indicates significant differences between one and the other two treatments, and a diamond (♦) indicates differences among all three treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

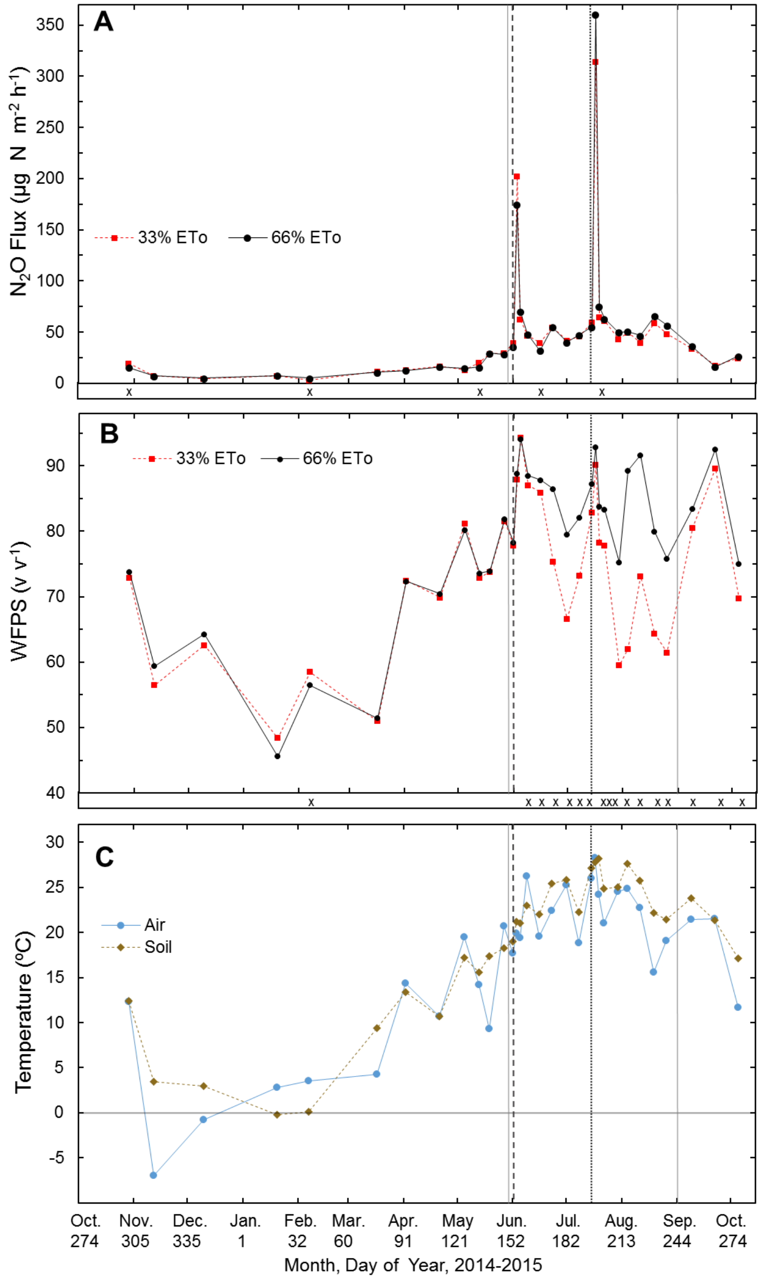

Figure 2.3. Year 1 of measurements from 29 Oct. 2014 (DOY 302) to 5 Oct. 2015 (278). (A) Fluxes of N_2O-N from zoysiagrass irrigated at 33% ET_o and 66% ET_o. On measurement days, (B) Water-filled pore space (WFPS) at 7.6 cm (C). Temperatures of soil at 7.6 cm and air at 2 m. Solid vertical lines represent summer period when rainout shelter was activated. Dashed vertical line at 2 June represents fertilization (urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}). Dotted vertical lines at 16 July represent 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between the two treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

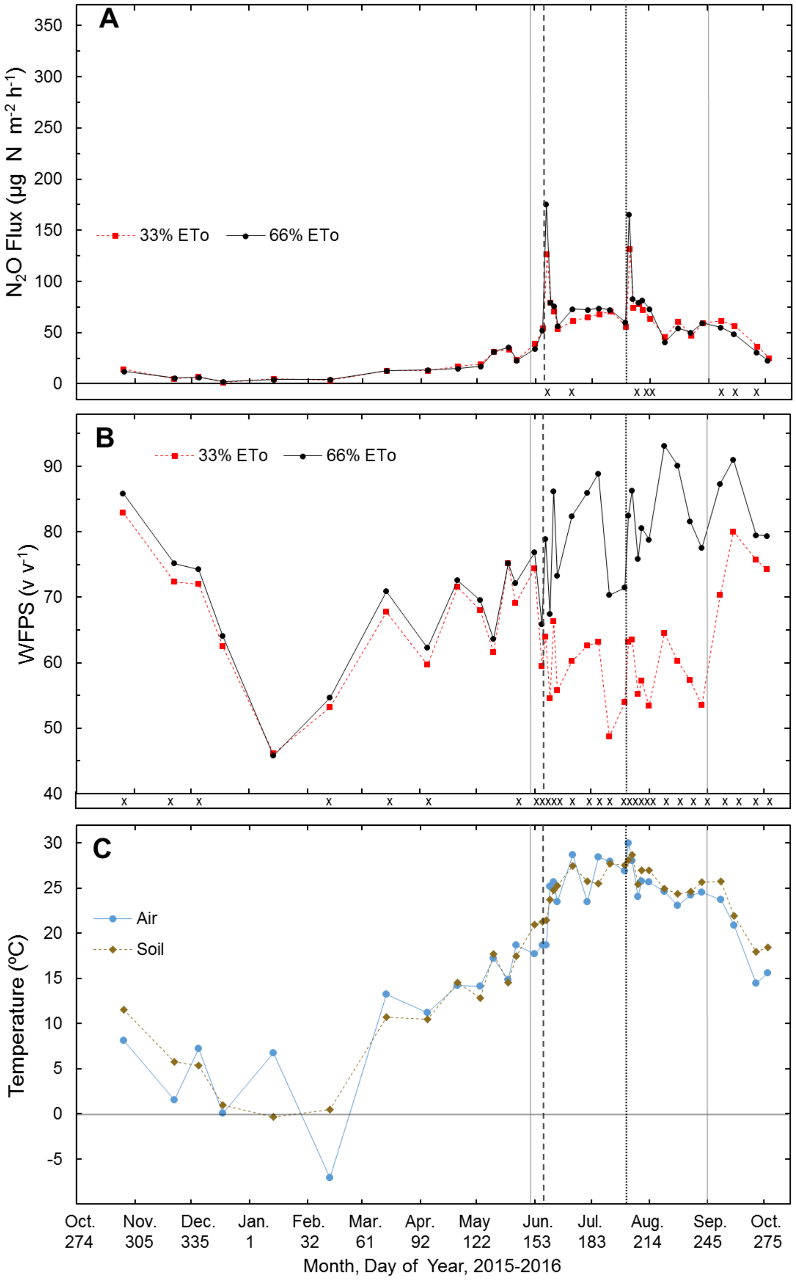

Figure 2.4. Year 2 of measurements from 26 Oct. 2015 (DOY 299) to 3 Oct. 2016 (277). (A) Fluxes of N_2O-N from zoysiagrass irrigated at 33% ET$_o$ and 66% ET$_o$. On measurement days, (B) Water-filled pore space (WFPS) at 7.6 cm (C). Temperatures of soil at 7.6 cm and air at 2 m. Solid vertical lines represent summer period when rainout shelter was activated. Dashed vertical line at 6 June represents fertilization (urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}). Dotted vertical lines at 20 July represent 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between the two treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

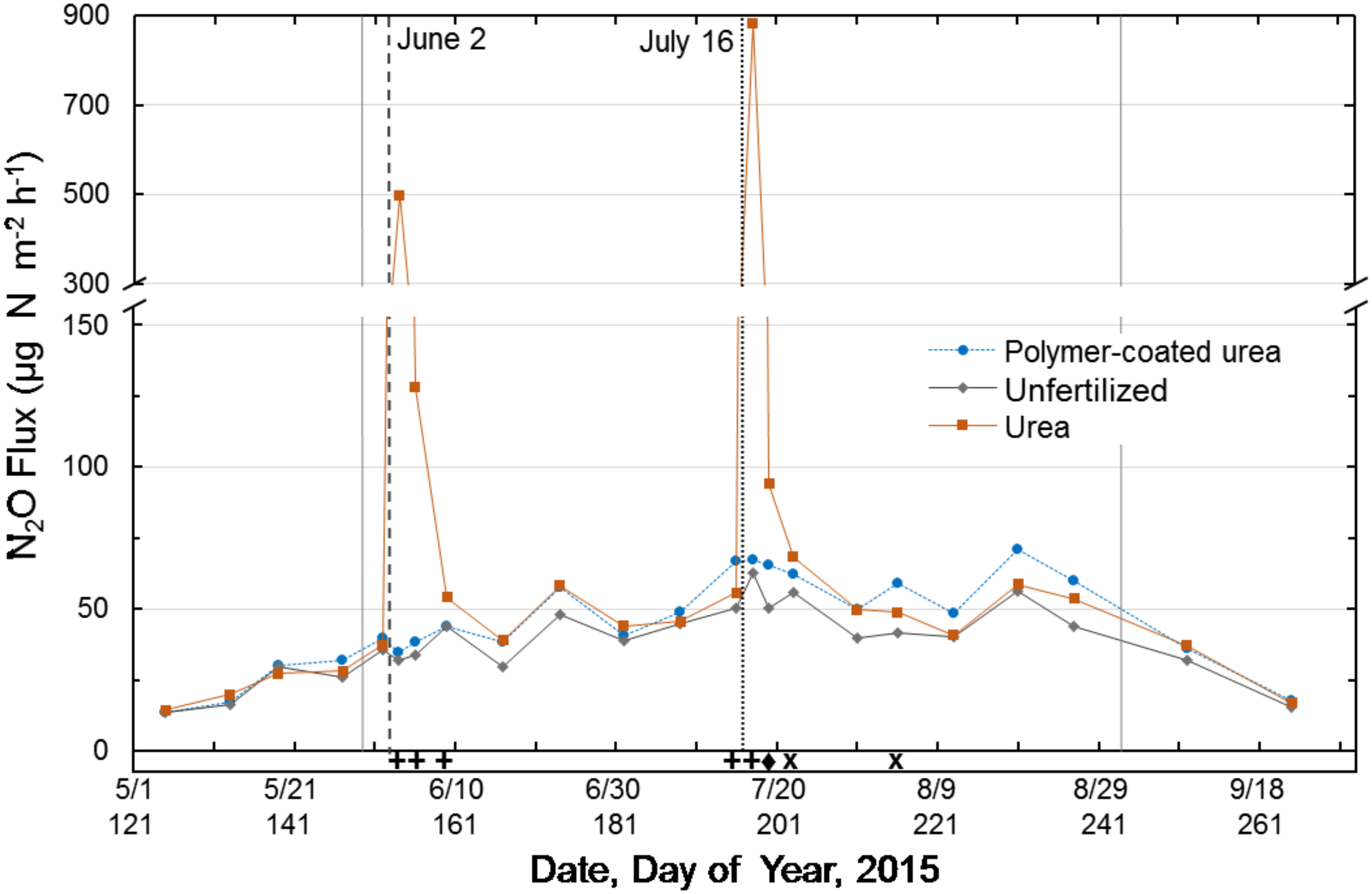

Figure 2.5. 2015 summer dates of measured fluxes of N_2O-N from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. Solid vertical lines represent the summer period when the rainout shelter was activated. Dashed vertical line at 2 June represent fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical lines at 16 July represent the 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between at least 2 treatments, a plus (+) indicates significant differences between one and the other two treatments, and a diamond (♦) indicates differences among all three treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

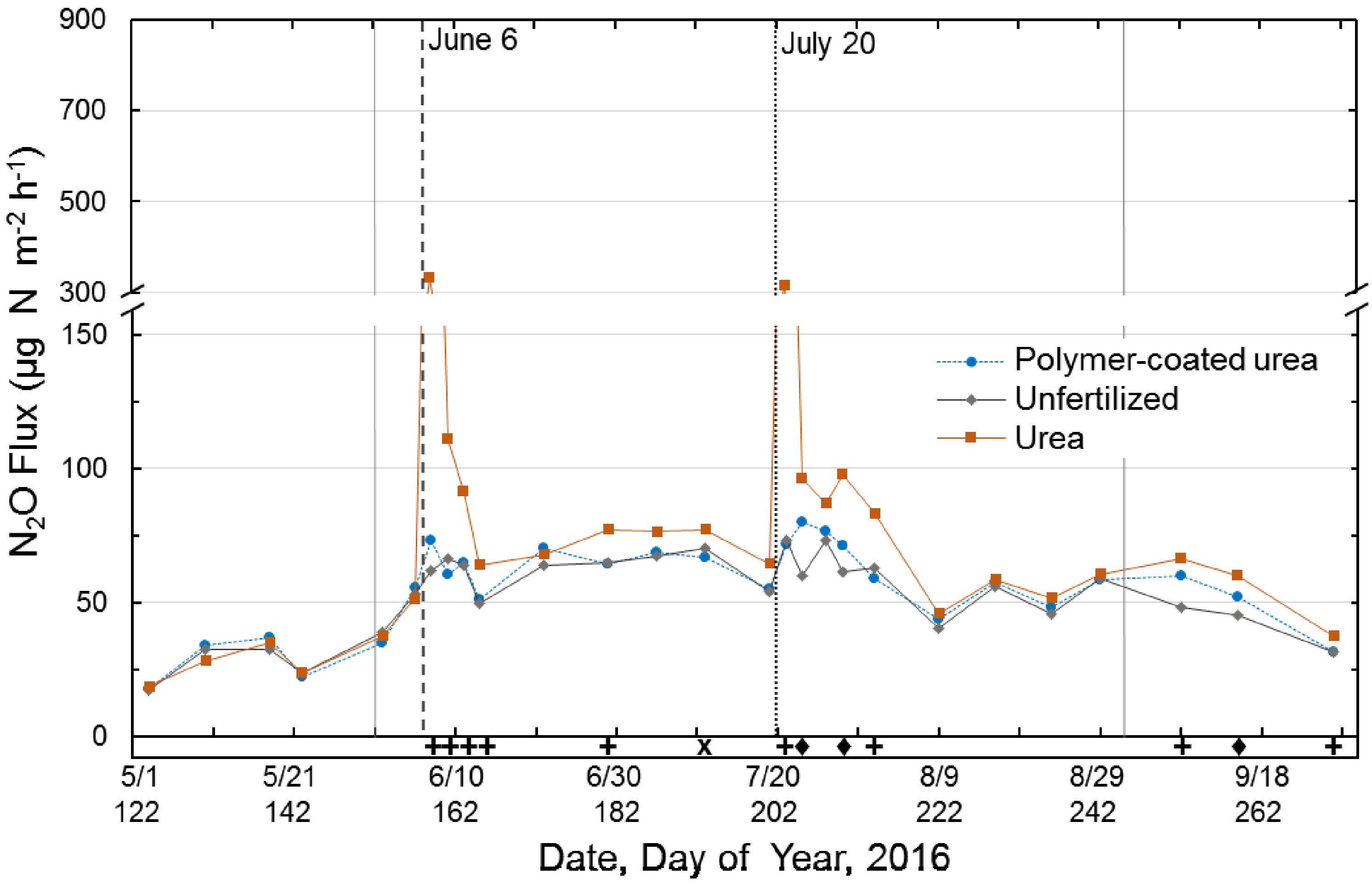

Figure 2.6. 2016 Summer dates of measured fluxes of N_2O-N from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. Solid vertical lines represent the summer period when the rainout shelter was activated. Dashed vertical line at 6 June represent fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical lines at 20 July represent the 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between at least 2 treatments, a plus (+) indicates significant differences between one and the other two treatments, and a diamond (♦) indicates differences among all three treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

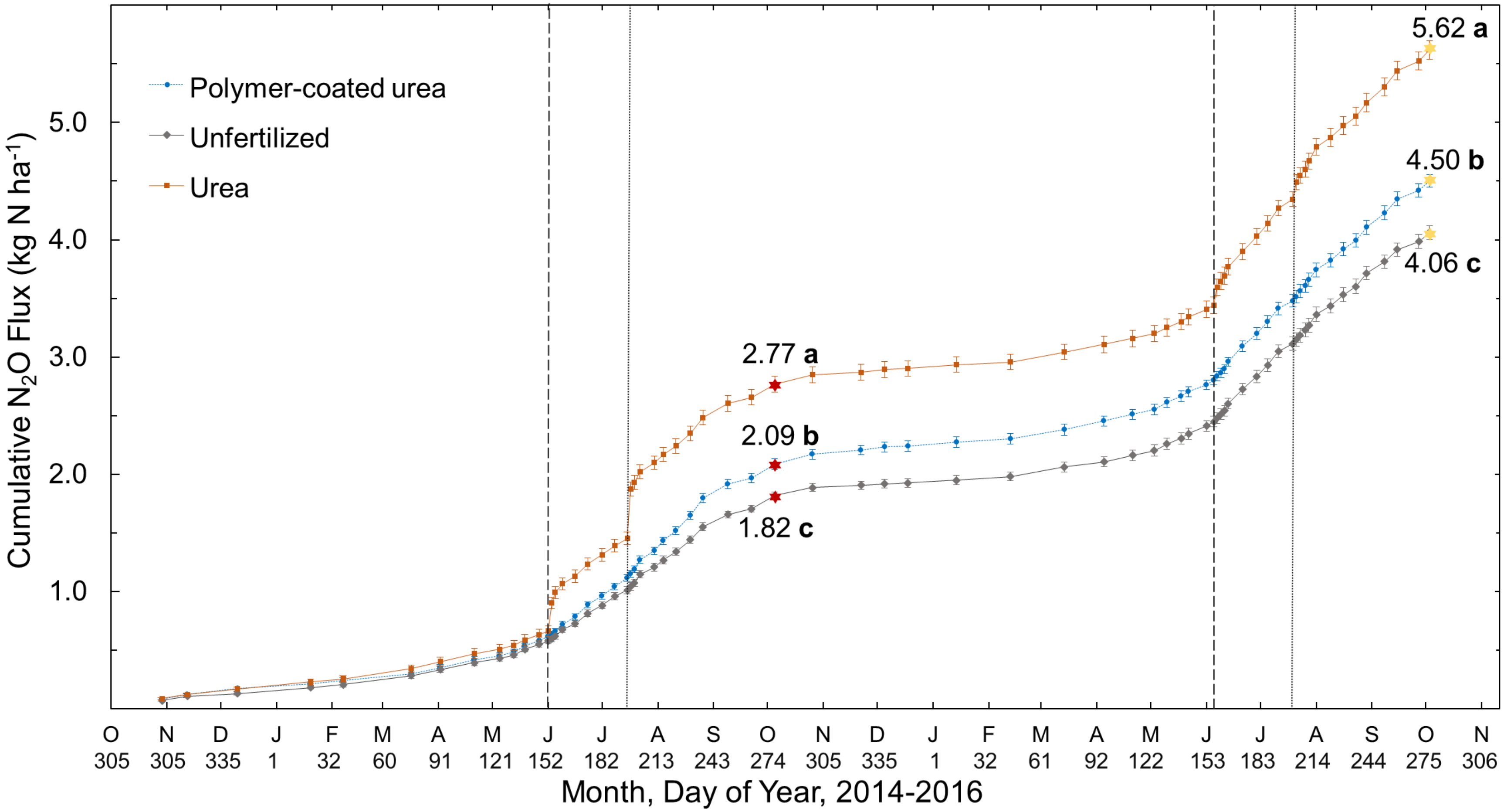

Figure 2.7. Cumulative fluxes of N_2O-N over a two-year period from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. Dashed vertical lines at June dates represent fertilization with urea applied a rate of 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical dashed lines at July dates represent the 2nd urea application at 49 kg N ha^{-1}. Vertical errors bars at each mean represent SE of the mean. At each date (the end of year 1 and the end of the two-year study), means with different letters are significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

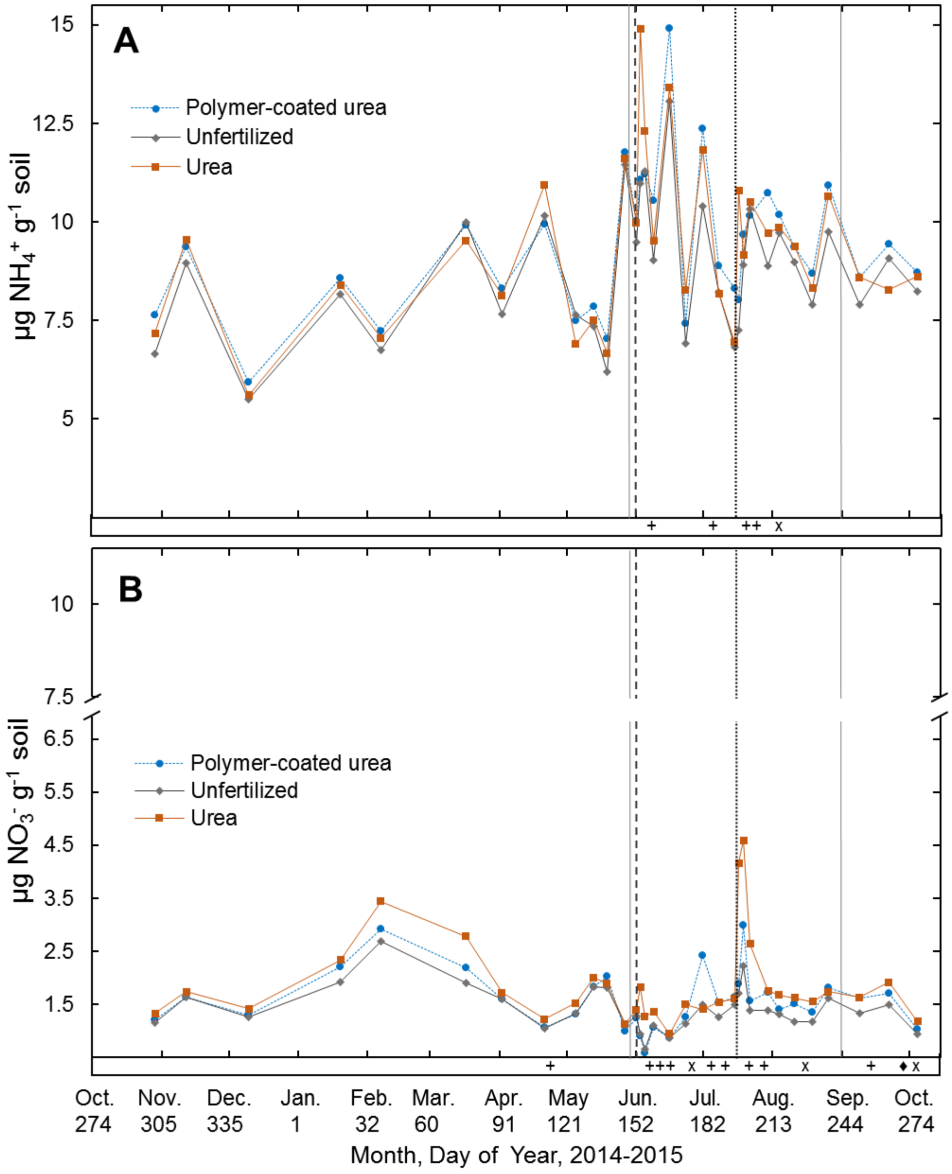

Figure 2.8. Year 1 of soil nitrogen measurements from 29 Oct. 2014 (DOY 302) to 5 Oct. 2015 (278). (A) Average soil ammonium (NH_4^+) and (B) soil nitrate (NO_3^-) concentrations from 0 to 12.7 cm from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. Solid vertical lines represent the summer period when the rainout shelter was activated to prevent precipitation on plots. Dashed vertical line at 2 June represents fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea at 98 kg N ha^{-1}. Dotted vertical lines at 16 July represent the 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between at least 2 treatments, a plus (+) indicates significant differences between one and the other two treatments, and a diamond (♦) indicates differences among all three treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

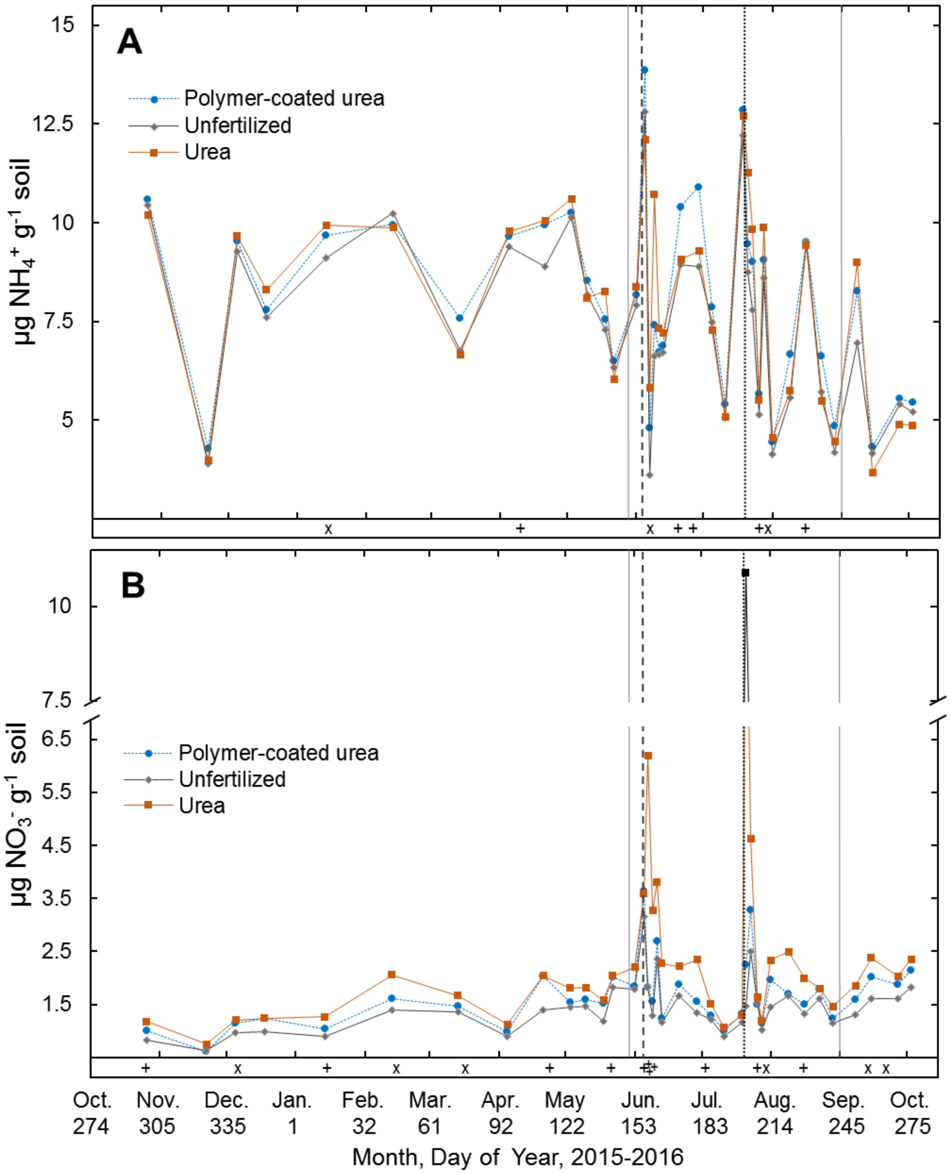

Figure 2.9. Year 2 of soil nitrogen measurements from 26 Oct. 2015 (DOY 299) to 3 Oct. 2016 (277). (A) Average soil ammonium (NH_4^+) and (B) soil nitrate (NO_3^-) concentrations from 0 to 12.7 cm from zoysiagrass treated with polymer-coated urea, no fertilizer (unfertilized), and urea. Solid vertical lines represent the summer period when the rainout shelter was activated to prevent precipitation on plots. Dashed vertical line at 6 June represents fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea at 98 kg N ha^{-1}. Dotted vertical lines at 20 July represent the 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between at least 2 treatments, a plus (+) indicates significant differences between one and the other two treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

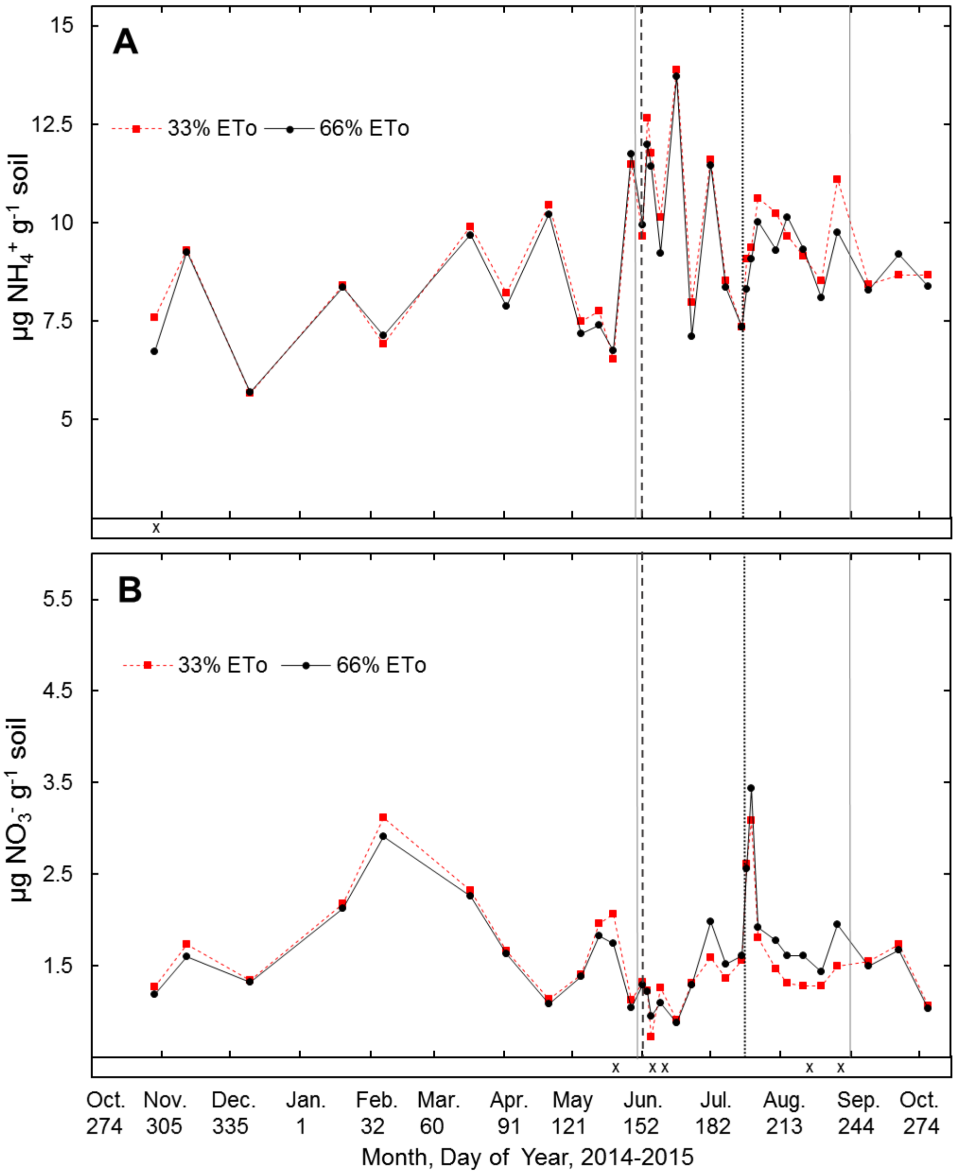

Figure 2.10. Year 1 of soil nitrogen measurements from 29 Oct. 2014 (DOY 302) to 5 Oct. 2015 (278). (A) Average soil ammonium (NH_4^+) and (B) soil nitrate (NO_3^-) concentrations from 0 to 12.7 cm depth from zoysiagrass irrigated at 33% ET_o and 66% ET_o. Solid vertical lines represent the summer period when the rainout shelter was activated to prevent precipitation on plots. Dashed vertical line at 2 June represents fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea at 98 kg N ha^{-1}. Dotted vertical lines at 16 July represent the 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between the two treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

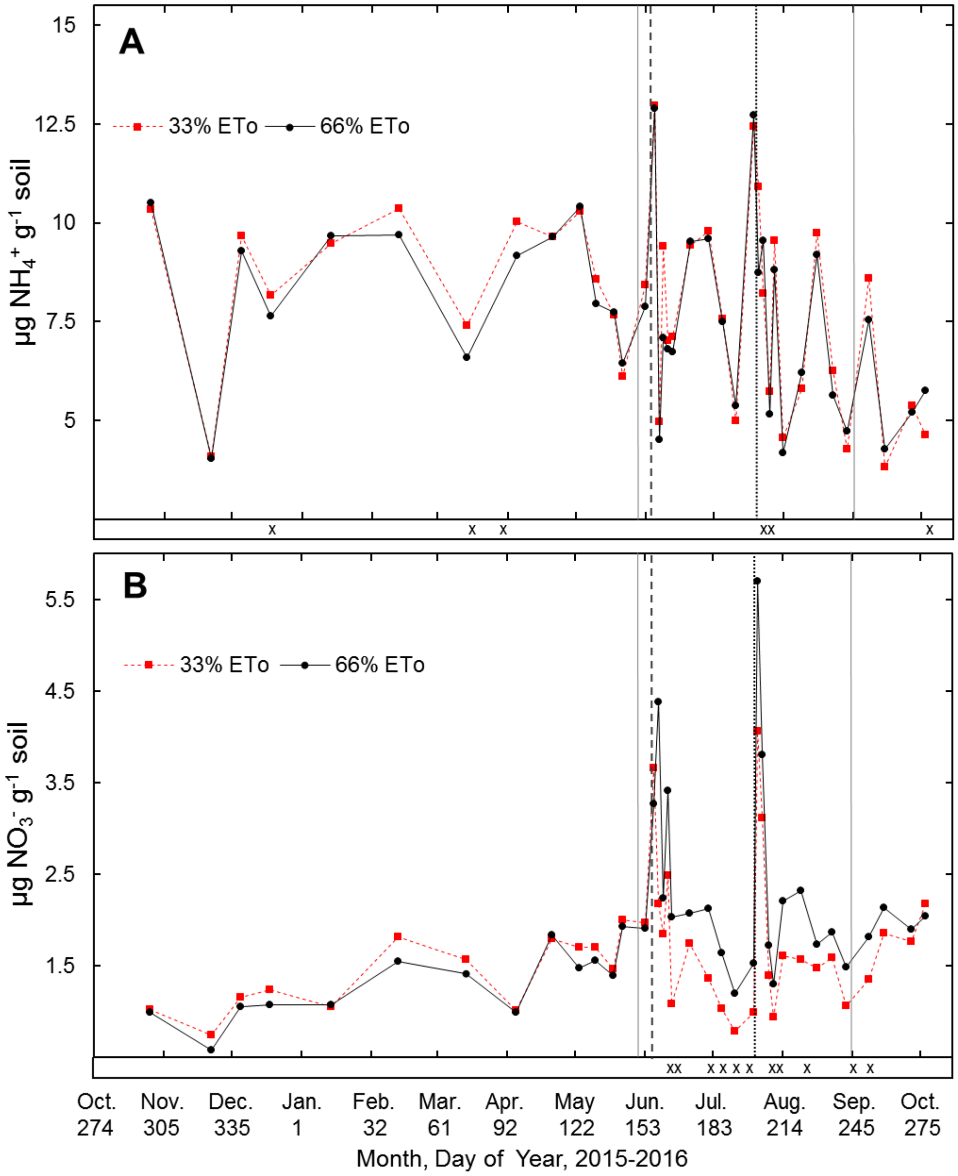

Figure 2.11. Year 2 of soil nitrogen measurements from 26 Oct. 2015 (DOY 299) to 3 Oct. 2016 (277). (A) Average soil ammonium (NH_4^+) and (B) soil nitrate (NO_3^-) concentrations from 0 to 12.7 cm depth from zoysiagrass irrigated at 33% ET_o and 66% ET_o. Solid vertical lines represent the summer period when the rainout shelter was activated to prevent precipitation on plots. Dashed vertical line at 6 June represents fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea at 98 kg N ha^{-1}. Dotted vertical lines at 20 July represent the 2nd urea application at 49 kg N ha^{-1}. Symbols (X) along the abscissa indicate significant differences between the two treatments on a given date according to Fisher's Protected LSD ($P \leq 0.05$).

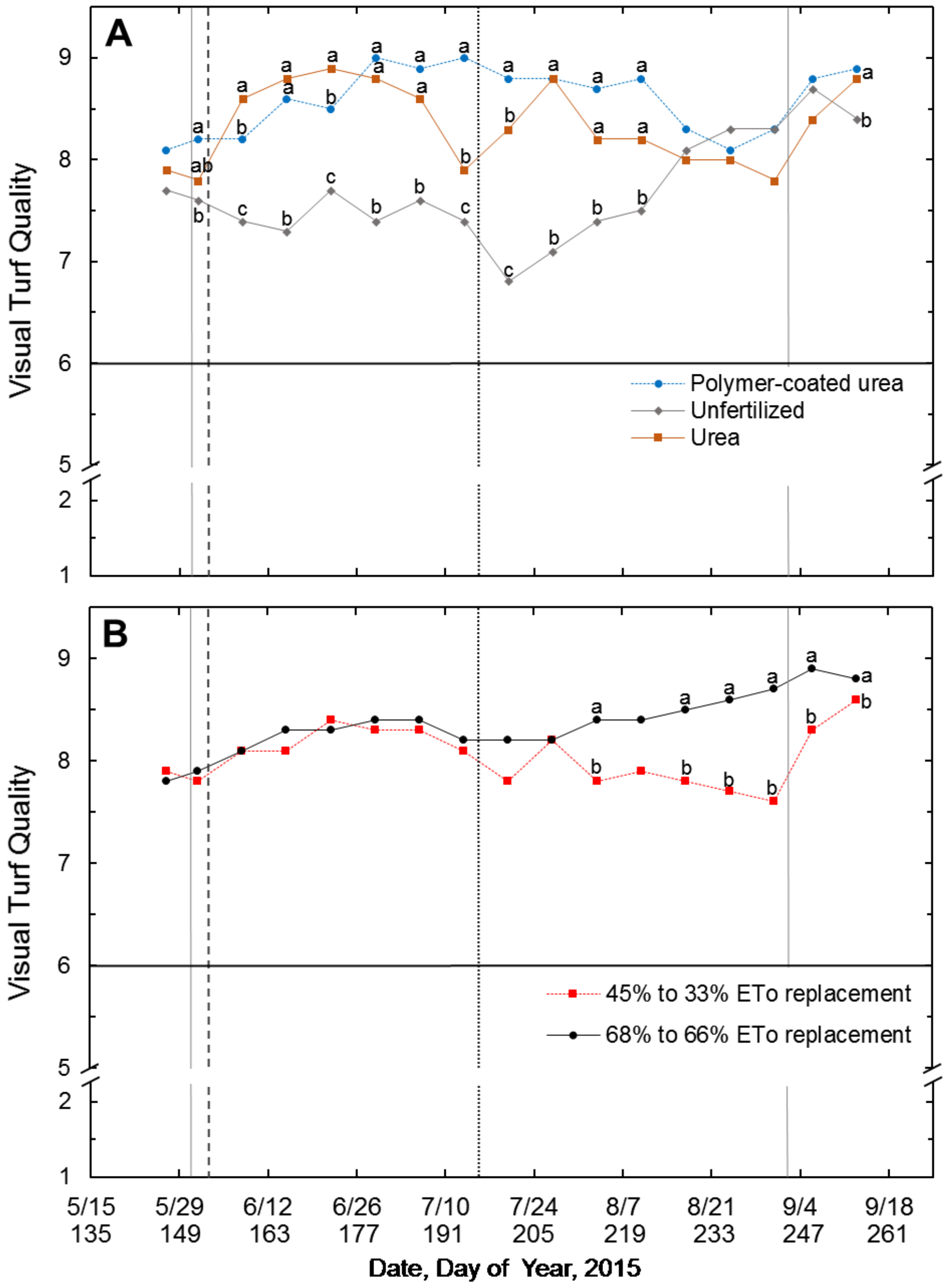

Figure 2.12. Effects of the (A) fertilizer main effect and (B) irrigation main effect on visual turf quality of zoysiagrass in 2015. Solid vertical lines represent the summer period when the rainout shelter was activated and irrigation treatments were applied. Dashed vertical line at 2 June represent fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical lines at 16 July represent the 2nd urea application at 49 kg N ha^{-1}. Solid horizontal black line signifies minimum rating for acceptable turf quality. Within each main effect, means at each date with the same letter not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

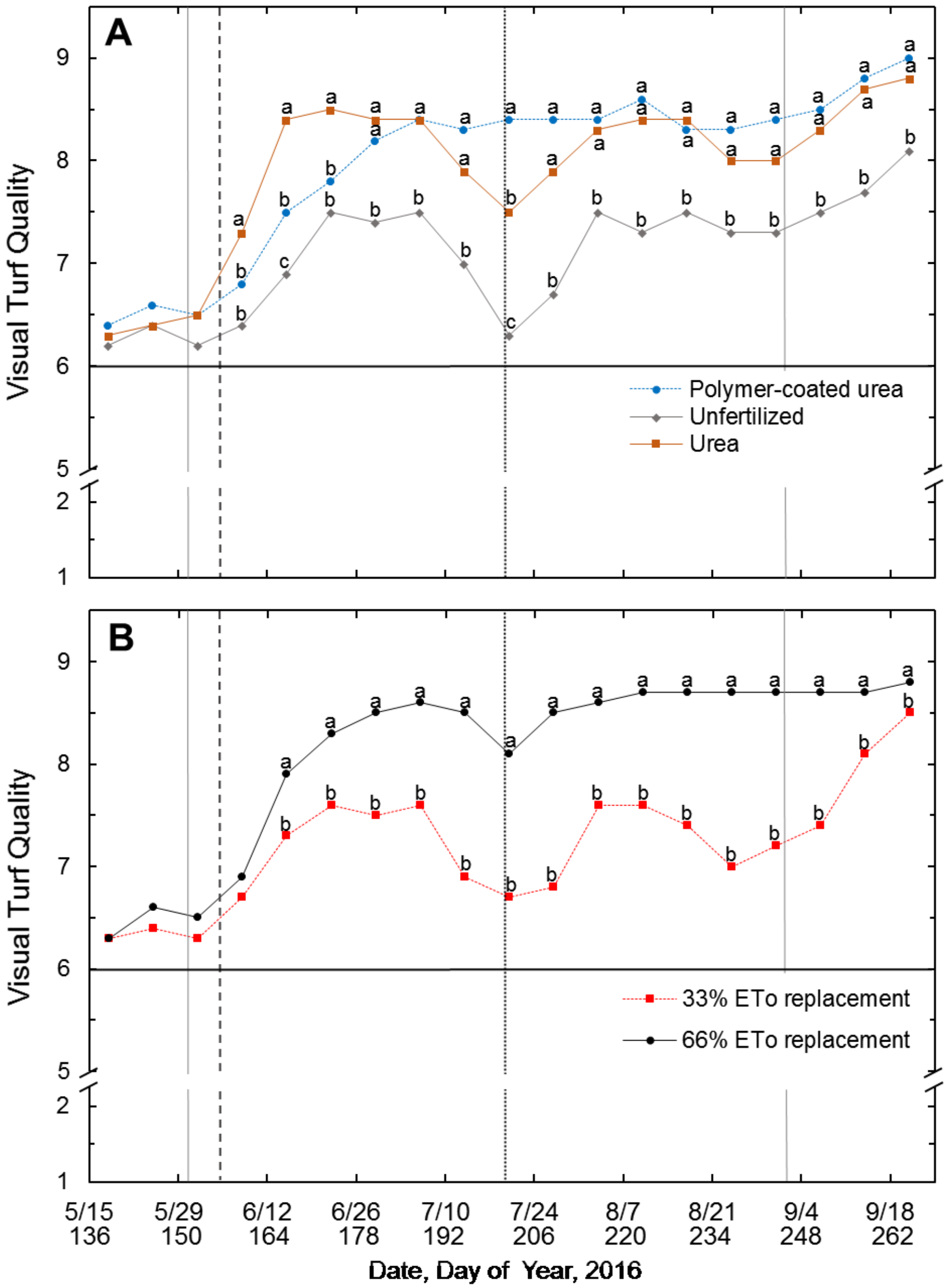

Figure 2.13. Effects of the (A) fertilizer main effect and (B) irrigation main effect on visual turf quality of zoysiagrass in 2016. Solid vertical lines represent the summer period when the rainout shelter was activated and irrigation treatments were applied. Dashed vertical line at 6 June represent fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical lines at 20 July represent the 2nd urea application at 49 kg N ha^{-1}. Solid horizontal black line signifies minimum rating for acceptable turf quality. Within each main effect, means at each date with the same letter not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

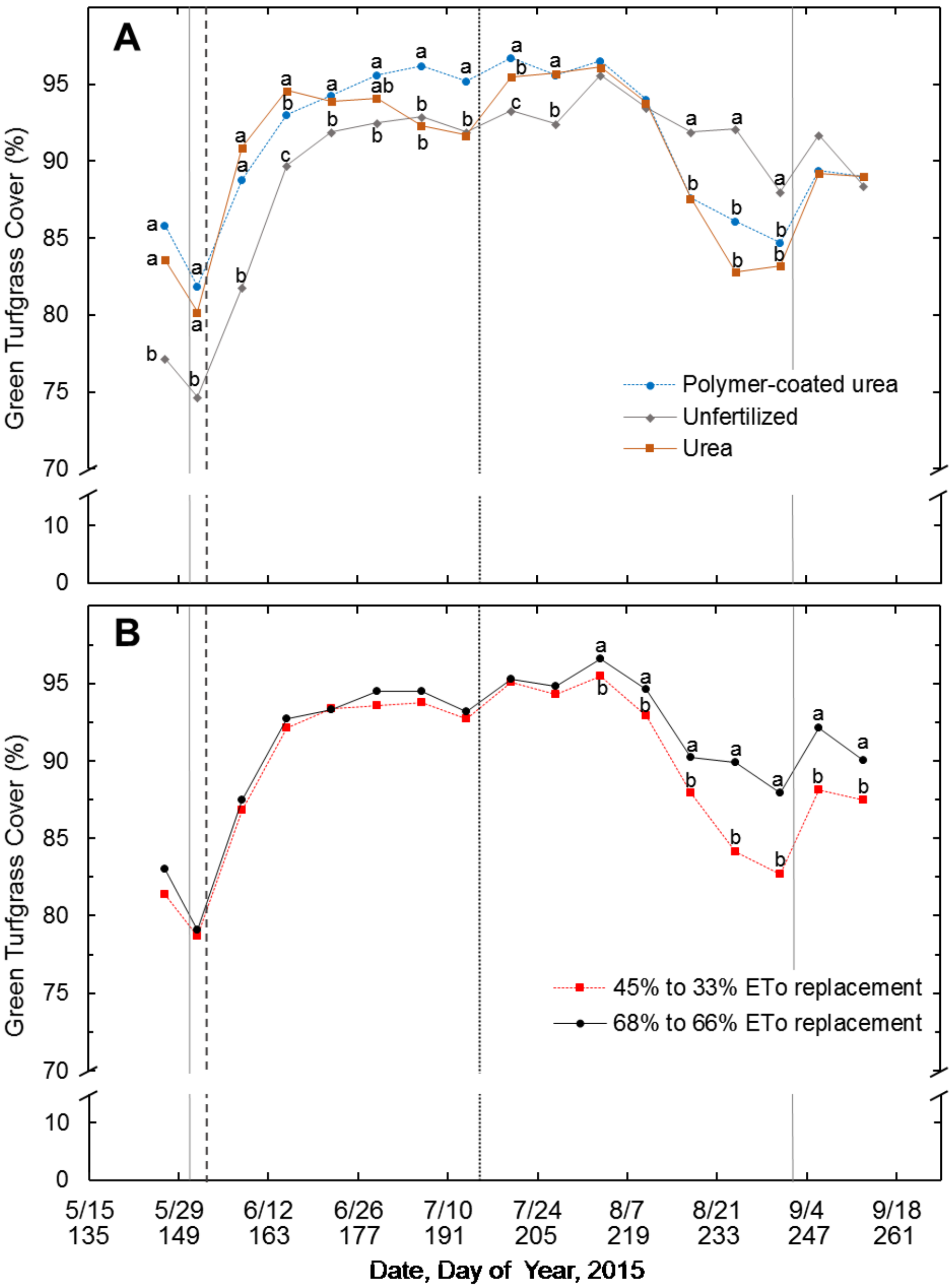

Figure 2.14. Effects of the (A) fertilizer main effect and (B) irrigation main effect on percent green turfgrass cover of zoysiagrass in 2015. Solid vertical lines represent the summer period when the rainout shelter was activated and irrigation treatments were applied. Dashed vertical line at 2 June represent fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical lines at 16 July represent the 2nd urea application at 49 kg N ha^{-1}. Within each main effect, means at each date with the same letter not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

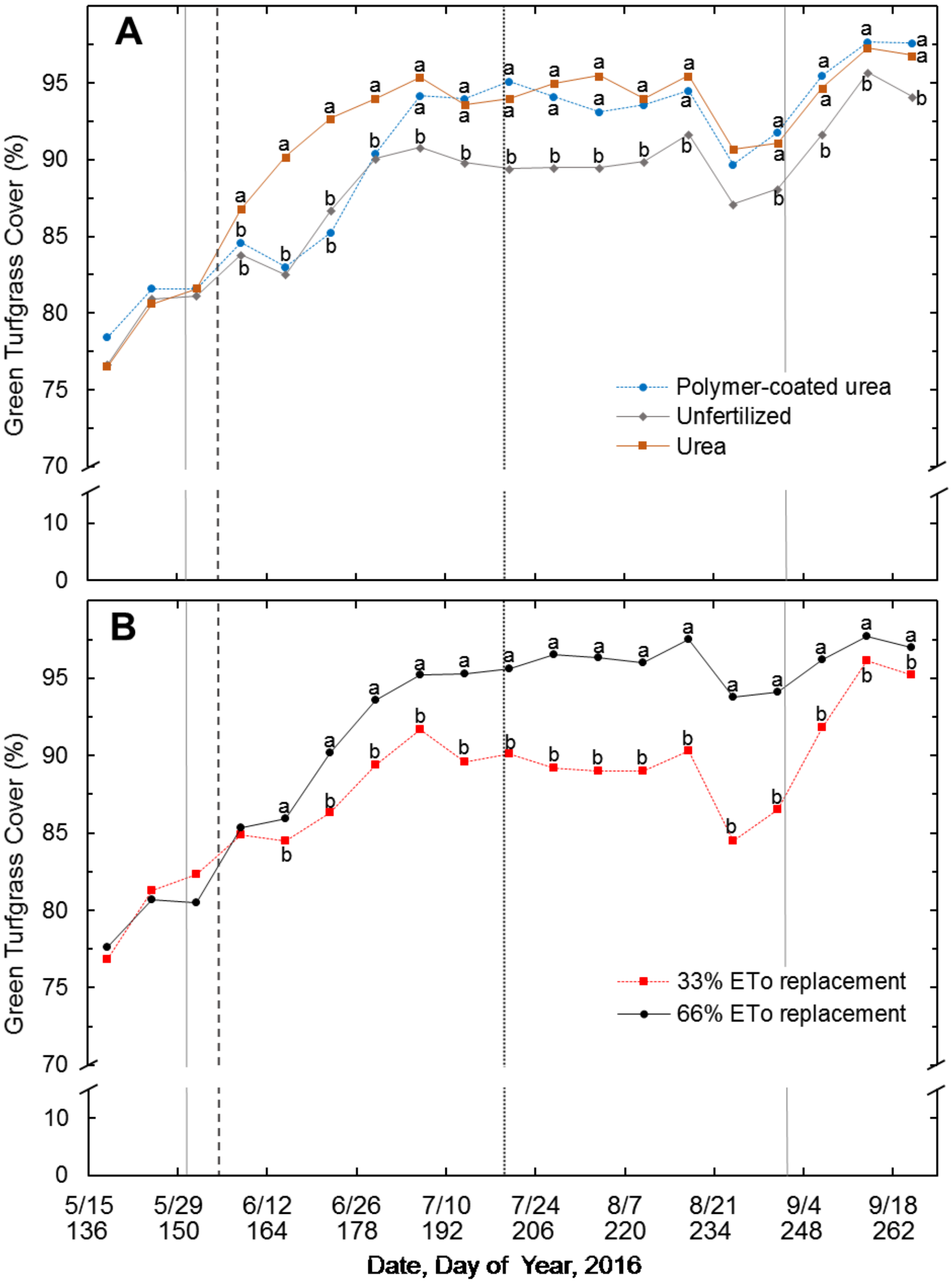

Figure 2.15. Effects of the (A) fertilizer main effect and (B) irrigation main effect on percent green turfgrass cover of zoysiagrass in 2016. Solid vertical lines represent the summer period when the rainout shelter was activated and irrigation treatments were applied. Dashed vertical line at 6 June represent fertilization with urea applied at 49 kg N ha^{-1} and polymer-coated urea applied at 98 kg N ha^{-1}. Dotted vertical lines at 20 July represent the 2nd urea application at 49 kg N ha^{-1}. Within each main effect, means at each date with the same letter not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).

Table 2.1. Analyses fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on cumulative nitrous oxide emissions in ‘Meyer’ zoysiagrass during the summer periods (June – August) in year 1 (2015) and year 2 (2016).

	Cumulative Summer N_2O-N Emissions		
Source of variation	Year 1	Year 2	Total
	N_2O-N kg ha^{-1}	N_2O-N kg ha^{-1}	N_2O-N kg ha^{-1}
Fertilizer			
Unfertilized (UF)	0.974 c[†]	1.31 b[†]	2.28 c[†]
Polymer-coated urea (PCU)	1.18 b	1.35 b	2.53 b
Urea	1.82 a	1.77 a	3.59 a
Irrigation			
33% ET_o	1.29 b[‡]	1.42 b[§]	2.71 b[¶]
66% ET_o	1.36 a	1.53 a	2.88 a
Fertilizer x Irrigation			
UF*33%	0.973	1.29	2.27 d[‡]
UF*66%	0.975	1.32	2.29 d
PCU*33%	1.10	1.27	2.37 d
PCU*66%	1.26	1.42	2.68 c
UREA*33%	1.80	1.70	3.50 b
UREA*66%	1.84	1.84	3.68 a

ANOVA

Source	p-value		
Fertilizer	**<.0001**	**<.0001**	**<.0001**
Irrigation	**0.0289**	**0.0027**	**0.0006**
Fertilizer x Irrigation	0.0901	0.2046	**0.0437**

[†] Within fertilizer main effect, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.0001$).

[‡] Within source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

[§] Within source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.01$).

[¶] Within source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.001$).

Table 2.2. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on mowing frequency of ‘Meyer’ zoysiagrass during 2015 and 2016.

	Cumulative Mowing Frequency[†]	
Source of variation	2015	2016
Fertilizer	# of mowings yr^{-1}	# of mowings yr^{-1}
Unfertilized (UF)	14.8 c[‡]	14.5 c[‡]
Polymer-coated urea (PCU)	22.1 a	22.8 b
Urea	21.0 b	23.8 a
Irrigation		
33% ET_o	18.1 b[§]	19.0 b
66% ET_o	20.4 a	21.7 a
Fertilizer x Irrigation		
UF*33%	13.3	13.2
UF*66%	16.8	15.8
PCU*33%	21.3	21.3
PCU*66%	22.8	24.2
UREA*33%	19.7	22.5
UREA*66%	22.3	25.0
	ANOVA	
Source	p-value	
Fertilizer	**<.0001**	**<.0001**
Irrigation	**<.0001**	**<.0001**
Fertilizer x Irrigation	0.2350	0.9472

[†] Cumulative mowing frequency of Meyer zoysiagrass between March to November, in each respective year. Every 4 to 7 days, grass height was measured at four random locations within each plot. If the grass height was $\geq$ 3.8 cm in at least one of four locations within a plot, that plot was mowed on that day. A maximum height of 3.8 cm was established for the 2.54 cm mowing height due to the general guidelines of not removing more than 1/3 of the turfgrass canopy. Cumulative mowing frequency was summed separately for each plot and treatment means were then calculated.

[‡] Within each source of variation, means in a column with different letters are significantly different according to Fisher’s Protected LSD *($P \leq$* 0.05).

Table 2.3. Analyses of management schedule on soil bulk density (ρ_b), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N) in 2013, 2016, and average annual change in soil organic carbon (ΔSOC) at each depth.

Management Schedule	ρ_b (g cm^{-3})		SOC (Mg C ha^{-1})		SON (Mg N ha^{-1})		C/N		ΔSOC (Mg C ha^{-1} yr^{-1})
	2013	2016	2013	2016	2013	2016	2013	2016	
					0-10 cm				
High	1.42	1.42	23.8 b[†]	29.4 a	2.15	2.00	11.1	14.9	1.77
Low	1.42	1.44	24.1 b	29.2 a	2.29	2.43	10.6	12.3	1.61
					10-20 cm				
High	1.50	1.51	17.3	19.5	1.65	1.45	10.5	15.4	0.70
Low	1.55	1.54	19.6	20.4	1.84	1.37	10.8	20.6	0.24
					20-30 cm				
High	1.48	1.45	12.6	14.6	1.41	0.72	8.9 b	25.5 A[‡]a	0.63
Low	1.52	1.50	13.7	16.1	1.56	1.46	8.8	13.1 B	0.76

[†] Within a row, within each category, means with different lower-case letters are significantly different according to $\alpha_{bon} = 0.0083$.

[‡] Within a column, means with different upper-case letters are significantly different according to $\alpha_{bon} = 0.0083$.

Table 2.4. Analyses of management schedule on soil bulk density (ρ_b), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N) in 2013, 2016, and average annual change in soil organic carbon (ΔSOC) across all depths (0-30 cm).

Management Schedule	ρ_b (g cm^{-3})		SOC (Mg C ha^{-1})		SON (Mg N ha^{-1})		C/N		ΔSOC (Mg C ha^{-1} yr^{-1})
	2013	2016	2013	2016	2013	2016	2013	2016	
High	1.47	1.46	17.9 b[†]	21.2 a	1.74	1.39	10.2 b	18.6 a	1.03
Low	1.49	1.49	19.1 b	21.9 a	1.89	1.75	10.1	15.3	0.87

[†] Within a row, within each category, means with different lower-case letters are significantly different according to $\alpha_{bon} = 0.025$.

[‡] Within a column, means with different upper-case letters are significantly different according to $\alpha_{bon} = 0.025$.

Table 2.5. Analyses of depth on soil bulk density (ρ_b), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N) in 2013, 2016, and average annual change in soil organic carbon (ΔSOC).

Depth	ρ_b (g cm^{-3})		SOC (Mg C ha^{-1})		SON (Mg N ha^{-1})		C/N		ΔSOC (Mg C ha^{-1} yr^{-1})
	2013	2016	2013	2016	2013	2016	2013	2016	
0-10 cm	1.42 B[†]	1.43 B	23.9 Ab[‡]	29.3 Aa	2.22 A	2.21 A	10.9	13.6	1.69 A
10-20 cm	1.53 A	1.53 A	18.5 B	20.0 B	1.74 B	1.41 B	10.7 b	18.0 a	0.47 B
20-30 cm	1.50 A	1.47 AB	13.1 Cb	15.3 Ca	1.48 B	1.09 B	8.9 b	19.3 a	0.70 B

[†] Within a column, means with different upper-case letters are significantly different according to $\alpha_{bon} = 0.0083$.

[‡] Within a row, within each category, means with different lower-case letters are significantly different according to $\alpha_{bon} = 0.016$.

Chapter 3 - Performance and Recovery of Turfgrasses Subjected to Drought and Traffic Stresses: Shoot and Soil Water Content Aspects

Abstract

Future water availability is a serious issue and drought restrictions may be imposed on turf managers with no regard for damage to turfgrass. During drought, turfgrass areas such as golf courses receive vehicular or foot traffic. My objectives of this study were to evaluate shoot and soil water content responses of two cool-season (C3) [Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.)] and two warm-season (C4) grasses {buffalograss [*Buchloe dactyloides* (Nutt.) Engelm] and zoysiagrass *(Zoysia japonica* Steud.)} at 1.6 cm (golf course fairway) and 6.4 cm (golf course rough) mowing heights, with and without simulated golf-cart traffic during a drought and the subsequent recovery period (without traffic). A 41-day drought field study with no irrigation or precipitation, and with and without traffic, followed by a 40-day recovery without traffic was conducted in Manhattan, KS in 2015 and 2016 under a stationary rainout shelter. Across both traffic treatments, C4 grasses typically maintained higher visual quality (VQ) and percent green cover (PGC) than both C3 grasses during drought and recovery. Across all species, the rough mowing height was more impacted by traffic during drought stress. Averaged across all drought dates in both years, traffic applied to Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass maintained at fairway height maintained acceptable VQ for 18, 22, 41, 33 days, respectively; and at rough height for 15, 18, 22, 22 days, respectively. In both years, buffalograss consistently maintained the highest soil moisture among species during the drought. As soil moisture decreased, the surface became more firm across all turf species, but especially at the lower mowing height; traffic enhanced this effect. During recovery, C4 grasses recovered faster than C3 grasses. Overall, traffic application during drought will have negative and accelerated impacts on turfgrass shoots, which will vary with turf species and mowing height.

Introduction

One of the most important challenges facing golf course superintendents is decreasing water availability for irrigation. Increasingly, state and local drought restrictions may be imposed on turf managers with no regard for damage to turfgrass (Beard and Kenna, 2008). During periods of severe drought and water shortages, turfgrass may receive little to no irrigation for extended periods.

Drought resistance and recuperative potential of turfgrass species has been investigated extensively. Overall, drought resistance is a combination of the plant's ability to avoid and tolerate drought (Fry and Huang, 2004). The ability to maintain quality during drought stress, typically by deep rooting, is referred to as drought avoidance, whereas the ability to recover after experiencing symptoms of drought stress is referred to as drought tolerance (Fry and Huang, 2004). In general, warm-season (C4) turfgrass species have better resistance to drought stress than cool-season (C3) species due to their more efficient photosynthetic pathway, lower evapotranspiration (ET) rates, higher levels of osmotic adjustment, higher cell wall elasticity, better tolerance of low leaf relative water content, and other possible contributing factors (Beard, 1973; Beard and Kenna, 2008; Biran et al., 1981; Fu et al., 2004; Fry and Huang, 2004; Huang and Fry, 1999; Kim and Beard, 1988; Meyer and Gibeault, 1986; Qian and Fry, 1997).

Biran et al. (1981) reported that C4 grasses, which included: 'Chiov' kikuyugrass (*Pennisetum clandestinum* Hochst.); unreported cultivars of St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze], seashore paspalum (*Paspalum vaginatum* Sw.), and centipedegrass [Erermochloa ophiuroides (Munro.) Hack.]; 'Santa Ana' and 'Swannee' bermudagrasses [*Cynodon dactylon* (L.) Pers.]; and 'Emerald' zoysiagrass [*Zoysia matrella* (L.) Merr.] had 45% lower water consumption than two C3 grasses: 'Alta' tall fescue (*Festuca arundinacea* Schreb. Syn *Schedonorus arundinaceus* Schreb.) and 'Pennfine' perennial ryegrass (*Lolium perenne* L.). Biran et al. (1981) also reported that less frequent irrigation reduced water consumption by 6 to 18% in C4 grasses and 24 to 34% in C3 grasses. When mowing height was increased from 3 to 6 cm, water consumption increased 3 to 15% in C4 grasses and 25 to 29% in C3 grasses, with transpiration rates for C3 grasses being almost double that of C4 grasses. Warm-season grasses have a clear advantage when it comes to tolerating drought stress due to their lower ET rates, which helps them resist and possibly avoid drought conditions better than most cool-season grasses.

Not only are there differences in drought stress responses between C4 and C3 grasses, but also among species within C3 and C4 grasses. For example, 'Midnight' Kentucky bluegrass (*Poa pratensis* L.), a C3 grass, exhibited superior survival and recovery via turf quality (leaf color), leaf turgidity, leaf chlorophyll content, and photochemical efficiency compared to the C3 grass 'Paragon GLR' perennial ryegrass (*Lolium perenne*), under drought conditions in a growth chamber study (Chai et al., 2010). Conversely, in a 3-year field study in Fort Collins, CO, cultivars of perennial ryegrass remained green and viable longer under drought and thus recovered faster than cultivars of Kentucky bluegrass (Minner and Butler, 1985). However, despite such mixed results it is generally accepted that Kentucky bluegrass typically has better drought tolerance than perennial ryegrass. There are also differences in drought tolerance among C4 grasses. Cathey et al. (2011) reported 'Empire' zoysiagrass (*Z. japonica* Steud. X *Z. matrella*) had lower water use rates and less leaf firing than 'Argentine' bahiagrass (*Paspalum notatum* Flugge) and 'Floratam' St. Augustinegrass (*Stenotaphrum secundatum)* under drought conditions in a greenhouse study.

Common aboveground responses to drought stress include decreased turf quality, growth vigor (clipping yield), verdure, shoot density, tillering, and color (greenness); and increased leaf wilt, firing, and canopy temperatures. Past drought studies in C3 and C4 grasses have indicated that turf species slowest to lose green ground turf cover were also the fastest to recover after rewatering (Karcher et al., 2008; Steinke et al., 2010). Other typical responses to drought include decreased stomatal conductance and/or xylem water potential and increased canopy temperatures, although the timing of these responses vary among turfgrass species (Leksungnoen et al., 2009; Steinke et al., 2009). During drought, turfgrass areas such as golf courses generally continue to receive play from golfers. This results in vehicular or foot traffic stress to turfgrass during conditions of drought stress. However, little research has been conducted on the combined effects of drought and traffic stress.

The National Golf Foundation estimated that 80,000 motorized golf carts were in use in 1963, by 1990 it increased to approximately 800,000 to 850,000 (Anonymous, 1964; Gast, 1991). In 2006, 69% of all rounds of golf in the United States were played with golf carts (Moeller, 2014). Golf cart traffic, regardless of golf cart type or tire design, can have immediate wear damage on turfgrass, especially if traffic frequency is high or traffic is applied by sharp-turns or semi-circle driving patterns (Carrow and Johnson, 1989, 1996). Two golfers using one golf cart has been estimated to increase the amount of turf area impacted by 48 times compared with walking golfers (Wienecke, 2004).

Past traffic research has simulated foot or wheel (vehicular) traffic through a variety of methods/instruments. Examples of foot-traffic simulators include a "wear simulator" (Perry, 1958; Youngner, 1961, 1962), a "custom-built studded drum rollers" (Van Der Horst, 1970; Fushtey et al., 1983), the "Brinkman Traffic Simulator" (Cereti et al., 2010; Cockerham and Brinkman, 1989; Dunn et al., 1994; Głąb and Szewczyk, 2014, 2015; Minner et al., 1993; Vanini et al., 2007), the "Differential Slip Wear Machine" (Canaway, 1976, 1981), the "FIFA-approved 'Lisport' machine" (CEN 2007; Lulli et al., 2012), the "Georgia (GA) SCW Traffic Simulator" (Carrow et al., 2001), and the "Cady Traffic Simulator" (Henderson et al., 2005; Vanini et al., 2007). Examples of wheel or smooth-traffic simulators of vehicular traffic include the "Nebraska SCW Traffic Simulator" (Shearman et al., 2001), the "GA W Traffic Simulator" (Shearman et al., 2001), a "small-plot wear simulator" (Shearman et al., 1974), a "custom-built golf cart traffic simulator towed behind a turf utility vehicle" (Alderman, 2016; Watkins et al., 2010) and use of actual "golf carts" (Carrow and Johnson, 1989, 1996). Regardless of the application method, traffic research has generally focused on well-watered turfgrass (non-drought).

Traffic stress can result in turfgrass wear damage, soil compaction, soil displacement, and turf removal or divots (Beard, 1973). Wear damage from traffic stress greatly impacts the above-ground portion of the turfgrass, whereas the below-ground portion is more influenced by soil compaction. Wear damage results from physical injury to the plant, such as a scuffing, tearing, crushing action and possible removal of the leaves, stems, and crown (Beard, 1973). This scuffing and tearing action can create openings for or exacerbate existing disease infections, weed encroachment, water loss, and other stresses such as drought stress (Beard, 1976). Wear damage to turfgrass can cause thinning of the canopy (decreased turf cover), decreased quality, leaf bruising, loss of color, less verdure, matting of the turf, and lower shoot density (Bear, 1976; Canaway, 1981; Carrow and Johnson, 1989, 1996). The appearance of wear injury will vary in extent depending on the intensity and duration of traffic (Carrow and Johnson, 1989). Wear damage from traffic stress is most likely to be noticed sooner due to immediate plant injury and possible matting, the laying or folding over of the turf leaves from traffic stress (Carrow and Johnson, 1989, 1996). Wear injury has been assessed by visual turf quality (VQ), visual green turf cover, digital percent green cover (PGC), visual color, leaf bruising, shoot/tiller density, verdure, percent chlorophyll per unit area, percent total cell wall content, and other methods (Carrow and Johnson, 1989, 1996; Shearman and Beard 1975a, 1975b, 1975c). Through correlation, Shearman and Beard (1975a) concluded that the four methods (visual ratings, percent verdure, percent total cell wall content, and percent chlorophyll per unit area) were all satisfactory in evaluating wear tolerance in turfgrass.

Physiological, morphological, and anatomical characteristics such as verdure, shoot density, leaf width, load bearing capacity, leaf tensile strength, leaf moisture, and relative turgidity may play a role in differences in wear tolerance in turfgrass species. However, Shearman and Beard (1975c) found no significant correlations between any of the characteristics mentioned above and wear tolerance of seven different C3 grasses. Leaf tensile strength and leaf width tended to contribute the most to variation in wear tolerance among the seven turfgrass species studied (Shearman and Beard, 1975c). Upon further investigation, anatomical features of more lignified cells and sclerenchyma fibers in stems and leaves of 'Kentucky-31' (K-31) tall fescue (*Festuca arundinacea*) may contribute to stronger and more stiff leaves and thus, better wear tolerance than rough bluegrass (*Poa trivialis* L.) (Shearman and Beard, 1975c). Shearman and Beard (1975b) reported that none of five cell wall components alone, including percent total cell wall, lignocellulose, cellulose, hemicellulose, or lignin, was strongly correlated to wear tolerance. A higher percent total cell wall content and/or higher lignin content in the leaves increased wear tolerance in multiple turfgrass species (Bourgoin et al., 1985; Brosnan et al., 2005; Dowgiewicz et al., 2011; Kilmartin, 1994; Trenholm et al., 2000). Higher lignin contents and carbohydrate concentrations were strongly correlated to better wear tolerance, with higher lignin content contributing to more resistance to compressive forces and higher carbohydrate concentrations promoting faster recovery (Lulli et al., 2012). Conversely, den Haan et al. (2009) found that higher total cell wall content and lignin content were linked to increased damage from wear stress. When exposed to 132 passes of wear stress, the top performing cultivars of perennial ryegrass had higher shoot density, green leaf biomass, leaf area index, finer leaves with short compact cells, and lower total cell wall and lignin content than poor-performing perennial ryegrass cultivars (den Haan et al., 2009). Shoot water content relative to wear tolerance has also shown mixed results (Bourgoin et al., 1985; Brosnan et al., 2005; Trenholm et al., 2000).

Cultivars of Kentucky bluegrass exhibited average wear tolerance compared to the high wear tolerance of perennial ryegrass and tall fescue cultivars because of its higher shoot density and recovery capabilities (Cereti et al., 2010). When maintained at 3.75-cm and subjected to studded roller traffic over a 3-year period in British Columbia, Canada, perennial ryegrass cultivars, followed by Kentucky bluegrass cultivars, had the highest wear tolerance determined by greater tiller density (Fushtey et al., 1983). However, Głąb et al. (2015) reported that greater tillering count did not improve wear tolerance, but rather an increase in the number of vascular bundles, leaf- width, -cross-section area, and -angle were associated with better wear tolerance. Trenholm et al. (2000) reported different wear tolerance mechanisms for both seashore paspalum ecotypes and bermudagrass hybrids (*C. dactylon* X *C. transvaalensis* Burtt-Davy**)**.

Wear tolerance of turfgrass depends on a variety of factors such as species, cultivar, intensity of culture practices, environmental conditions, maturity of stand, intensity of traffic, type of traffic, mowing height, thatch depth, and other factors (Beard, 1973; Canaway, 1981; Cereti et al., 2010; Dunn et al., 1994; Minner et al., 1993; Lulli et al., 2012; Shearman and Beard, 1975a Youngner, 1961, 1962). Some turf characteristics and management practices appear more frequently linked to improved wear tolerance than others. These include increased mowing height, thatch thickness, shoot density, leaf green biomass; and moderate fertility levels; with mixed results with total cell wall content, lignin content, leaf width, and tillering number (Beard, 1973, 1976; Brosnan et al., 2005; Cereti et al., 2010; den Haan et al., 2009; Głąb et al., 2015; Lulli et al., 2012; Shearman and Beard, 1975a, 1975b, 1975c; Trenholm et al., 1999, 2000; Youngner 1961, 1962). The importance of a single physiological, morphological, or anatomical trait for wear tolerance may depend on turfgrass species and environmental conditions at the time of traffic stress.

Differences in traffic tolerance have been reported not only between C3 and C4 turfgrasses, but also within both C3 and C4 grasses. Lulli et al. (2012) reported three C4 grasses including: 'Tifway 419' bermudagrass [*C. dactylon* var. *dactylon* x *C. transvaalensis* Burt-Davy], 'Zeon' zoysiagrass (*Z. matrella*), and 'Salam' seashore paspalum (*Paspalum vaginatum*), had better wear tolerance than a mixed stand of C3 grasses consisting of 70% perennial ryegrass + 30% Kentucky bluegrass; all grasses were maintained at 3-cm and subjected to simulated studded foot traffic by 'Lisport' machine in a greenhouse study.

Dunn et al. (1994) applied traffic with a modified Brinkman traffic simulator in the spring and fall to turf plots consisting of mixtures of 'Midiron' bermudagrass (*C. dactylon)* + varying C3 grass species. They reported the "bermudagrass only" and three mixtures of bermudagrass + fine fescue [Chewings fescue (*Festuca rubra* L. subsp. *commutata* Gaud.); or bermudagrass + Hard fescue (*Festuca longifolia* Thuill.); or bermudagrass + creeping red fescue (*Festuca rubra* L. subsp. *rubra* Gaud.)] were the most damaged, while mixtures of bermudagrass + Kentucky bluegrass (blends of 'Touchdown', 'Midnight', 'A-34', and 'America') or mixtures of bermudagrass + perennial ryegrass (blends of 'Citation II', 'Manhattan II', 'Palmer', 'Gator', and 'Tara') had the best traffic tolerance, which was mostly due to the time of year of traffic application. Traffic was applied to turf plots in the spring and fall in Missouri, which are times of the year that are more favorable for growth for the C3 grasses Kentucky bluegrass and perennial ryegrass than the C4 grass bermudagrass, thus more able to recover from traffic than bermudagrass. Therefore, weather conditions, soil moisture, and time of the year of traffic play a significant role into which C3 or C4 grasses can better tolerate traffic and recover more rapidly.

Past traffic research in C3 grasses has consistently reported that perennial ryegrass and tall fescue have the highest wear tolerance among C3 grasses and Kentucky bluegrass to have slightly lower traffic tolerance than the two aforementioned turf species (Canaway, 1981; Cereti et al., 2010; Shearman and Beard, 1975a).

Differences in traffic tolerance have been observed among cultivars within turfgrass species (Beard, 1976; Brosnan et al., 2005; Cereti et al., 2010; den Haan et al., 2009; Fushtey et al., 1983; Głąb et al., 2015; Minner et al., 1993; Trappe et al., 2011). Minner et al. (1993) evaluated numerous cultivars of Kentucky bluegrass, perennial ryegrass, and tall fescue during several multi-year National Turfgrass Evaluation Performance (NTEP) trials subjected to 10 passes per day, three days per week, with the Brinkman Traffic Simulator. 'America' Kentucky bluegrass received an "Excellent" rating, but there were clear differences in traffic tolerance among cultivars of all three species (Minner et al., 1993). The same authors reported there was more variation in traffic tolerance among cultivars of Kentucky bluegrass than among tall fescue or perennial ryegrass cultivars. 'Meyer' zoysiagrass (*Z. japonica*) was one of the top performing zoysiagrass cultivar's trafficked under full-sun plots in one of two years (Trappe et al., 2011).

Typically, turfgrasses with aggressive growth habits will recover more quickly from traffic. Youngner (1961) reported stoloniferous warm-season grasses such as 'Meyer' zoysiagrass and bermudagrass (Common and 'U-3') recovered faster than eight C3 grasses. Furthermore, wear tolerance was consistently greater in zoysiagrass, bermudagrass, and 'Alta' tall fescue than in other turfgrass species.

In general, C4 grasses such as zoysiagrass and bermudagrass have greater wear tolerance than other C4 grasses and most C3 grasses (Beard, 1973; Carrow, 1995; Lulli et al., 2012; Youngner, 1961). Also, perennial ryegrass and tall fescue tend to have the best wear tolerance among C3 grasses, with Kentucky bluegrass having less- or equal wear tolerance to perennial ryegrass (Beard, 1973; Canaway, 1981; Carrow, 1995; Cereti et al., 2010; Dunn et al., 1994; Fushtey et al., 1983; Minner et al., 1993; Sherman and Beard, 1975a; Youngner, 1961). Minimal wear-tolerance research has been conducted on buffalograss [*Buchloe dactyloides* (Nutt.) Engelm] compared to other turfgrass species. Alderman (2016) reported medium to good traffic tolerance of 'Cody' buffalograss (*Buchloe dactyloides)* at 7.6-cm when exposed to varying rates of traffic and nitrogen fertilization. More research is needed on the traffic tolerance of buffalograss compared to other species with good to excellent traffic tolerance such as zoysiagrass, perennial ryegrass, or Kentucky bluegrass.

These previous studies were all conducted on well-watered turfgrass. Based on personal observations and not intensively studied, Carrow and Johnson (1996) and Beard (1976) stated traffic applied during periods of dry weather conditions or wilt stress can possibly exacerbate wear damage. Therefore, turf managers may need to be more cautious with traffic control during dry periods. Because water restrictions for turf irrigation will likely increase, the effects of traffic during drought stress requires further evaluation.

Therefore, objectives of this study were to evaluate shoot and soil water content responses due to golf cart traffic on both C3 and C4 turfgrass species maintained at two golf course related heights (fairway- and rough-height) during simulated drought and subsequent recovery periods (without traffic) under a stationary rainout shelter.

Materials and Methods

Study Site

This field experiment was conducted in 2015 and 2016 at the Rocky Ford Turfgrass Research Center, Manhattan, KS (lat. 39° 13' 53" N, 96° 34'51" 6 W). The soil was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls). Field plots under an existing stationary rainout shelter were established in Sept. 2014. The rainout shelter was a commercial greenhouse design (Thermolator; Agra Tech Inc., Pittsburg, CA), measuring 10.67 m wide x 29.26 m long, with an eave height of 1.07 m, and a ridge height of 4.27 m. Turfgrass buffer strips (space between the edge of the structure and the plots) were established at a width of 1.22 m running along eave (north and south) sides and a width of 3.05 and 3.96 m on east and west ends, respectively. Rain gutters were installed along the eaves to capture runoff from the cover during rain and move the water away from the plots. A new 0.15 mm clear greenhouse film (Warp's Flex-O-Glass® Greenhouse Films - 6 Mil 4-Year UV Clear Film, Warp Bros., Chicago, IL) was installed for each 41-day simulated-drought period on 30 June 2015 and 27 June 2016 and removed on 10 Aug. 2015 and 7 Aug. 2016.

Treatments

Sixty-four plots measuring 1.83 x 1.37 m each included 4 replicates of each treatment combination. This study was a 4-way factorial treatment design. The turfgrass main effect included: 1) ‘America’ Kentucky bluegrass, 2) ‘Paragon GLR’ perennial ryegrass, 3) ‘Sharps Improved II’ buffalograss (*Buchloe dactyloides*), and 4) ‘Meyer’ zoysiagrass with each species being randomly assigned to a “column” within each block. The mowing height main effect consisted of: 1) fairway- (1.6 cm) and 2) rough-height (6.3 cm), each randomly assigned to a “row” within each block. The traffic main effect included: 1) No traffic (untreated control) and 2) traffic (16 passes per week), each randomly assigned to a “whole subrow” across the entire study due to space restrictions. The time main effect consisted of each rating date treated as a repeated measure within each drought and recovery period.

Traffic was applied weekly in straight lines with a golf cart during the drought period at eight passes in opposite directions for a total of 16 passes per week. To minimize the cumulative traffic effects across years, traffic in 2016 was applied to a different area of the plots than in 2015. The golf cart was a 2001 electric 36-volt EZ-GO TXT Standard golf utility cart with canopy and steel bed (472 kg) (1418825, E-Z-GO, Augusta, GA) with supplemental weight to simulate two golfers & equipment (175 kg) traveling at 13 km h^{-1}. The front tires were a Kenda Hole-N-1 18x8.5-8 4-ply tubeless tires (103890868B1, Kenda Rubber Industrial Company, Yuanlin, Taiwan) and the back tires were Carlisle Fairway Pro 18x8.50-8 4-ply tubeless tires (5189761, The Carlstar Group LLC, Franklin TN); all tires were maintained at a pressure of 124 kPa.

Plot Maintenance

The two C3 turfgrass species were established by seeding. Kentucky bluegrass was seeded at a rate of 147 kg ha^{-1} and perennial ryegrass at a rate of 244 kg ha^{-1} in its respective columns on 11 Sept. 2014. The two C4 species, buffalograss and zoysiagrass were sodded into its respective columns from established swards at the Rocky Ford Turfgrass Research Center on 22 Sept. 2014. After plots were seeded or sodded, a starter fertilizer (18-24-12; LESCO Inc. Cleveland, OH) was applied at 37 kg N ha^{-1} (22 kg Phosphorus ha^{-1}) on 11 Sept. and 22 Sept. 2014, respectively. The plots were irrigated regularly to promote germination and establishment. All plots were well established before the beginning of the first simulated drought in late June of 2015.

Standard agronomic golf industry fertilization procedures were implemented specifically for both C3 grasses and C4 grasses. Therefore, fertilization timings and amounts differed between C3 and C4 grasses. Urea (46-0-0; Thrive Branded Fertilizer, Mears Fertilizer Inc. El Dorado, KS) was applied at 49 kg N ha^{-1} on 8 Apr., 21 Sept., and 21 Oct. in 2015, and 1 Apr. 2016 on the C3 species; and 24.5 kg N ha^{-1} on 22 Apr. 2015 and 21 Apr. 2016 on the C4 species. A polymer-coated urea (43-0-0; Duration 120 (120-day release), Koch Agronomic Services, LLC, Wichita, KS) was applied at 49 kg N ha^{-1} on 18 May 2015 and 22 May 2016 on the C3 species and 74 kg N ha^{-1} on 18 May 2015 and 22 May 2016 on the C4 species. Thus, the C3 species received 196 kg N ha^{-1} yr^{-1} and the C4 species received 98 kg N ha^{-1} yr^{-1}.

Fungicides for preventing and controlling *Rhizoctonia* large patch (*Rhizoctonia solani* Kühn Anastomosis Group (AG)-2-2 LP) were applied to zoysiagrass on 14 Sept. 2014 and 19 Sept. 2015. Individual- or tank mix fungicides for prevention of dollar spot (*Sclerotinia homoeocarpa*), brown patch (*Rhizoctonia solani* Kühn), and gray leaf spot (*Pyricularia grisea*), and other turf diseases were applied to perennial ryegrass and Kentucky bluegrass on multiple dates throughout the summers of 2015 and 2016 (Appendix Table B.1). Fungicides were alternated among different groups [= different modes of action / Fungicide Resistance Action Committee (FRAC) Codes] to reduce the risk of fungicide resistance. For more details on application dates, rates, and fungicides implemented see Appendix Table B.1.

A commercially available herbicide mixture containing 2,4-D acid + mecoprop-p acid + dicamba acid (Trimec Classic, PBI/Gordon Corporation, Kansas City, MO) was applied at 1.3 kg a.i. ha^{-1} on 31 Mar. and 28 Apr. in 2015, and 6 May 2016 as spot treatments for control of common dandelion (*Taraxacum officinale* Wigg.) and other broadleaf weeds. Oxadiazon, 2-tert-butyl-4-2dichloro-5-isopropoxyphenyl (Quali-Pro Oxadiazon 2G, Control Solutions Inc., Pasadena, TX) was applied to the entire site at 2 kg a.i. ha^{-1} on 8 Apr. 2015 and 4 kg a.i. ha^{-1} on 8

Mar. 2016 for control of summer annual weeds {smooth crabgrass (*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.) and large crabgrass [*D*. sanguinalis (L.) Scop.]}. Other various weeds were removed by hand from 2014 through 2016.

An insecticide, imidacloprid, 1-[(6-Chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimine (Merit 0.5 G, Bayer Environmental Science, Research Triangle Park, NC), was applied to the entire site at 0.37 kg a.i. ha^{-1} on 29 May 2015 and 22 May 2016 for the control of billbug (*Sphenophorus* spp.), southern masked chafer (*Cyclocephala lurida* Bland) and May beetle (*Phyllophaga* spp.) larvae.

Plots were mowed at least twice a week and irrigated to prevent drought stress outside of the designated drought period.

Data Collection

Data were collected from 26 June to 18 Sept. 2015 and 23 June to 15 Sept. 2016. Visual turf quality, PGC, turf firmness, and volumetric soil water content (θ_v) were measured 4 days prior to the drought period (baseline "pre-drought" period), then weekly throughout the drought and recovery periods each year (Appendix Figs. B.1, B.2, and B.3). All four response variables (VQ, PGC, turf firmness, and θ_v) were always measured on the same day. Visual turf quality was rated and averaged from two locations per plot on a 1 to 9 scale (1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality) according to color, texture, density, and uniformity (Morris and Shearman, 1999). Percent green cover was measured from two locations per plot with digital photographs taken with a Nikon D5000 digital camera (Nikon Inc., Tokyo, Japan) using a lighted camera box (51 cm x 61 cm x 56 cm) attached with a custom pink template border that provided an area of 50.8 cm x 18.8 cm. The camera was adjusted to manual settings of: f-stop of 5.6, 1/125 sec exposure time, and 800 ISO-speed. Images were analyzed with SigmaScan Pro 5.0 (ver. 5.0, SPSS Science Marketing Dept., Chicago, IL) using the "Turf Analysis" macro for batch analysis for three separate runs to account for template and green turf pixels (Karcher and Richardson, 2005). To determine green pixels, the macro threshold settings were adjusted to hue = 45 to 107 and saturation = 0 to 100 (Scan 1). For template pixels, the macro threshold settings were adjusted to hue = 0 to 32 (Scan 2), and again at hue = 108 to 255 (Scan 3), both at a saturation = 0 to 100. These threshold settings allowed for estimation of pixels, expressed as percentage of green turf color for each plot, calculated for each image by using equation 3.1:

$$Percent\ Green\ Cover\ (\%) = \frac{Scan\ 1\ pixels}{[Total\ Image\ Pixels - (Scan\ 2\ pixels + Scan\ 3\ pixels)]} \qquad [3.1]$$

where scan 1 pixels is the number of green pixels, total image pixels is the number of pixels for the entire image, and scans 2 and 3 are the total number of pink template pixels.

Turf firmness, or depth of travel (mm), was measured from four locations per plot using a turf firmness meter (FieldScout TruFirm Turf Firmness Meter, Spectrum Technologies Inc., Aurora, IL). In 2015, turf firmness was not measured at baseline (26 June) or during the first week of the drought (3 July) because the instrument was not available. Volumetric soil water content (θ_v) was measured at a 7.6 cm (averaged from 4 measurements per plot) with time domain reflectometry (TDR), (FieldScout TDR 300 Soil Moisture Meter, Spectrum Technologies Inc., Aurora, IL).

Ancillary Measurements

Weather data was collected from an on-site weather station positioned in full sun within 100 m of the study area. To evaluate potential microclimate effects, air temperature and relative humidity (RH) were monitored inside and outside of the rainout shelter during the drought period. These weather variables were measured using shaded, ventilated sensors, and recorded and logged every hour (HOBO Pro V2, Onset Computer Corp., Bourne, MA); sensors were placed at 15 cm above the ground, which was slightly above the turf canopies. Hourly vapor pressure deficit (VPD) was calculated for both inside and outside the shelter. Photosynthetic active radiation (PAR) was measured at approximately 1300 CST on 1 Aug. 2015 and 18 July 2016 using a ceptometer (LP-80, Decagon Devices Inc., Pullman, WA). Sixteen random PAR measurements collected from inside the shelter were averaged and compared with twelve random measurements collected from outside the shelter.

Statistical Analysis

All four response variables (VQ, PGC, turf firmness, and θ_v) were analyzed using a four-way analysis of variance (ANOVA) with turf species, mowing height, and traffic as fixed effects, block as a random effect, and date as a repeated measure; and the three study periods (baseline, drought, recovery) were each analyzed separately in Proc MIXED of SAS (SAS 9.4, SAS Institute Inc., Cary, NC, USA). A several step process was used to assure proper ("best") model specification for each baseline, drought, and recovery period of each year for each response variable. First non-estimable covariance parameters were removed and appropriate denominator degrees of freedom (DDF) were specified. Next, different variance-covariance structures {compound symmetry [CS], autoregressive [AR(1)], toeplitz [TOEP], heterogenous compound symmetry [CSH], heterogeneous autoregressive [ARH(1)], and heterogeneous toeplitz [TOEPH]} were investigated to find the best fitting model. AIC = Akaike's Information Criteria and BIC = Bayesian Information Criteria were utilized to assess best fitting model (lower is better). Furthermore, studentized residuals were investigated to check assumptions of normal distribution and homogeneous variance properties. If necessary, additional variance group arrangements were specified. Significant outliers were also detected utilizing a conservative Bonferroni adjustment and removed from the dataset. Once final model was determined, summary of the statistical output was analyzed for each period (Appendix Table B.2). After analysis of type III tests for fixed effects, the F test for slice effects and the t test for slice differences within each period were conducted utilizing a conservative Bonferroni adjustment test for multiple comparisons.

For θ_v, the turf species x date interaction was significant across both the drought and recovery periods in each year (Appendix Table B.3). However, overall the turf species main effect contributed to the majority of differences among treatments at each date. Therefore, for θ_v, turf species x date interaction means were sliced by date to compare the turf species main effect at each date within both the drought and the recovery period as well as the baseline period in both years (Appendix Tables B.4 and B.5).

For both PGC and VQ, there were multiple treatment x date interactions significant for the type III tests of fixed effects for each study period and the four-way interaction of turf species x mowing height x traffic x date was only significant in year 2 (Appendix Tables B.6 and B.7). Upon further statistical analysis, traffic treatments within each mowing height of each turf species at each date were having a significant effect on PGC and VQ in each study period. Therefore, for PGC and VQ, the four-way cell means were sliced by turf species x mowing height x date to compare the two traffic treatments within each mowing height within each turf species at each date of each period, including the baseline periods (Appendix Tables B.8, B.9, B.10, and B.11).

For turf firmness, there were multiple treatment x date interactions significant for the type III tests of fixed effects for each study period (Appendix Table B.12). Further statistical analysis revealed different responses to traffic treatments within each mowing height of each turf species at each date. Therefore, for turf firmness, the four-way cell means were sliced by turf species x date to compare the four traffic x mowing height treatment interactions within each turf species at each date of each baseline, drought, and recovery period (Appendix Tables B.13 and B.14).

For each response variable, a set of pre-planned contrasts were conducted to compare C3 vs. C4 turf species overall and at each treatment interaction (Appendix Tables B.3, B.6, B.7 and B.12).

Results and Discussion

Site Weather Data

Monthly air temperatures averaged slightly higher during the drought period in 2016 than in 2015 (Table 3.1). The average air temperature during the drought period (June-August) was 24.8 °C in 2015, 25.8 °C in 2016, and 25.3 °C for the 30-year climate normal according to National Oceanic & Atmospheric Administration (Table 3.1). The average air temperature during the recovery period (August-September) was 23.6 °C in 2015, 23.5 °C in 2016, and 23 °C for the 30-year climate normal (Table 3.1). In 2016, maximum and minimum temperatures were higher in June and July, and minimum temperatures were higher in August, than in 2015. Therefore, slight differences in air temperatures may have influenced turf performance and recovery between years.

Air temperature and VPD were slightly but consistently higher inside than outside the rainout shelter (Appendix Fig. B.4). The inside-to-outside air temperature differences during daytime and nighttime were an average 1.09 °C and 1.26 °C, respectively, in 2015 and 0.67 °C and 0.94 °C, respectively, in 2016. The inside-to-outside VPD differences during daytime and nighttime were an average 14% higher and 25.6% higher, respectively, in 2015 and 12.5% higher and 18.5% higher, respectively, in 2016.

In both years, there was a 10-11% reduction in PAR due to the plastic cover (data not shown). This did not likely negatively impact the turfgrasses, because 25 to 40% reductions in full sunlight are typically required before shading symptoms become evident (McBee and Holt, 1966; Goss et al., 2002).

Soil Water Content

Volumetric soil water content was measured in each turf plot to evaluate the effects of treatments on soil water content during the drought and recovery periods. All four turfgrass species were well watered before the drought period in each year, with θ_v ranging from 45.4 to 51% (Figs. 3.1 and 3.2). There were statistical differences among species even at relatively high θ_v at the beginning of both years. However, the differences did not likely confound turf performance during the drought. For example, buffalograss started with lower soil moisture, but then became higher among species during the drought.

In both years, as the drought progressed, differences emerged among species in the rate of decline of θ_v, which was more noticeable at 4 to 11 days of drought, and thereafter θ_v among species continued to separate as the drought advanced (Figs. 3.1 and 3.2). At 11 days of drought in 2015, buffalograss and perennial ryegrass maintained θ_v above 29% while Kentucky bluegrass was lower at 26.7% and zoysiagrass was not statistically different than other species at 27.7% (Fig. 3.1). At 11 days of drought in 2016, again buffalograss and perennial ryegrass maintained θ_v above 30% while both Kentucky bluegrass and zoysiagrass were lower at 26.7% and 25.8%, respectively (Fig. 3.2). In both years, as the drought progressed onward from 11 days, θ_v was higher in buffalograss and perennial ryegrass than in zoysiagrass and/or Kentucky bluegrass. During the drought, each turfgrass species exhibited a similar trend for both years in their rate of decline of θ_v. By the end of the 41-day drought in 2015, θ_v was similar between buffalograss and perennial ryegrass at 17.1% and 16.9%, respectively and both were higher than in zoysiagrass and Kentucky bluegrass, which were both at 14.6% (Fig. 3.1). By the end of the drought in 2016, θ_v was higher in buffalograss at 21% than in all other species, which ranged from 14.6 to 16.9% (Fig. 3.2). The different rates of decline in θ_v during drought may have been related to different water use rates among turf species. Typically, C4 grasses use less water than C3 grasses, especially buffalograss (Beard and Kenna, 2008). A lower water use rate would likely result in higher θ_v, which could improve the turf's ability to tolerate drought stress as time progresses. The ability of buffalograss to extract water at deeper depths due to its deep and extensive rooting ability may have contributed to less soil water use near the surface and correspondingly, to the higher θ_v among species in both years (Qian et al., 1997). Hydraulic lift has been documented in buffalograss to improve surface soil water status, this also could be reason for higher θ_v of buffalograss at 0-7.6 cm (Huang, 1999).

Early in the recovery period in both years, θ_v increased rapidly among turf species due to irrigation. In both years, θ_v increased faster in C3 than in C4 grasses. This may have been because the C3 grasses were more dormant than the C4 grasses by the end of the drought, based on visual observations and PGC and VQ ratings. If the C3 grasses were at an increased dormant state, less water would be used during a slower exit from dormancy and initial regrowth. Meanwhile, the C4 grasses were less dormant or perhaps not dormant at all. Thus, C4 grasses were still actively growing and could utilize water immediately in the recovery period; hence, lower corresponding θ_v.

Percent Green Cover and Visual Turf Quality

Percent green cover was measured and VQ was rated in each turf plot to evaluate the effects of treatments on the performance of turfgrass shoots. Different responses to traffic during drought were observed among species within each mowing height and between mowing heights of each species during both the drought and recovery (Figs. 3.3, 3.4, 3.5, and 3.6). Prior to the drought and any application of traffic stress, PGC and VQ were similar between traffic treatments within each mowing height of each species (Figs. 3.3, 3.4, 3.5, and 3.6). During the drought, PGC and VQ generally declined faster in trafficked than in non-trafficked plots due to characteristics such as thinning of the turf canopy, loss of turf color, and/or matting of the turf.

Drought

Within each mowing height there were more dates during the drought with differences in PGC and VQ, and typically differences were larger, between traffic treatments in C4 grasses than in C3 grasses, and this trend was observed in both years (Figs. 3.3, 3.4, 3.5, and 3.6). During the 6 measurement dates of the 2015 drought, PGC differences between traffic treatments within the fairway mowing height in Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass were significant at 2, 0, 5, 3 dates, respectively, while differences between traffic treatments within the rough height were significant at 2, 1, 6, 4 dates, respectively (Fig. 3.3). During the 6 dates of the 2016 drought, PGC differences between traffic treatments within the fairway mowing height in Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass were significant at 0, 0, 4, 4 dates, respectively, while differences between traffic treatments within the rough height were significant at 0, 3, 6, 5 dates, respectively (Fig. 3.4). Averaged across all drought dates in both years, traffic applied to Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass at fairway height reduced PGC by 14.3, 9.8, 12.4, 16.5%, respectively, while traffic applied at rough height reduced PGC by 11.6, 17, 29.1, 26.4%, respectively (Fig. 3.3 and 3.4). A similar trend was observed in VQ ratings (Fig. 3.5 and 3.6). However, this does not mean C4 grasses have less traffic tolerance than C3 grasses. The better drought tolerance of C4 than C3 grasses resulted in higher PGC and VQ of C4 grasses in the no traffic plots, regardless of mowing height. Conversely, the lower drought tolerance of C3 than C4 grasses resulted in lower PGC and VQ in no traffic C3 plots. This implies that when traffic occurs during drought stress, there is less chance for a decline in C3 grasses because they are already in poorer shape than C4 grasses, even before traffic stress is applied. Nevertheless, if traffic is applied to C3 grasses during drought stress, PGC and VQ will decrease faster than if no traffic was applied, as observed in both mowing heights in both Kentucky bluegrass and perennial ryegrass in both years (Figs 3.3, 3.4, 3.5, and 3.6).

Reductions in PGC due to traffic mentioned above occurred more frequently in the rough than the fairway mowing height. The larger separation between traffic treatments within the (higher) rough compared to the (lower) fairway mowing height may be due to several factors. Although leaf area was not measured in my study, the rough mowing height likely had more leaf area than the fairway (Lee et al., 2011), allowing more opportunity for green cover and quality loss. One might suspect the higher mowing height (rough) that received traffic would perform better than turf at fairway height that received traffic, but this was not observed in my study. Youngner (1962) reported contrary findings to my study that wear tolerance in C3 grass mixtures was reduced at lower (1.27-cm) mowing height compared to higher (5.08-cm) height. However, Youngner (1962) subjected the turf to traffic with a different type of traffic wear stress machine, and the turfgrass was not under drought conditions. Also, the turfgrass maintained at the lower 1.27-cm mowing height in Youngner (1962) may have received a lower quality of cut due to lower quality mowing equipment at the time compared to the high quality of cut provided by present mowing equipment that has been improved since 1962.

In my study, at the end of the 41-day drought in 2015, PGC in trafficked *fairway* plots averaged 20% lower in C3 and 25% lower in C4 grasses than respective non-trafficked *fairway* plots, while in trafficked *rough* plots PGC averaged 26% lower in C3 and 42% lower in C4 grasses than respective non-trafficked *rough* plots. At the end of the 41-day drought in 2016, PGC in trafficked *fairway* plots averaged 6% lower in C3 and 27% lower in C4 grasses than respective non-trafficked *fairway p*lots, while PGC in trafficked *rough* plots averaged 36% lower in C3 (excluding Kentucky bluegrass) and 44% lower in C4 grasses than respective non-trafficked *rough* plots. Therefore, traffic stress during a drought period may be more apparent on higher mowed turfgrass.

In both years, the only statistical differences in PGC between traffic treatments at 4 days of drought (16 traffic passes applied) occurred in the rough-height buffalograss and no other turf species (Fig. 3.3 and 3.4). This may have occurred due to traffic applied to the buffalograss at rough height caused a matting of the turfgrass leaves, thus loss of green cover (personal observation). Trafficked rough height buffalograss continued to decline in PGC until 18 to 25 days, then started to increase in PGC.

The highest PGC and VQ in non-trafficked turfgrass at the end of the 41-day drought were in the two C4 grasses in both years (Fig. 3.3, 3.4, 3.5, and 3.6). More specifically, in 2015 the highest PGC at the end of the drought was 85.6% and 93.6% at the fairway and rough heights, respectively, in non-trafficked zoysiagrass; buffalograss and perennial ryegrass followed closely, ranging from 78.8 to 84.9% (Fig. 3.3). In 2016, the highest PGC at the end of the drought was in non-trafficked buffalograss, with 76.7% and 84.5% at the fairway and rough heights, respectively, and zoysiagrass was not far off at 75.6% and 77.6% at the fairway and rough heights, respectively (Fig. 3.4). In both years, non-trafficked buffalograss at both the fairway and rough heights had the highest VQ at the end of the drought period with ratings from 7.3 to 8.9; zoysiagrass plots receiving no traffic were next highest from 6.3 to 6.9 (Figs. 3.5 and 3.6).

In 2015, the highest PGC in trafficked plots at the end of the drought was in perennial ryegrass with 62.5% and 50.8% at the fairway and rough heights, respectively (Fig. 3.3). However, both trafficked buffalograss with 57.3% and 46.7% at the fairway and rough heights, respectively, and trafficked zoysiagrass with 58.7% and 48% at the fairway and rough heights, respectively, followed closely within each mowing height (Fig. 3.3). Trafficked Kentucky bluegrass had considerably lower PGC with 22% and 17.9% at the end of the drought (Fig. 3.3). In 2016, across all plots receiving traffic, it was quite clear that PGC was highest in buffalograss at both the fairway and rough heights at the end of the drought with 57.7% and 48.8%, respectively (Fig. 3.4). At the end of the drought in 2016, trafficked zoysiagrass had 41% and 25.7% at fairway and rough heights, respectively; trafficked perennial ryegrass had 9% and 8% at fairway and rough heights, respectively; and trafficked Kentucky bluegrass had 13% and 0.1% at fairway and rough heights, respectively (Fig. 3.4). For trafficked plots, again buffalograss exhibited the highest VQ at the end of the drought period in both years and at both the fairway and rough heights with ratings from 5.2 to 7.5; zoysiagrass was next highest with ratings from

4.3 to 5.5; and trafficked C3 grasses ranged from 1 to 3.8 (Figs. 3.5 and 3.6). The ability of buffalograss to maintain higher θ_v as the drought period progressed may have influenced its ability to maintain higher VQ and PGC during the drought period. In both years, regardless of mowing height or traffic treatment, PGC of buffalograss at 18 to 25 days of drought began to increase as the drought progressed (Fig. 3.3 and 3.4). The higher θ_v, excellent drought resistance, extensive root system, and osmotic adjustment ability of buffalograss may have been contributing factors (Huang, 1999; Qian and Fry, 1997; Qian et al., 1997).

Non-trafficked buffalograss and zoysiagrass maintained acceptable VQ ($\geq$ 6 rating) at both mowing heights for the entire 41-day drought in both years. Whereas, across both years, non-trafficked Kentucky bluegrass and perennial ryegrass both maintained acceptable VQ for an average 22 days at fairway height and 18 days and 29 days, respectively, at rough height. Across both years at fairway height, VQ was acceptable in trafficked Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass for an average of 18, 22, 41, 33 days, respectively, and for an average of 15, 18, 22, 22 days, respectively, at trafficked rough height. Our findings that traffic during drought will accelerate the decline in PGC and VQ is similar to that of a comparable traffic study (Hejl et al., 2016). Those authors reported that summer foot-traffic on fairway height 'Tifway' bermudagrass [*Cynodon dactylon* var. *dactylon* x *C. transvaalensis* Burt-Davy] reduced PGC and VQ at varying deficit irrigation levels, including an unirrigated treatment, although all plots still received any occurring rainfall.

Recovery

At the start of the recovery period, PGC and VQ quickly increased after irrigation began (Figs. 3.3, 3.4, 3.5, 3.6). During the 6 measurement dates of the 2015 recovery, differences in PGC between traffic treatments within the fairway mowing height in Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass were significant at 0, 1, 1, 1 dates, respectively, while differences between traffic treatments within the rough height were significant at 0, 2, 1, 2, dates, respectively (Fig. 3.3). During the 6 measurement dates of the 2016 drought, PGC differences between traffic treatments within the fairway mowing height in Kentucky bluegrass, perennial ryegrass, buffalograss, and zoysiagrass were significant at 0, 0, 0, 2 dates, respectively, while differences between traffic treatments within the rough height were significant at 0, 2, 3, 1 dates, respectively (Fig. 3.4). A similar trend in the recovery period was observed for VQ ratings (Figs. 3.5 and 3.6). The one-to-two more dates of statistical differences that occurred between traffic treatments in the C4 grasses was due to the larger separations in PGC and VQ, mentioned above, which developed during the drought. Therefore, the trafficked C4 grasses required longer to return to similar PGC and VQ ratings as respective non-trafficked plots. However, trafficked C4 grasses were either already above acceptable VQ at the start of the recovery period or if below acceptable VQ then recovered faster than C3 grasses (Figs. 3.5 and 3.6). More specifically, across both years, C4 grasses in both traffic treatments were already at an acceptable VQ ($\geq$ 6 rating) at the start of the recovery period, with two minor exceptions. Namely, it required 12 days for trafficked zoysiagrass to recover to acceptable VQ at rough height in 2015 and at fairway height in 2016 (Fig. 3.5 and 3.6). Meanwhile, trafficked C3 grasses averaged 31 days to recover to acceptable VQ, while non-trafficked C3 grasses averaged 28 days to recover. This trend of recovery was similar to PGC measurements (Figs. 3.3 and 3.4). Across both years trafficked C4 grasses averaged 12 days to recover to 75% PGC, while non-trafficked C4 grasses were already above 75% PGC at the start of the recovery. One exception was non-trafficked buffalograss at fairway height in 2015, which required 12 days to recover to 75% PGC. Across both years, C3 grasses subjected to traffic averaged 23 days to recover to 75% PGC, while non-trafficked C3 grasses averaged 18 recovery days (Figs. 3.3 and 3.4). The time required for non-trafficked Kentucky bluegrass at both heights in 2015 and non-trafficked Kentucky bluegrass at fairway height in 2016 to recover based on PGC and VQ was similar to the reported three-week recovery time observed in past drought research conducted on Kentucky bluegrass, which implies a period of three to four weeks may be required for drought-stressed Kentucky bluegrass to recover (Leksungnoen et al., 2009). Consistent with past drought research, the turfgrasses with the slowest loss of green cover (buffalograss and zoysiagrass in our study) typically recovered faster upon rewatering (Karcher et al., 2008; Steinke et al., 2010).

The performance and recovery of the C3 grasses Kentucky bluegrass and perennial ryegrass varied from year to year, although PGC and VQ were typically higher in perennial ryegrass than Kentucky bluegrass within each mowing height in both years. Past drought research on these two species has reported inconsistencies (Chai et al., 2010; Minner and Butler, 1985). Chai et al. (2010) reported better drought survival and recovery via VQ in Kentucky bluegrass than perennial ryegrass, whereas, Minner and Butler (1985) reported cultivars of perennial ryegrass performed better than Kentucky bluegrass during drought and recovery. In our study, PGC and VQ were typically higher in perennial ryegrass during drought and also recovered faster than Kentucky bluegrass within each mowing height x traffic combination in 2015. In 2016, non-trafficked and trafficked perennial ryegrass at the rough height performed better and recovered faster than Kentucky bluegrass.

Interestingly, PGC and VQ declined rapidly in Kentucky bluegrass at rough height regardless of traffic treatment, with an atypical slow recovery in 2016 (Figs. 3.4 and 3.6). This phenomenon was not observed among any of the other turf species in either year. More specifically, in 2015, rough height Kentucky bluegrass declined to below 50% PGC at 41 days of drought in non-trafficked plots and 25 days in trafficked plots. Whereas, in 2016, rough height Kentucky bluegrass had declined to below 50% PGC at 18 days in non-trafficked plots and 11 days in trafficked plots and reached considerably lower PGC values by the end of the drought. A similar trend was observed in the VQ ratings. One possible reason for this difference between years may be due to a cumulative effect from repeating the drought on the same turf plots as the previous year, therefore possibly a reduction in carbohydrate reserves in 2016. The other C3 turf plots, including Kentucky bluegrass at fairway height and perennial ryegrass at both heights, exhibited a slight reduction in performance and recovery in 2016 as well. However, this trend was not observed in C4 grasses, and buffalograss actually had better performance and recovery in 2016 than in 2015. Another possible reason for poor performance in rough height Kentucky bluegrass in 2016 may be the slightly higher air temperatures during the drought in 2016 than in 2015, as mentioned above (Table 3.1). Although soil moisture in all turf was maintained at adequate levels prior to the drought in both years, the higher air temperatures during June 2016 could have led to Kentucky bluegrass at rough height experiencing more heat stress prior to the drought period than in 2015. Therefore, in 2016, Kentucky bluegrass may have started the drought period with a less healthy turf stand and possibly weaker root system. When compared to the 2015 baseline period values, PGC and VQ ratings were considerably lower in 2016, confirming a less healthy turf stand prior to the start of drought in 2016 (Appendix Tables B.8, B.9, B.10, B.11). This phenomenon was only observed at rough height in Kentucky bluegrass, and none of the other turf species. However, the PGC in rough-height Kentucky bluegrass began to increase at the end of the 40-day recovery period (Fig. 3.4). Based on past research by Goldsby et al. (2015), if a longer recovery period was made available in my study, it may have likely recovered to 75% or higher PGC. Unfortunately, continued measurement of the recovery past the 40-day period in 2016 was not possible due to a new research project was planned to be established under the stationary drought shelter.

Turf Firmness

Turf firmness was measured in each turf plot to evaluate the effects of treatments on the firmness (surface hardness) of the turfgrass. Out of the 11 measurement dates in 2015, there were two to four more dates with statistical differences among the mowing height x traffic treatment interactions within Kentucky bluegrass and zoysiagrass turf species than buffalograss and perennial ryegrass (Fig. 3.7). In 2016, all 13 measurement dates had statistical differences among the mowing height x traffic treatment interactions within each turf species, except four dates for Kentucky bluegrass (Fig. 3.8).

Across both years, the general trend in all four species at each mowing height and traffic interaction was that the surface became more firm as the drought period progressed and θ_v decreased, and also as cumulative traffic passes increased (Figs. 3.7 and 3.8). In both years, within each turfgrass species the lower fairway mowing height resulted in a firmer surface than the higher mowing height, in respect to each traffic treatment. Also, there were more statistical differences between traffic treatments within the higher rough mowing height than the fairway height, this was more evident in 2016 due to more measurement dates (Figs. 3.7 and 3.8). Therefore, the turf firmness was more impacted by traffic in the rough mowing height than in the fairway height. However, these turf firmness values in all plots were quickly alleviated and a deeper depth of travel (softer surface) was achieved immediately after the start of the recovery period, most likely due to the rewetting of the soil surface with irrigation.

In both years, turf firmness was within a similar range among Kentucky bluegrass, perennial ryegrass, and buffalograss at each comparative traffic x mowing height combination during the drought and recovery period (i.e., 7.5 to 23 mm) (Figs. 3.7 and 3.8). However, zoysiagrass generally resulted in a softer surface compared to the other turf species at each respective treatment combination during both the drought and recovery periods in both years. This may be because zoysiagrass had a thicker thatch layer than the other turf species, based on personal observations.

Dunn et al. (1994) reported a 36% to 74% increase in surface hardness readings by the Clegg Impact Soil Tester (CIST) on trafficked compared to non-trafficked turf, with the highest ratings occurring at lower soil moisture levels. The Clegg Impact Soil Tester (also called Clegg

Hammer or Clegg Decelerometer) is used to obtain a measurement of the deceleration of a free-falling hammer from a set height onto a surface under test to determine hardness via an electric pulse. The instrument used in my study is a slightly newer instrument, but is essentially measuring the same variable as the CIST. The turf firmness meter uses a hemisphere-shaped hammer to measure maximum penetrating depth (displayed in 1/100th of an inch readings). Turf firmness measures maximum penetrating depth, while CIST measures deceleration upon impact. Past research has shown there is a strong negative linear and non-linear (exponential decay model) relationship between measurements from the two instruments (O'Brien et al., 2014). Results from my study are consistent with findings from other research. For example, Rogers and Waddington (1990) reported decreased peak deceleration (softer surface) with increasing soil moisture levels. Peak deceleration also decreased with increasing thatch and turf cover (Dunn et al., 1994; Rogers and Waddington, 1992). The cushioning effect of thatch not only creates a softer turf surface, but may also increase wear tolerance (Beard, 1973), which may have contributed to better performance of zoysiagrass while under traffic stress in my study.

Conclusions

Overall, buffalograss consistently maintained the highest soil moisture 0 to 7.6 cm depth among species during the 41-day drought. The trends in VQ within treatments were similar to PGC. Overall, across all four turf species, PGC and VQ declined as drought stress progressed, which was accelerated by traffic stress. The effects of traffic stress were more apparent, with greater differences in PGC and VQ values between traffic treatments in the two C4 than in the C3 grasses. This was because no traffic treatments in C4 grasses maintained high PGC and VQ throughout the drought due to better drought tolerance than the C3 grasses. The fairway mowing height displayed fewer differences between traffic treatments compared to rough mowing height within each turf species; therefore, traffic stress during a drought period may be more apparent on higher mowed turfgrass. The C4 grasses maintained and usually ended the 41-day drought with higher PGC and VQ in both traffic treatments and mowing heights than the C3 grasses. Consequently, C4 grasses recovered faster to higher PGC and VQ than C3 grasses. The ability of buffalograss to maintain higher soil moisture during drought may have improved its ability to maintain higher VQ and PGC than the other species. Overall, as θ_v decreased, the surface of the turf species became more firm, especially at the lower mowing height. This effect was enhanced by the application of traffic. The influence of traffic on turf firmness will depend on a variety of soil factors such as soil moisture and turf species. The turf firmness may affect playability or the safety of the surface; therefore, it is an important factor to consider during times of drought. Overall, traffic application during drought will have negative and accelerated impacts on the above-ground portion of turfgrass, which will vary with turf species and mowing height. Further research on the combined effects drought and traffic stress on the above-ground turf variables should be conducted on additional turf species, especially turf species that are known to have improved drought resistance. Also, future research should investigate different mowing heights, traffic application intensities, and various lengths of drought.

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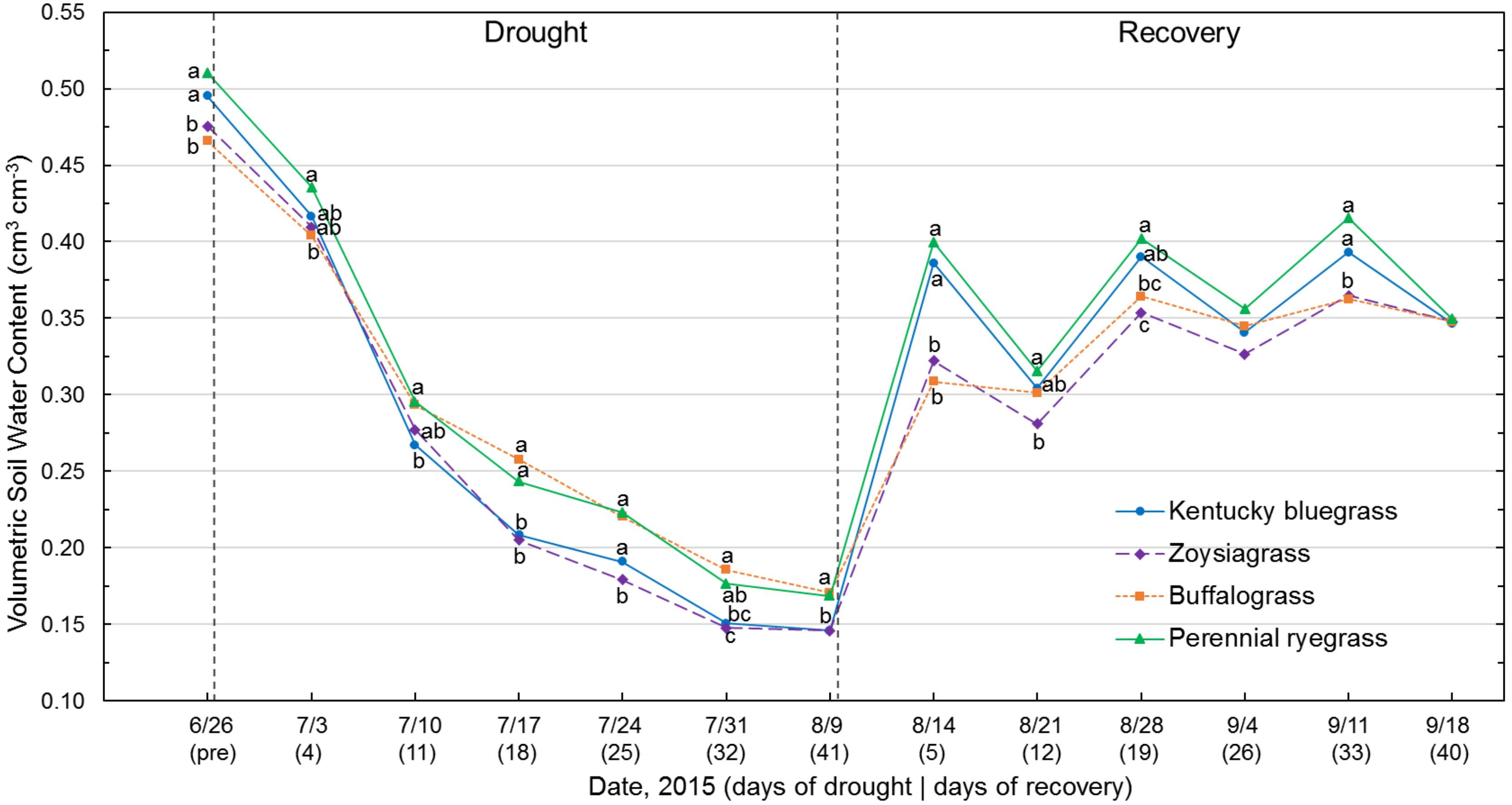

Figure 3.1. Effect of turf species x date interaction sliced by date on volumetric soil water content (θ_v, cm^3 cm^{-3}) at 0 to 7.6 cm in Kentucky bluegrass, zoysiagrass, buffalograss, and perennial ryegrass in 2015. Drought consisted of a 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Baseline, drought, and recovery periods were analyzed separately. Means are average over four blocks, two mowing heights, and two traffic treatments. At baseline (26 June), means with the same letter are not significantly different according to Tukey's HSD test ($P \leq 0.05$). At all other dates, means with the same letter are not significantly different at $\alpha_{\text{bon}} = 0.001389$.

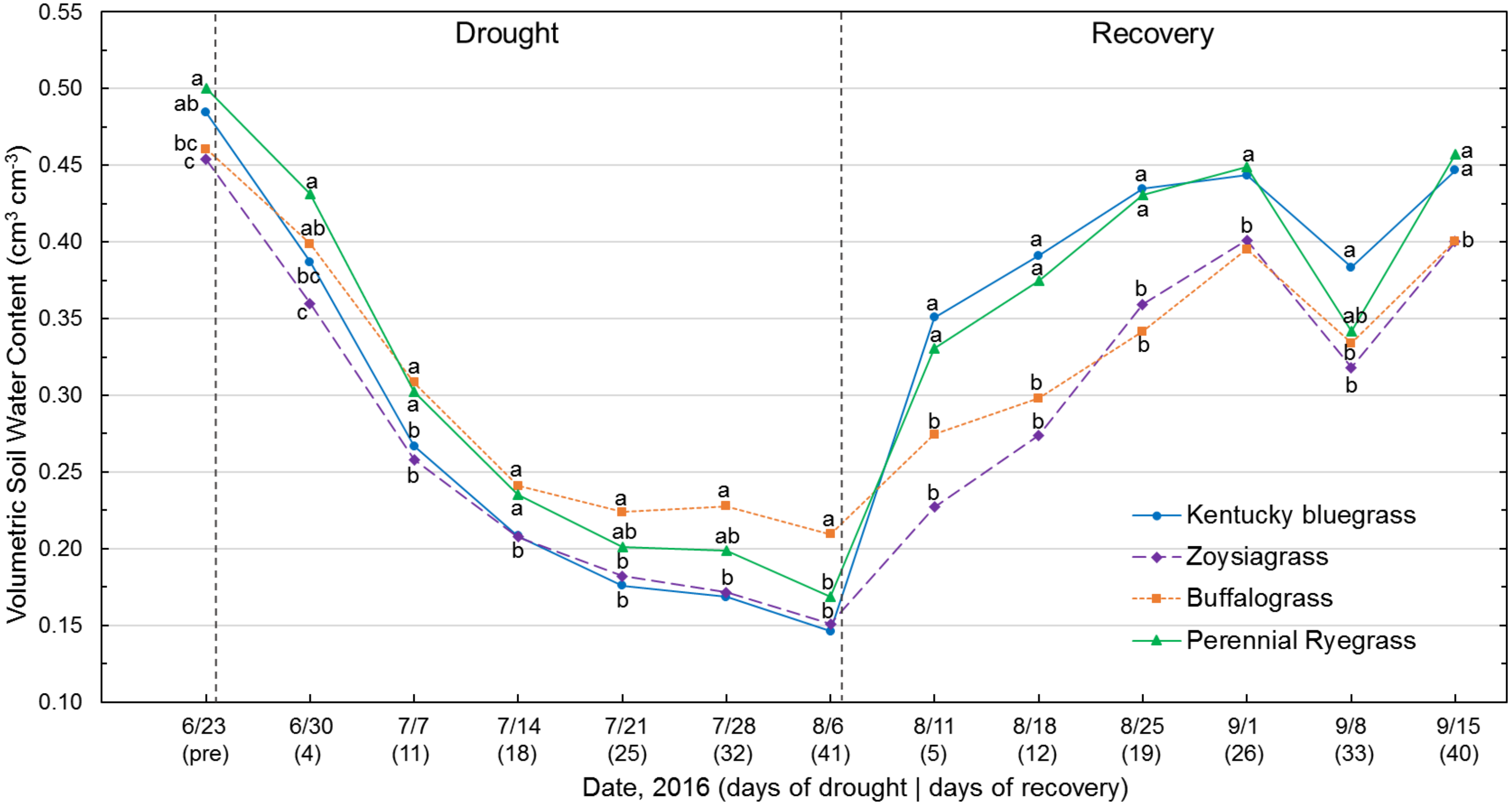

Figure 3.2. Effect of turf species x date interaction sliced by date on volumetric soil water content (θ_v, cm^3 cm^{-3}) at 0 to 7.6 cm in Kentucky bluegrass, zoysiagrass, buffalograss, and perennial ryegrass in 2016. Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Baseline, drought, and recovery periods were analyzed separately. Means are average over four blocks, two mowing heights, and two traffic treatments. At baseline (23 June), means with the same letter are not significantly different according to Tukey's HSD test ($P \leq 0.05$). At all other dates, means with the same letter are not significantly different at $\alpha_{\text{bon}} = 0.001389$.

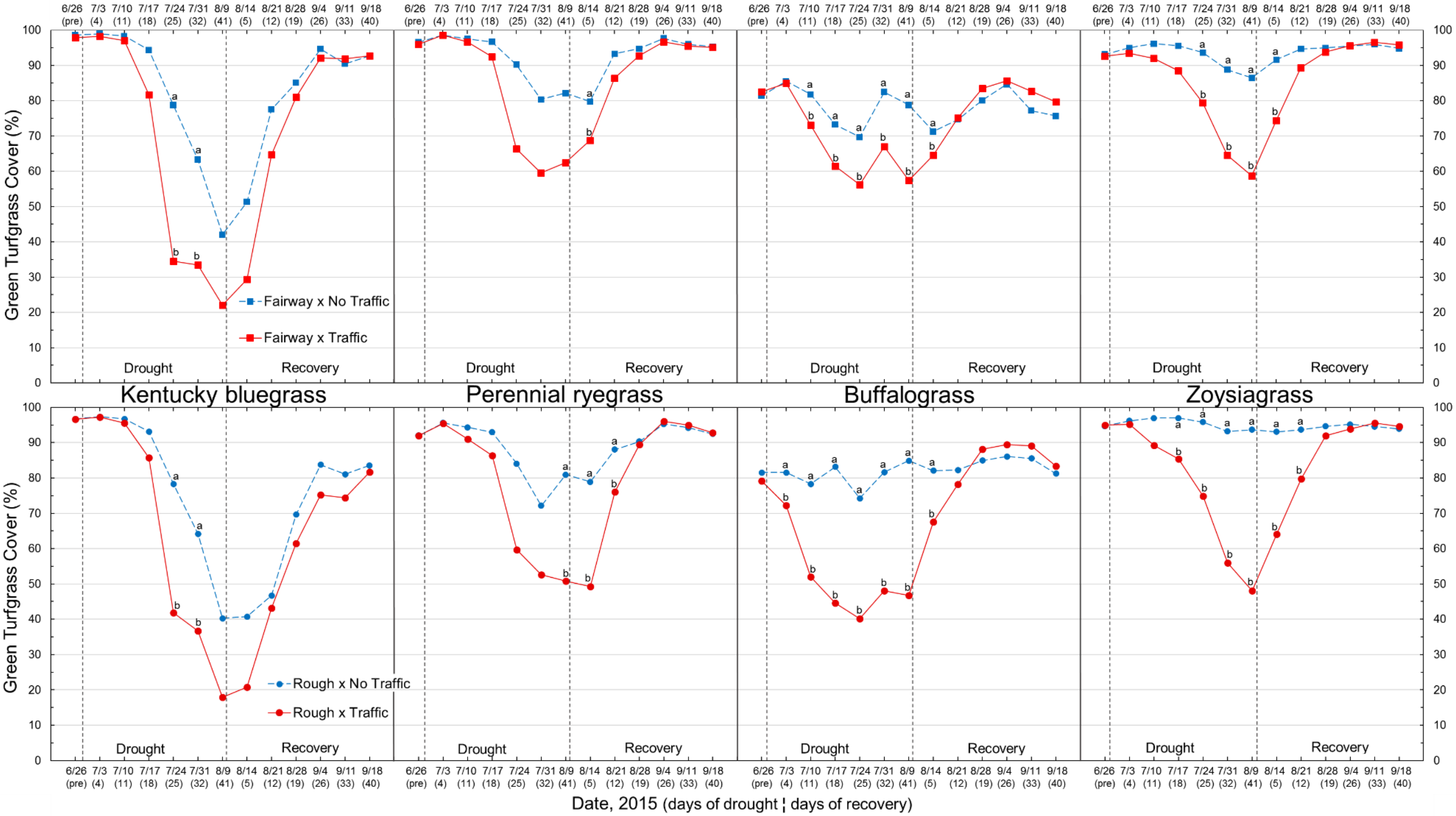

Figure 3.3. Comparison of percent green turfgrass cover (%) between traffic treatments sliced by turf species, mowing height, and date in 2015. Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Baseline (26 June), drought (3 July to 9 Aug), and recovery (14 Aug. to 18 Sept.) periods were analyzed separately. At each date, within each mowing height of each turf species, means with the same letter or no letters are not significantly different at $\alpha_{\mathrm{bon}} = 0.00625$ for 26 June and $\alpha_{\mathrm{bon}} = 0.001$ for 3 July through 18 Sept.

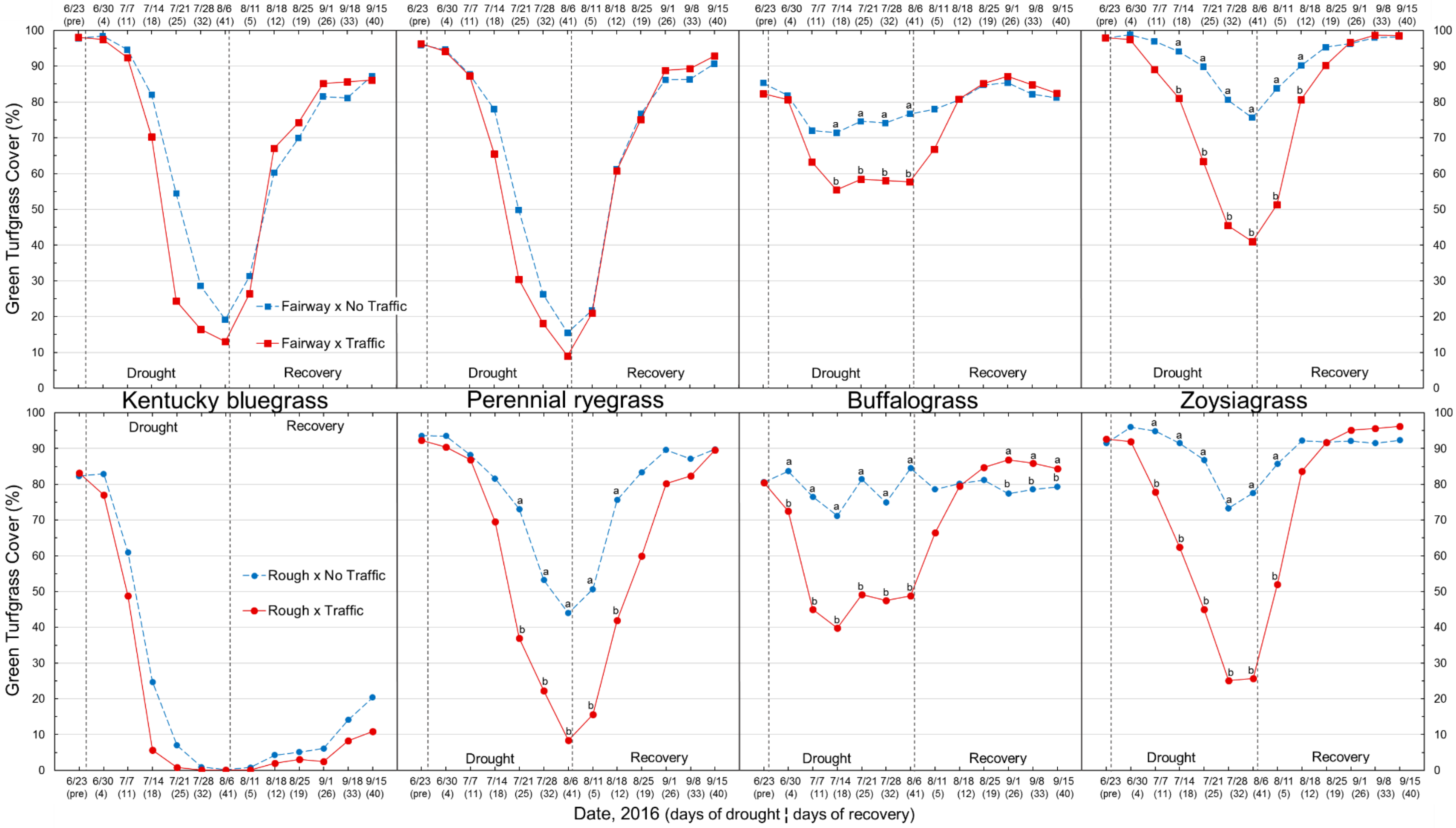

Figure 3.4. Comparison of percent green turfgrass cover (%) between traffic treatments sliced by turf species, mowing height, and date in 2016. Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Baseline (23 June), drought (30 June to 6 Aug), and recovery (11 Aug. to 15 Sept.) periods were analyzed separately. At each date, within each mowing height of each turf species, means with the same letter or no letters are not significantly different at $\alpha_{bon} = 0.00625$ for 23 June and $\alpha_{bon} = 0.001$ for 30 June through 15 Sept.

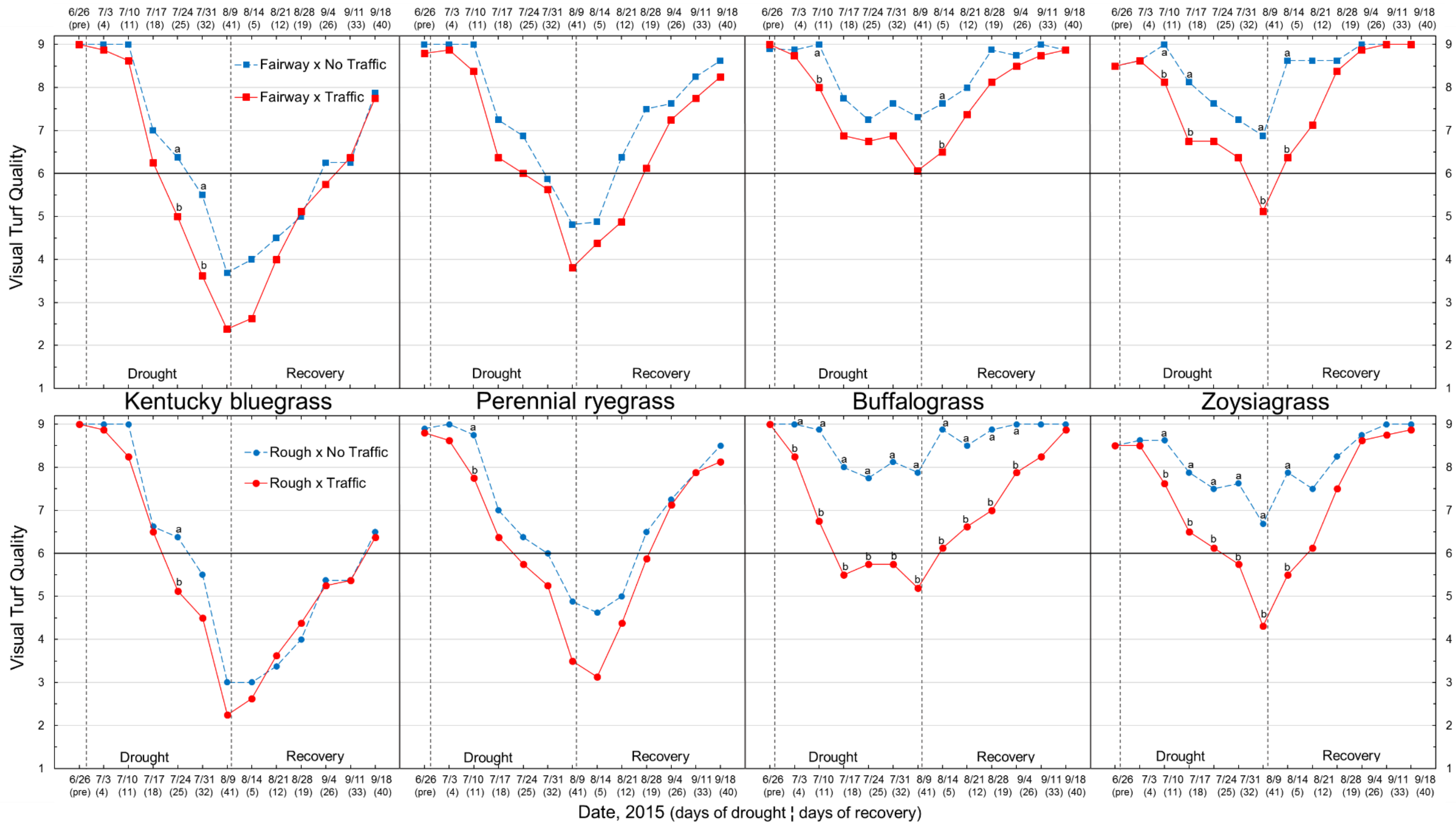

Figure 3.5. Comparison of visual turf quality between traffic treatments sliced by turf species, mowing height, and date in 2015. Visual turf quality was rated and averaged on a 1 to 9 scale (1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality). Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Solid horizontal black line signifies minimum rating for acceptable turf quality. Baseline (26 June), drought (3 July to 9 Aug), and recovery (14 Aug. to 18 Sept.) were analyzed separately. At each date, within each mowing height of each turf species, means with the same letter are not significantly different at $\alpha_{bon} = 0.00625$ for 26 June and $\alpha_{bon} = 0.001$ for 3 July through 18 Sept.

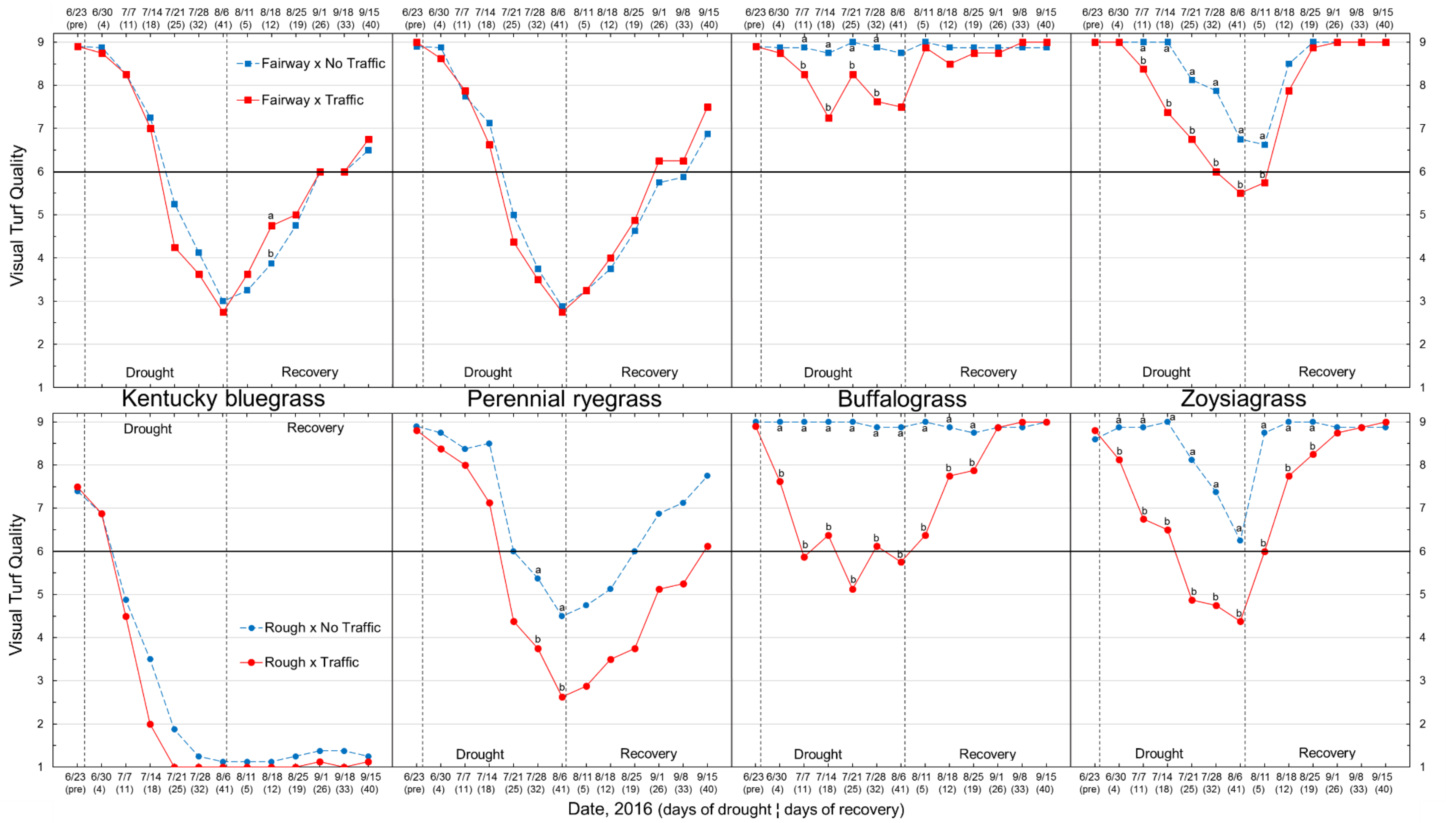

Figure 3.6. Comparison of visual turf quality between traffic treatments sliced by turf species, mowing height, and date in 2016. Visual turf quality was rated on a 1 to 9 scale (1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality). Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Solid horizontal black line signifies minimum rating for acceptable turf quality. Baseline period (23 June), drought period (30 June to 6 Aug), and recovery period (11 Aug. to 15 Sept.) were analyzed separately. At each date, within each mowing height of each turf species, means with the same letter are not significantly different at α_{bon} = 0.00625 for 23 June and α_{bon} = 0.001 for 30 June through 15 Sept.

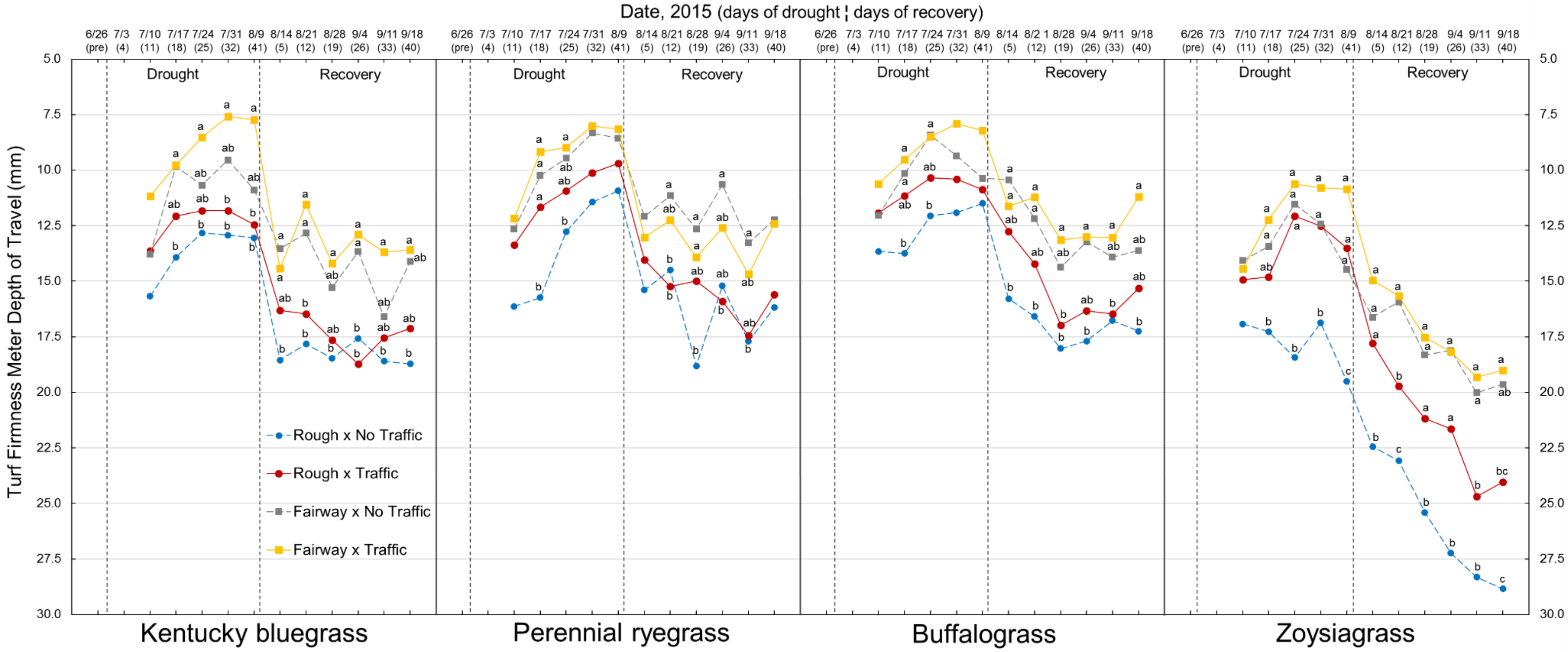

Figure 3.7. Comparison of turf firmness (depth of travel, mm) between mowing height x traffic treatments sliced by turf species and date in 2015. Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Drought (3 July to 9 Aug), and recovery (14 Aug. to 18 Sept.) were analyzed separately. At each date, within each turf species, means with the same letter are not significantly different at $\alpha_{bon} = 0.000417$ for 10 July through 9 Aug. and $\alpha_{bon} = 0.000347$ for 14 Aug. through 18 Sept.

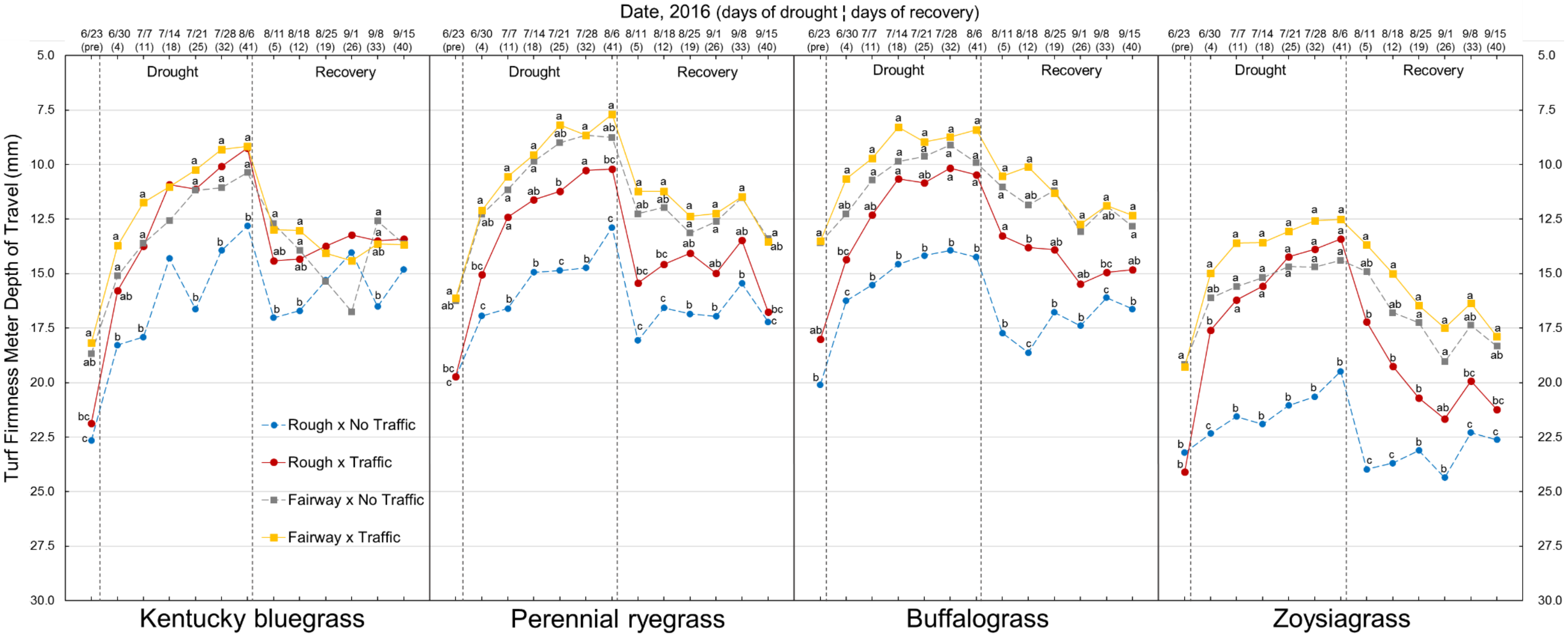

Figure 3.8. Comparison of turf firmness measurements (depth of travel, mm) between mowing height x traffic treatments sliced by turf species and date in 2016. Drought consisted of 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 passes by the end of the drought. Recovery consisted of 40-days with no traffic and turfgrasses kept well-watered. Baseline (23 June), drought (30 June to 6 Aug), and recovery (11 Aug. to 15 Sept.) were analyzed separately. At each date, within each turf species, means with the same letter or no letters are not significantly different at $\alpha_{\mathrm{bon}} = 0.00208$ for 23 June and $\alpha_{\mathrm{bon}} = 0.000347$ for 30 June through 15 Sept.

Table 3.1. Monthly maximum, minimum, and mean air temperatures from Aug. 2014 through Sept. 2016 from an on-site weather station and 30-year climate monthly normals.

	Monthly Mean Temperature (°C)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2014												
Min	--	--	--	--	--	--	--	19.6	13.7	7.2	-4.3	-2.7
Max	--	--	--	--	--	--	--	32.6	26.6	21.5	9.7	5.7
Mean	--	--	--	--	--	--	--	26.1	20.1	14.4	2.7	1.5
2015												
Min	-8.9	-9.6	-0.3	6.9	11.8	18.4	20.7	17.3	17.2	8.0	2.5	-2.4
Max	6.7	3.7	16.2	20.2	22.8	30.5	31.6	30.4	29.4	21.9	15.9	9.1
Mean	-1.1	-2.9	7.9	13.5	17.3	24.4	26.2	23.9	23.3	14.9	9.2	3.3
2016												
Min	-6.4	-3.4	2.1	7.2	11.0	19.4	21.2	19.4	16.0	--	--	--
Max	4.2	11.5	17.9	20.8	23.6	32.5	32.0	30.2	28.2	--	--	--
Mean	-1.1	4.1	10.0	14.0	17.3	26.0	26.6	24.8	22.1	--	--	--
Climate Monthly Normals												
Min	-8.1	-5.9	-0.9	5.4	12.0	17.2	20.2	18.8	13.2	6.2	-0.7	-6.7
Max	4.8	8.1	13.9	19.6	24.8	30.1	33.1	32.3	27.7	20.9	13.0	5.8
Mean	-1.6	1.1	6.4	12.5	18.4	23.7	26.6	25.6	20.4	13.6	6.2	-0.4

Chapter 4 - Performance and Recovery of Turfgrasses Subjected to Drought and Traffic Stresses: Soil and Root Aspects

Abstract

During drought, turfgrass on golf courses continues to receive vehicular or foot traffic. Drought resistance and traffic tolerance in turfgrasses have been investigated separately. My objectives were to evaluate soil impacts and root responses of two cool-season (C3) [Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.)] and two warm-season (C4) grasses {buffalograss [*Buchloe dactyloides* (Nutt.) Engelm] and zoysiagrass *(Zoysia japonica* Steud.)} at golf course-related mowing heights [1.6-cm (fairway) and 6.4-cm (rough)], with and without simulated traffic during a simulated drought and subsequent recovery period (without traffic). Measurements included gravimetric soil water content (*w*) and soil bulk density (ρ_b), both at 0-6 cm, soil penetration resistance (SPR) at five depths from 0-10.16 cm, and root biomass, root length density, average root diameter, and root surface area at 0-30.5 cm depth. Buffalograss had higher *w* at the end of drought. During drought, SPR at deeper depths and more commonly in fairway plots increased and exceeded the critical value of 2.0 MPa. After recovery, SPR returned to a similar range as the pre-drought period. The decreasing soil moisture due to drought led to a minimal impact from traffic on ρ_b, SPR, and root measurements. The two C3 grasses had higher root biomass, surface area, and root length density in the upper soil profile than the two C4 grasses at the end of 41-day drought. However, buffalograss, zoysiagrass, and perennial ryegrass had larger root diameters, which may have led to better soil compaction resistance and greater capabilities of exploring deeper depths, thus better drought performance than Kentucky bluegrass. Most differences within soil and root measurements were due to the effects of drought stress, while the traffic main effect was not significant across all below-ground measurements. Therefore, turf managers may see minimal impacts on soil and root characteristics from traffic application during a drought period. Further research is recommended to attain better understanding of the combined effects of drought and traffic stress on soil impacts and root responses of turfgrasses.

Introduction

Irrigation of turfgrass areas during periods of drought has become more restricted and negatively viewed by the public. During periods of severe drought and water shortages, turfgrass may receive little to no irrigation for extended spans of time. Drought resistance and recuperative potential of turfgrass species has been researched extensively in the past. Overall, drought resistance is a combination of the plant's ability to avoid and tolerate drought (Fry and Huang, 2004). The ability to maintain quality during drought stress, typically by deep rooting, is referred to as drought avoidance, whereas the ability to recover after experiencing symptoms of drought stress is referred to as drought tolerance (Fry and Huang, 2004). In general, the warm-season (C4) turfgrass species have better resistance to drought stress than cool-season (C3) species due to their more efficient photosynthetic pathway, lower evapotranspiration (ET) rates, higher levels of osmotic adjustment, higher cell wall elasticity, and better tolerance to low leaf relative water content, all of which provide better drought resistance than C3 grasses (Beard, 1973; Beard and Kenna, 2008; Biran et al., 1981; Fu et al., 2004; Fry and Huang, 2004; Huang and Fry, 1999; Kim and Beard, 1988; Meyer and Gibeault, 1986; Qian and Fry, 1997). Common aboveground responses to drought stress include a decrease in turf quality, growth vigor (clipping yield), verdure, shoot density, tillering, and color (greenness); and an increase in leaf wilt, firing, and canopy temperatures. For more information on above-ground responses see Chapter 3. Differences have also been reported among turf species in root production and viability during drought stress (Aronson et al., 1987; Beard, 1973; Carrow, 1996a, 1996b; Huang et al., 1997a, 1997b; Minner and Butler, 1985; Su et al., 2008).

One plant mechanism that is known to help avoid drought conditions is the ability to produce deep roots (Levitt, 1980). Root growth and function are significantly impacted due to dry-down of soil surface layer (Smucker et al., 1991). When cultivars of tall fescue (*Festuca arundinacea* Schreb. Syn *Schedonorus arundinaceus* Schreb.) were exposed to moderate drought stress during a two-year field study in Griffin, GA, greater root length densities deeper in the soil profile at the 20-60 cm depth were associated with less leaf firing and wilt, whereas greater root length density in the upper soil profile at the 3-10 cm depth related to greater leaf firing and wilt (Carrow, 1996a). As the upper profile of the soil dries, some turf species may increase root production at deeper depths. Carrow (1996b) reported a 25-fold difference in root length density at 20-60 cm depth across seven turfgrass species. Differences in rooting among species and/or cultivars has been observed under both well-water conditions and fully-dried conditions (Carrow, 1996a, 1996b; Ensign and Wiser, 1975; Hays et al., 1991; Huang, 1999; Lehman and Engelke, 1991; Leksungnoen et al., 2009; Marcum et al., 1995a,1995b; Qian et al., 1997; Salaiz et al., 1991; Su et al., 2008).

Root elongation was greater with ‘Prairie’ buffalograss [*Buchloe dactyloides* (Nutt.) Engelm] than with ‘Meyer’ zoysiagrass (*Zoysia japonica* Steud.) under both well-watered or fully-dried soil profile conditions (Huang, 1999). Buffalograss has excellent drought resistance due to its deep, extensive root system and zoysiagrass has been shown to be more drought sensitive and possess a shallower root system than buffalograss (Huang, 1999; Marcum et al., 1995a, 1995b; Qian and Fry, 1997; Qian et al., 1997). Differences in root distribution may affect water uptake rates among turf species (Huang, 1999). ‘609’ Buffalograss (*Buchloe dactyloides)* and eight cultivars of bermudagrass [*Cynodon dactylon* (L.) Pers.] all survived a 60-day drought in San Antonio, TX grown on an unrestricted native silty clay soil, but neither survived when rooting was restricted to a 10-cm soil depth (Steinke et al., 2011). ‘Mustang’ tall fescue (*Festuca arundinacea*) produced 180 to 270% greater total root length from 0-120 cm than three C4 grasses in the greenhouse and 39 to 140% greater total root length from 0-90 cm than C4 grasses in the field in Manhattan, KS (Qian et al., 1997). Qian et al. (1997) also reported during the five 7- or 12-day precipitation-free periods in the field, tall fescue extracted 50% more soil water than bermudagrass and zoysiagrass at 90 cm, and buffalograss extracted 66% more soil water than zoysiagrass at 90 cm during one of the precipitation-free periods. Cathey et al. (2011) reported ‘Empire’ zoysiagrass [*Z. japonica* X Z. *matrella* (L.) Merr.], ‘Argentine’ bahiagrass (*Paspalum notatum* Flugge), and ‘Floratam’ St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] all extracted similar water amounts, although zoysiagrass had the lowest water use rate and less leaf firing under increasing drought stress than the other grasses. Therefore, although rooting depth and distribution play a major role in water uptake and drought avoidance, differences in water use rates among turf species also plays a major role in drought resistance.

Not only are there differences in rooting characteristics among turfgrass species, but also among cultivars within turf species. Differences in root production have been recorded among cultivars of tall fescue (Carrow, 1996a); creeping bentgrass (*Agrostis palustris* Huds.) (Lehman and Engelke, 1991; Salaiz et al., 1991); Kentucky bluegrass (*Poa pratensis* L.) (Ensign and

Weiser, 1975); buffalograss (Marcum et al., 1995a); zoysiagrass (Marcum et al., 1995b); and bermudagrass (Hays et al., 1991).

Differences have also been observed among turf species in rooting in well-watered plots. Su et al. (2008) reported differences in rooting characteristics from well-watered (100% ET replacement) plots, ‘Dynasty’ tall fescue (*Festuca arundinacea*) had higher root production at deeper depths (30-20 cm), while ‘Thermal Blue’ hybrid bluegrass (*Poa arachnifera* Torr. X *Poa pratensis*) had greater root length density and root surface area at shallow depths (0-30 cm) than ‘Dynasty’ tall fescue, ‘Apollo’ Kentucky bluegrass (*Poa pratensis*), and ‘Reveille’ hybrid bluegrass (*Poa arachnifera* X *Poa pratensis*) under a rainout shelter. However, the greater root length density and root surface area in the upper soil layer (0-30 cm) of ‘Thermal Blue’ hybrid bluegrass did not translate to better above-ground performance during water deficit (Su et al., 2008). Overall, turfgrasses with deeper rooting capabilities and greater root production are likely to retrieve more water from deeper in the profile and thus, will typically have an advantage during periods of drought (Huang et al., 1997b).

During drought, turfgrass areas such as golf courses generally continue to receive play from golfers. This results in vehicular or foot traffic stress to turfgrass during conditions of drought stress. However, little research has been conducted on the combined effects of drought and traffic stress. The National Golf Foundation estimated that 80,000 motorized golf carts were in use in 1963, by 1990 it increased to approximately 800,000 to 850,000 (Anonymous, 1964; Gast, 1991). In 2006, 69% of all rounds of golf in the United States were played with golf carts (Moeller, 2014). Golf cart traffic, regardless of golf cart type or tire design, can have immediate wear damage on turfgrass, especially if traffic frequency is high or traffic is applied by sharp-turns or semi-circle driving patterns (Carrow and Johnson, 1989; 1996). Two golfers using one golf cart has been estimated to increase the amount of turf area impacted by 48 times compared with walking golfers (Wienecke, 2004). For more details on traffic application methodologies in past turf research see Chapter 3.

Traffic stress can result in turfgrass wear damage, soil compaction, soil displacement, and turf removal or divots (Beard, 1973). Turfgrass wear damage from traffic stress greatly impacts the above-ground portion of the turfgrass and is discussed in more detail in Chapter 3, whereas the below-ground portion is more influenced by soil compaction.

When traffic stress is applied, it is very unlikely wear damage will occur without some degree of soil compaction as well. Soil compaction is the pressing of soil particles more tightly together, thus reducing pore space and creating a denser soil mass. In turfgrass systems, this typically occurs in the upper soil profile, near the surface. The intensity of soil compaction will be influenced by soil texture, soil structure, moisture content, particle-size distribution, plant factors, type of traffic applied, and frequency of pressure applied from traffic (Beard, 1973; Carrow and Petrovic, 1992). Soil compaction can be measured by soil bulk density (ρ_b) and soil penetration resistance (SPR) (syn. soil compaction or soil strength). A high ρ_b and/or SPR usually indicates high soil compaction due to low soil porosity, poor infiltration, restricted root growth and more. Compacted soil can affect plant health by restricting root growth penetration and growth, reducing soil aeration, nutrient uptake, and water movement (Beard, 1973; Carrow and Petrovic, 1992). Soil compaction will also reduce shoot growth, thus reducing the recuperative potential for a turfgrass that has been injured by wear (O'Neil and Carrow, 1983). Similar to wear damage, the effects of traffic stress on soil compaction can also be immediate but is more likely to be the outcome of long-term or high frequency traffic stress (Carrow and Johnson, 1996).

The soil water content at the time of traffic can play a large role in the amount of compaction, i.e. maximum compaction of the soil usually occurs when soil water content is near field capacity, the air-filled pores can be over-compressed due the water acting as a lubricant. As soil water content decreases below field capacity or increases above field capacity, the potential for soil compaction decreases (Lunt, 1952; Merkel, 1952; Swartz and Kardos, 1963). Boufford and Carrow (1980) confirmed this in a stand of 'Kentucky 31' tall fescue (*Festuca arundinacea*) subjected to traffic at different soil moisture levels. The highest bulk density measurements occurred at and below field capacity (24 and 72 hours after watering, respectively) compared to when the soil was at saturation or partial saturation (0 and 4 hours after watering, respectively) (Boufford and Carrow, 1980). Therefore, one may suspect that traffic application on drier soils, such as during drought, may have less of an impact on ρ_b and/or SPR, although further research is required. At medium to high soil moisture levels, turfgrass receiving traffic will likely increase in soil compaction (ρ_b and SPR) compared to turfgrass receiving no traffic. Higher values of SPR and ρ_b were reported in trafficked plots compared to non-trafficked plots of 'Barleroy' tall fescue (*Festuca arundinacea*), 'Bargreen II' chewings fescue (*Festuca rubra* L. subsp. *commutata*

Gaud.), 'Limousine' Kentucky bluegrass (*Poa pratensis*), and 'Bargold' perennial ryegrass (*Lolium perenne* L.), all under well-watered conditions (Głąb and Szewczyk, 2014).

Root length and concentration in the upper soil profile has decreased as ρ_b increased (Lipiec et al., 1991, 2003). The effects of traffic on the turfgrass root system may not be immediately evident after application of traffic, but may require time before detrimental effects are seen; this effect of traffic on soil compaction has be referred to as the "hidden effect" (Beard, 1973). When 0x, 12x, and 24x soil compaction treatments were applied to three C3 species, 'Pennfine' perennial ryegrass (*Lolium perenne*), 'Baron' Kentucky bluegrass (*Poa pratensis*), and 'Kentucky-31' tall fescue (*Festuca arundinacea*) maintained at 5.1 cm mowing height in Manhattan, KS reductions were seen in visual quality, percent turf cover, and total nonstructural carbohydrate as compaction traffic levels increased (Carrow, 1980). Perennial ryegrass was less affected by soil compaction than tall fescue and Kentucky bluegrass (Carrow, 1980). The only adverse effects on perennial ryegrass from soil compaction were a reduction in root weight, whereas Kentucky bluegrass exhibited reductions in verdure, shoot density, and root weight, and tall fescue in verdure (Carrow, 1980). Visual quality and percent turf cover were highly correlated with compaction tolerance, i.e. a higher compaction tolerance also had a higher visual quality rating (Carrow, 1980). However, an increase in compaction traffic resulted different root biomass responses within each turf species at two soil depth zones (0 to 10 cm and 10 to 20 cm), therefore, an increase in compaction traffic treatments did not always result in a decrease in root growth (Carrow, 1980). Thirty-five passes of traffic via a water filled, smooth power roller on 'Kentucky-31' tall fescue under different soil moisture levels resulted in a 39% reduction in root biomass at a 0-10 cm depth at four weeks after traffic was applied immediately after irrigating the turf area to a standing water condition [0-hour traffic treatment, 46.2% gravimetric soil water content (w)] compared to uncompacted (non-traffic) check (Boufford and Carrow, 1980). At four weeks after thirty-five traffic passes, root biomass at 0-10 cm was lower in the 0-hour treatment (traffic immediately applied after irrigating the turf to a standing water condition) (5.08 mg cm^{-3}) than the 24-hour treatment (traffic applied 24 hours after irrigating) (7.13 mg cm^{-3}), 72-hour traffic (7.27 mg cm^{-3}) and non-traffic check (8.31 mg cm^{-3}); while no statistical differences occurred at the 10-20 cm depth. At ten weeks after the traffic application, there were no statistical differences in root biomass among the treatments at both depths (Boufford and Carrow, 1980). Boufford and Carrow (1980) also reported a reduction in visual quality in compacted plots at 2, 6, and 10 weeks after traffic treatments, again this occurred in plots that had been subjected to traffic when the soil was saturated or near field capacity.

Głąb and Szewczyk (2014) investigated the effects of traffic from a Brinkman traffic simulator on 'Barleroy' tall fescue, 'Bargreen II' chewings fescue, 'Limousine' Kentucky bluegrass, and 'Bargold' perennial ryegrass maintained at 2.5 cm mowing height under well-water conditions. At 0-15 cm there was less root biomass in trafficked plots (6.80 mg cm^{-3}) than non-trafficked plots (7.99 mg cm^{-3}) (Głąb and Szewczyk, 2014). Regardless of traffic treatment, tall fescue and perennial ryegrass had the highest root biomass at 0-15 cm (Głąb and Szewczyk, 2014). Traffic reduced root length densities in tall fescue and Kentucky bluegrass, but not in chewings fescue or perennial ryegrass. Głąb and Szewczyk (2015) reported that wear tolerance of turfgrasses was better estimated by using turf cover ratings, although turfgrasses with a higher root biomass, root surface area, and average root diameter also had improved wear tolerance, with root length density of perennial ryegrass cultivars being positively correlated to wear tolerance.

Overall, the effects of traffic stress can take many different forms, one being the "hidden effect" of soil compaction. Soil compaction can negatively affect the overall health and vigor of the turfgrass. The majority of the previously mentioned traffic studies have been conducted during well-watered conditions, with minimal investigation into the effects of traffic during dry conditions, typically experienced during drought periods. Therefore, the combined effects of drought and traffic stresses on turf species needs to be further investigated to understand how the soil and root systems are affected to help develop possible management decisions.

Therefore, my objectives were to evaluate the impacts on soil from, and the responses of roots to golf cart traffic on both C3 and C4 turfgrass species maintained at two golf course related heights (fairway- and rough-height) during a simulated drought and subsequent recovery period (without traffic) using a stationary drought shelter.

Materials and Methods

Study Site

This field experiment was conducted in 2015 and 2016 at the Rocky Ford Turfgrass Research Center, Manhattan, KS (lat. 39° 13' 53" N, 96° 34'51" 6 W). The soil was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls). Field plots under an existing stationary rainout shelter were established in September 2014. The rainout shelter was a commercial greenhouse design (Thermolator; Agra Tech Inc., Pittsburg, CA) with a 0.15 mm clear greenhouse film (Warp's Flex-O-Glass® Greenhouse Films - 6 Mil 4-Year UV Clear Film, Warp Bros., Chicago, IL) installed for each 41-day simulated-drought period on 30 June 2015 and 27 June 2016 and removed on 10 Aug. 2015 and 7 Aug. 2016. For rainout shelter dimensions and details see Chapter 3.

Treatments

Sixty-four plots measuring 1.83 x 1.37 m each included 4 replicates of each treatment combination. This study was a 4-way factorial treatment design. The turfgrass main effect included: 1) 'America' Kentucky bluegrass (*Poa pratensis)*, 2) 'Paragon GLR' perennial ryegrass *(Lolium perenne)*, 3) 'Sharps Improved II' buffalograss (*Buchloe dactyloides*), and 4) 'Meyer' zoysiagrass with each species being randomly assigned to a "column" within each block. The mowing height main effect consisted of: 1) fairway- (1.6 cm) and 2) rough-height (6.3 cm), each randomly assigned to a "row" within each block. The traffic main effect included: 1) No traffic (untreated control) and 2) traffic (16 passes per week), each randomly assigned to a "whole subrow" across the entire study due to space restrictions. The time main effect consisted of each rating date treated as a repeated measure within each drought and recovery period.

Traffic was applied weekly in straight lines with a golf cart during the drought period at eight passes in opposite directions for a total of 16 passes per week. To minimize the cumulative traffic effects across years, traffic in 2016 was applied to a different area of the plots than in 2015. The golf cart was a 2001 electric 36-volt EZ-GO TXT Standard golf utility cart with canopy and steel bed (472 kg) (1418825, E-Z-GO, Augusta, GA) with supplemental weight to simulate two golfers & equipment (175 kg) traveling at 13 km h^{-1}. The front tires were a Kenda Hole-N-1 18 x 8.5-8" 4-ply tubeless tires (103890868B1, Kenda Rubber Industrial Company, Yuanlin, Taiwan) and the back tires were Carlisle Fairway Pro 18 x 8.50-8" 4-ply tubeless tires (5189761, The Carlstar Group LLC, Franklin TN); all tires were maintained at a pressure of 124 kPa.

Plot Maintenance

Standard agronomic golf industry fertilization procedures were implemented specifically for both C3 grasses and C4 grasses. Therefore, fertilization timings and amounts differed between C3 and C4 grasses. Urea (46-0-0; Thrive Branded Fertilizer, Mears Fertilizer Inc. El

Dorado, KS) was applied at 49 kg N ha^{-1} on 8 Apr., 21 Sept., and 21 Oct. in 2015, and 1 Apr. 2016 on the C3 species; and 24.5 kg N ha^{-1} on 22 Apr. 2015 and 21 Apr. 2016 on the C4 species. A polymer-coated urea (43-0-0; Duration 120 (120-day release), Koch Agronomic Services, LLC, Wichita, KS) was applied at 49 kg N ha^{-1} on 18 May 2015 and 22 May 2016 on the C3 species and 74 kg N ha^{-1} on 18 May 2015 and 22 May 2016 on the C4 species. Thus, the C3 species received 196 kg N ha^{-1} yr^{-1} and the C4 species received 98 kg N ha^{-1} yr^{-1}.

Plots were mowed at least twice a week and irrigated to prevent drought stress outside of the designated drought period. See Chapter 3 for additional details on plot establishment and maintenance procedures such as pesticide applications.

Data Collection

Data were collected from 26 June to 18 Sept. 2015 and 23 June to 15 Sept. 2016. Weekly measurements of volumetric soil water content (θ_v), visual turf quality, percent green cover, and turf firmness were discussed in Chapter 3.

Prior to- and after the termination of the drought period in both years, soil bulk density (ρ_b, g cm^{-3}) at the 0-6 cm depth was determined by equation 4.1 in accordance to (USDA-ARS and NRCS, 2001) methods:

$$Soil\ Bulk\ Density\ \left(\frac{g}{cm^3}\right) = \frac{Dry\ Weight\ of\ Soil\ Core\ (g)}{Volume\ of\ Soil\ Core\ (cm^3)} \qquad [4.1]$$

where volume of the soil core was 137.26 cm^3. In 2015, ρ_b measurements during the pre-drought period were only collected in the fairway mowing height plots due to time constraints, but then collected in all 64 plots, at both mowing heights, after the drought period. In 2016, ρ_b was collected in all 64 plots prior to- and after the drought period. One ρ_b sample was collected from each plot. After samples were collected, they were weighed separately for moist soil weight, then dried in a forced-air oven for 48 h at 105 ºC, lastly weighed separately to determine dry weight. Gravimetric soil water content (w, g g^{-1}), which is the weight of soil water per unit of dry soil weight, was determined by equation 4.2:

$$Gravimetric\ Water\ Content\ \left(\frac{g}{g}\right) = \frac{Weight\ of\ Moist\ Soil - Weight\ of\ Oven\ Dry\ Soil}{Weight\ of\ Oven\ Dry\ Soil} \qquad [4.2]$$

for each plot prior to- and after the 41-day drought period.

Soil penetration resistance (SPR, MPa) was measured from two locations per plot at 5 depths; 0 cm, 2.54 cm, 5.08 cm, 7.62 cm, 10.16 cm using a hand-held digital cone penetrometer (FieldScout, SC 900 Soil Compaction Meter, Spectrum Technologies, Aurora, IL) three times each year (pre- and post-drought period, and post-recovery period). Penetrometer measurements are typically reported as the cone index (CI) which is the shear resistance of the soil. Cone index is measured in Pascals and is determined by equation 4.3:

$$CI = \left(\frac{F}{\pi}\right)\left(\frac{d}{2}\right)^2 \qquad [4.3]$$

where F is the total force needed to push the penetrometer into the soil in Newtons (N), and d is diameter of the cone (Jabro et al., 2014; Randrup and Lichter, 2001). The pre-drought period measurements signify SPR values prior to any drought or traffic stress applied. The post-recovery period measurements immediately followed the recovery period of 40-days with adequate soil moisture and no traffic applied. The post-drought period measurements were conducted five days after the drought ended and water was applied. This was because SPR measurements immediately after the drought period, before rewatering, would have not have yielded meaningful data because the soil moisture was too low as stated in the instrument's product manual. This was also noticed firsthand by the researchers when SPR measurements were taken on a weekly basis throughout the drought period in 2015.

In 2016, one soil core (5.08 diam. x 30.5 cm depth) was collected from each plot at the end of the drought period using a hand-held soil core sampler (SST SCS #404.67, AMS Inc., American Falls, ID). Roots were washed, dyed with methyl blue [acid blue 93 ($C_{37}H_{27}N_3O_9S_3Na_2$), Sigma Chemical Co., St. Louis, MO] and water solution (5 g methyl blue L^{-1} water), scanned at 800 dpi, and analyzed with WinRHIZO (version 2003 b, Regent Instruments, Quebec City, Canada) to determine root length (cm), average root diameter (mm), and root surface area (cm^2). Root length density ($cm\ cm^{-3}$) was calculated as root length divided by the volume of the soil core. Total root biomasses were then dried in a forced-air oven for 48 h at 105 ºC and weighed separately to determine dry root biomass ($mg\ cm^{-3}$).

Ancillary measurements

Weather data was collected from an on-site weather station positioned in full sun within 100 m of the study area. To evaluate potential microclimate effects, air temperature and relative humidity were monitored inside and outside of the rainout shelter. These weather variables were measured using shaded, ventilated sensors, and recorded and logged every hour (HOBO Pro V2, Onset Computer Corp., Bourne, MA); sensors were placed at 15 cm above the ground, which was slightly above the turf canopies. Hourly vapor pressure deficit (VPD) was calculated for both inside and outside the shelter.

Statistical Analysis

Gravimetric soil water content, soil bulk density, and root measurements were analyzed using a three-way ANOVA with turf species, mowing height, and traffic as fixed effects and block as a random effect. Soil penetration resistance was analyzed using a four-way ANOVA with turf species, mowing height, traffic as fixed effects, block as a random effect, and depth as a repeated measure. Gravimetric soil water content and soil bulk density were analyzed for each pre-drought and post-drought period separately. Soil penetration resistance was analyzed separately for each period of pre-drought, post-drought, and post-recovery period within each year. All variables were analyzed in Proc MIXED of SAS (SAS 9.4, SAS Institute Inc., Cary, NC, USA). A several step process was used to assure proper ("best") model specification for each pre- and post-drought period of each year for ρ_b and w, for 2016 post-drought period for root measurements, and for each of the three periods of each year for SPR. First non-estimable covariance parameters were removed and appropriate denominator degrees of freedom (DDF) were specified. Next, only for the SPR, different variance-covariance structures {compound symmetry [CS], autoregressive [AR(1)], toeplitz [TOEP], heterogenous compound symmetry [CSH], heterogeneous autoregressive [ARH(1)], and heterogeneous toeplitz [TOEPH]} were investigated to find the best fitting model. For all measured variables, AIC = Akaike's Information Criteria and BIC = Bayesian Information Criteria were utilized to assess best fitting model (lower is better). For all response variables, studentized residuals were investigated to check assumptions of normal distribution and homogeneous variance properties. If necessary, additional variance group arrangements were specified. Significant outliers were also detected utilizing a conservative Bonferroni adjustment and removed from the dataset. Once final model was determined, summary of the statistical output was analyzed for each period (Appendix Tables C.1 and C.2). After analysis of type III tests for fixed effects for SPR, the F test for slice effects and the t test for slice differences within each period were conducted utilizing a conservative Bonferroni adjustment test for multiple comparisons. For each response variable, a set of pre-planned contrasts were conducted to compare C3 vs. C4 turf species overall and at each treatment interaction. Correlations among root measurements, ρ_b, SPR, w, visual turf quality, percent green cover, θ_v, and turf firmness were performed for the combined post-drought periods of 2015 and 2016 with the correlation procedure (Pearson) of SAS 9.4. Correlations among ρ_b, SPR, w, θ_v, and turf firmness were performed across all pre-drought and post-drought periods of 2015 and 2016 with the correlation procedure (Pearson) of SAS 9.4.

Results and Discussion

Site Weather Data

Monthly air temperatures, reported in Chapter 3, averaged slightly higher during the drought period in 2016 than in 2015. Monthly soil temperatures measured at depths of 5.08 and 10.16-cm averaged slightly higher during the drought and recovery in 2016 than in 2015 (Table 4.1) Beard (1959) reported soil temperature measured at a 15.2-cm depth was the best indicator of turfgrass root growth. The optimal soil temperature range for growth is 10 to 18 °C for C3 grasses and 24 to 30 °C for C4 grasses (Aldous and Kaufmann, 1979; Dipaola and Beard, 1992; Huang et al., 1998; Huang and Liu, 2003; Pote et al., 2006). Averaged across both depths, the average soil temperature during the drought period (June-August) was 25.2 °C in 2015 and 26.6 °C in 2016 (Table 4.1). Averaged across both depths, the average soil temperature during the recovery period (August-September) was 23.7 °C in 2015 and 24.4 °C in 2016. In 2016, maximum soil temperatures at both depths were higher from March through September than in 2015. The variability in soil temperatures may have influenced turf performance and recovery between years. Air temperature and VPD were slightly but consistently higher inside than outside the rainout shelter. Refer to Chapter 3 for more information on inside-to-outside the shelter differences of air temperature and VPD.

Soil Water Content

Gravimetric soil water content was measured to evaluate the effects of treatments on soil water content at a 0-6 cm depth. The only statistical differences in w were due to the turf species main effect in the post-drought periods (Table 4.2). Prior to drought in each year, w values were at adequate levels (30.4 to 34.7%) for turfgrass growth and there were no statistical differences (Table 4.2). After the 41-day drought, buffalograss at 14.5% had higher w than the other three species (10.4 to 12.6%) in 2015, and buffalograss at 15.2% was higher than the other three species (11.4 to 12.3%) in 2016. Perennial ryegrass at 12.6% was also higher than Kentucky bluegrass at 10.4% at the end of the drought in 2015. These findings for the pre-drought and post-drought periods agree with θ_v as measured with TDR at 0-7.6 cm reported in Chapter 3.

When pooled over both pre-drought and post-drought periods for the entire 2-year study, a strong correlation occurred between w and θ_v measurements (r = 0.973; $P < 0.001$; n = 224) (Appendix Table C.3). Weekly θ_v throughout the drought and recovery periods was discussed in Chapter 3. Briefly, there were differences in θ_v among turf species within each date during the drought and recovery periods each year. Volumetric soil water content during the baseline (pre-drought) and recovery periods were adequate for turfgrass growth. During and at the end of the 41-day drought in both years, buffalograss consistently had the highest θ_v among species, with perennial ryegrass similar at times. By the end of the drought, θ_v was lowest in Kentucky bluegrass in 2015 and 2016 and also zoysiagrass in 2015.

The differences in w among turf species at the end of the 41-day drought may be due to different water use rates. Typically, C4 grasses use less water than C3 grasses, especially the C4 buffalograss (Beard and Kenna, 2008). The ability of buffalograss to extract water at deeper depths due to its deep and extensive rooting may have contributed to less soil water use near the surface and correspondingly, to its higher w at 0-6 cm depth among species in both years (Qian et al., 1997). Differences in water use rates will in-turn affect soil water content status, and potentially affect the turf's ability to tolerate drought stress and/or traffic stress as time progresses. One other possibility for higher w at 0-6 cm in buffalograss among species in both years could be due to hydraulic lift, which has been documented in buffalograss to improve surface soil water status (Huang, 1999).

Soil Bulk Density

Soil bulk density was measured to evaluate the effects of treatments on soil compaction at a 0-6 cm depth. The only statistical differences in ρ_b were due to the turf species main effect in the 2015 post-drought period (Table 4.3). In the pre-drought period of both years, ρ_b measurements among turf species were at similar levels of 1.27 to 1.29 g cm^{-3} in 2015 and 1.26 g cm^{-3} in 2016 (Table 4.3). After the 41-day drought in 2015, regardless of mowing height or traffic treatment, buffalograss had a significantly higher ρ_b at 1.44 g cm^{-3} than in Kentucky bluegrass at 1.33 g cm^{-3} and perennial ryegrass at 1.36 g cm^{-3}, but not zoysiagrass at 1.38 g cm^{-3} (Table 4.3). After the drought in 2016, turf species were not different, however, a similar trend occurred, as observed in 2015, where both C4 grasses at 1.37 g cm^{-3} had higher ρ_b values than both C3 grasses at 1.33 to 1.34 g cm^{-3} (Table 4.3). For the 2015 post-drought period, the higher ρ_b measured in buffalograss may have been due to a slightly thinner turf canopy and less thatch layer than the other turf species, based on personal observation, therefore, more impacted by traffic applied. However, this not likely the main contributing factor, because zoysiagrass had a denser turf canopy and thicker thatch layer than buffalograss, based on personal observations, but typically resulted in similar ρ_b values as buffalograss in each year.

According to USDA-ARS and NRCS (2001) guidelines, ideal ρ_b for a silty clay loam should be less than 1.40 g cm^{-3} for optimum plant growth; ρ_b at 1.55 to 1.60 g cm^{-3} in a silty clay loam will start to affect root growth; and ρ_b greater than 1.65 g cm^{-3} will restrict root growth. In both pre-drought periods, ρ_b of all plots were adequate and well below the ideal ρ_b of 1.40 g cm^{-3} threshold. The 2015 pre-drought period average across all 32 plots was 1.28 g cm^{-3} and the 2016 pre-drought period average across all 64 plots was 1.26 g cm^{-3}. The only occurrence above 1.40 g cm^{-3} within the turf species main effect was buffalograss at 1.44 g cm^{-3} in the 2015 post-drought period. More specifically, ρ_b above 1.40 g cm^{-3} for the 2015 post-drought period was typically measured in trafficked plots, with the trafficked buffalograss at fairway mowing height (1.51 g cm^{-3}) measuring the highest ρ_b (data not shown). In 2016, there were fewer instances than 2015 where ρ_b measured above the ideal 1.40 g cm^{-3} (data not shown), and similar to 2015, the highest ρ_b treatment interaction mean of 1.45 g cm^{-3} was in buffalograss receiving traffic at fairway height. Although, a ρ_b above 1.40 g cm^{-3} occurred more often in trafficked plots than non-trafficked plots for both post-drought periods, the traffic main effect was not significant (data not shown).

Contrast comparisons revealed that C4 grasses overall had higher ρ_b at 1.41 g cm^{-3} than C3 grasses overall at 1.34 g cm^{-3} in 2015 post-drought and C4 at 1.37 g cm^{-3} and C3 grasses at 1.33 g cm^{-3} in 2016 post-drought (Table 4.3). The mean ρ_b for each C3 and C4 grass grouping is the averages from values in Table 4.3. In both years, contrast comparisons revealed that C4 grasses resulted in higher ρ_b than C3 grasses when subjected to traffic, with C4 at 1.46 g cm^{-3} and C3 at 1.38 g cm^{-3} in 2015 and C4 at 1.40 g cm^{-3} and C3 at 1.36 g cm^{-3} in 2016 (Table 4.3). In both years, comparisons also revealed that C4 grasses resulted in higher ρ_b than C3 grasses at fairway mowing height, with C4 at 1.42 g cm^{-3} and C3 at 1.36 g cm^{-3} in 2015 and C4 at 1.39 g cm^{-3} and C3 at 1.34 g cm^{-3} in 2016. C4 grasses also had higher ρ_b than C3 grasses at rough mowing height and non-traffic treatments in 2015.

In well-watered conditions, Głąb and Szewczyk (2014) reported four trafficked C3 turfgrasses had higher ρ_b than their non-trafficked counterparts. However, in my study, decreasing soil moisture due to drought may have reduced differences in ρ_b between trafficked and non-trafficked plots. Therefore, traffic application on drier soils, such as during drought, may have a reduced effect on ρ_b compared with well-water conditions. My research is consistent with past research that showed decreased potential for soil compaction as soil moisture decreases below, or increases above field capacity (Boufford and Carrow, 1980; Lunt, 1952; Merkel, 1952; Swartz and Kardos, 1963).

Even though not statistically compared, after the 41-day drought, ρ_b values were numerically higher across all plots compared to pre-drought period values. Therefore, after a period of drought stress, regardless of turf species, mowing height, or traffic application, turf managers may likely see a change in ρ_b compared to pre-drought stress due to spatial variability, soil heterogeneity, and temporal changes due to shrinking and swelling of the soil (Cambardella et al., 1994; Logsdon and Cambardella, 2000; Nielsen et al., 1973). However, during drought, traffic may not necessarily increase ρ_b in turfgrass. In my study, traffic was applied for a short duration during summer, results may vary if traffic is applied over longer duration of drought conditions, such as cumulative years, this should be further investigated in future research. Nevertheless, as mentioned in Chapter 3, the combined effects from traffic and drought stress will exacerbate the decline of the above-ground portion of turfgrass even though ρ_b levels may remain similar.

Soil Penetration Resistance

Soil penetration resistance was measured to evaluate the effects of treatments on soil compaction at 0 cm, 2.54 cm, 5.08 cm, 7.62 cm, and 10.16 cm depths. No treatment (turf species, mowing height, or traffic) x depth interaction was observed across all measurement periods in each year. (Appendix Table C.4). Although, turf species at each depth within a mowing height x traffic combination were having a significant effect on SPR within each period (pre-drought, post-drought, and post-recovery). Therefore, the four-way cell means were sliced by mowing height x traffic treatment x depth to compare the four species at each measurement depth of a mowing height x traffic combination within a respective period (Appendix Tables C.5 and C.6).

Post-drought measurements were conducted five days after the 41-day drought period ended (i.e., after rewatering) due to instrumentation limitation mentioned above in the materials and methods. Consequently, since soil moisture was higher at five days than immediately after the drought, SPR was likely lower than if it had been measured immediately following the drought (before rewatering). Nevertheless, post-drought measurements still exhibited the effects of drought and/or traffic, as explained below.

Differences among the four species at each depth within a mowing height x traffic combination occurred once (2015) and twice (2016) during the pre-drought period; once (2015) and none (2016) during the post-drought period; and twice (2015) and five times (2016) during the post-recovery period (Figs. 4.1 and 4.2). Similar to ρ_b results, differences in the pre-drought period can be attributed to lack of drought and traffic treatments being implemented. The few statistical occurrences for each period may be due to the high variability among SPR measurements within each treatment interaction, especially after the 41-day drought, which was also likely due to soil heterogeneity after a drought, and/or possible instrumentation limitations. Therefore, differences that did occur may not likely be due to treatment. Also, the limited occurrences of statistical significance with the test for slice effects (comparison of turf species with combination of depth, mowing height, and traffic per respective periods across both years) may be due to the conservative Bonferroni adjustment ($P < 0.0025$) used (Appendix Tables C.5, and C.6). This was necessary to control the family-wise error rate due to simultaneous multiple comparisons. Thereby reducing the likelihood of obtaining false-positive results (type I errors) by chance. There were incidences, across both years, where test for slice effects p-values were close to adjustment level ($\alpha_{bon} = 0.0025$), but non-significant, and could be regarded as a false negative result.

A higher SPR would signify more compact and unfavorable soil conditions for root elongation and health. Silva et al. (1994) reported a critical value for SPR of 2.0 MPa, at which point root growth would be strongly impeded. In both years, SPR exceeded the critical value of 2.0 MPa only in the post-drought period. In both years, the smallest differences in SPR among turf species within each depth x mowing height x traffic combination typically occurred during the pre-drought period, which is expected due to no drought or traffic stress present. Across both years and all five measurement depths, the minimum and maximum measured SPR during the pre-drought period was 0.220 and 0.939 MPa, respectively (Figs. 4.1 and 4.2). Across both years and all five depths, the minimum and maximum measured SPR during the post-drought period was 0.509 and 3.06 MPa, respectively. After the drought, SPR exceeded 2.0 MPa on 12 occurrences in 2015 and 26 occurrences in 2016. These were typically at lower depths, but also more commonly in fairway mowing height plots. In both years, after a 40-day recovery, SPR values typically returned to a similar range as the pre-drought period. Across both years and all five depths, the minimum and maximum measured SPR during the post-drought period was 0.362 and 1.53 MPa, respectively.

Even though not statistically compared, after a period of drought stress, regardless of turf species, turf managers may likely see SPR at higher values, especially at deeper depths, and possibly in lower mowing heights. However, there was not a consistent increase SPR due to traffic application during drought stress. The effects of drought may have reduced the impacts from traffic, whereas Głąb and Szewczyk (2014) reported increased SPR in four trafficked C3 turfgrasses compared to non-trafficked plots at well-watered conditions. After a period of recovery with adequate soil moisture and no traffic, 40 days in my study, turf managers may likely see SPR return to similar values as that of pre-drought stress. Past research has shown that turf species with good wear tolerance also have good soil compaction tolerance (Beard, 1973; Carrow, 1980, 1995; Głąb and Szweczyk, 2014, 2015). Therefore, results from Chapters 3 and 4 indicate the better above-ground performances of buffalograss, zoysiagrass, and at times, perennial ryegrass compared to Kentucky bluegrass may possibly be due to better soil compaction tolerance.

Root Measurements

Root biomass, root length density, average root diameter, and root surface area were measured to evaluate the effects of treatments on the root system at a 0-30.5 cm depth. Mowing height and traffic had minimal effects on root parameters (Table 4.4). Turf species main effect was significant across all root parameters. Statistical differences occurred at the turf species x mowing height interaction for average root diameter (Fig. 4.3).

Immediately after the drought in the second year there were similar trends in three of the four root parameters for the turf species main effect. Namely, root biomass, root length density, and root surface area at 0-30.5 cm were higher in the two C3 grasses than the two C4 grasses following the 41-day drought period (Table 4.4). For both root biomass and root surface area, Kentucky bluegrass and perennial ryegrass had 46 to 70% more root biomass and 170 to 200% more root surface area than zoysiagrass and buffalograss (Table 4.4). Kentucky bluegrass had a greater root length density than the other three species, and perennial ryegrass was higher than the two C4 grasses. Overall, the C3 grasses had 150 to 290% greater root length density than C4 grasses. However, Kentucky bluegrass had the smallest root diameter than the other three species, with a 20 to 23% decrease in root diameter compared to the other three species. (Table 4.4). Buffalograss and zoysiagrass may have had a deeper root system, thus more roots below the measured 0 to 30.5 cm depth. Mowing height and traffic main effects were not significant for any five root parameters. Contrast comparisons of C3 vs C4 grasses overall, at each mowing height, and traffic treatment for each rooting parameter were all highly significant and mirrored the results from the turf species main effect (Table 4.4).

The only significant treatment interaction was turf species x mowing height for root diameter (Fig. 4.3). This interaction provided a clearer representation of the effects of drought, regardless of traffic treatments, on root diameter of each turf species x mowing height combination. The highest average root diameters occurred in buffalograss and zoysiagrass both at rough mowing height and perennial ryegrass at fairway mowing height, all three were higher than Kentucky bluegrass at both mowing heights, which had the lowest root diameters. The root diameter of the two C4 grasses at fairway mowing height and perennial ryegrass at rough height were also higher than Kentucky bluegrass at fairway height, but not Kentucky bluegrass at rough height. There were no differences between the two mowing heights of Kentucky bluegrass. Based on these results, the roots of Kentucky bluegrass, regardless of mowing height, were the smallest in diameter of the studied turf species. However, as mentioned above, the other root parameters were typically highest in Kentucky bluegrass. Based on personal observations, Kentucky bluegrass generally had a dense mass of numerous small (thin) diameter roots compared to the other species, with perennial ryegrass exhibiting some similarities to Kentucky bluegrass. However, the root systems of zoysiagrass and buffalograss were quite different than Kentucky bluegrass, and, at times, perennial ryegrass. Zoysiagrass and buffalograss roots were generally less dense, with fewer but larger diameter and longer intact roots. If the root system has a dense mass of small (thin) diameter roots, as was observed with Kentucky bluegrass, then root length density and root surface area would measure greater. When pooled over the post-drought period, a positive correlation occurred between root biomass, root surface area, and root length density, while a negative correlation occurred between root diameter and the other root parameters (Appendix Table C.7). Other correlations among root parameters, ρ_b, SPR, w, visual turf quality, percent green cover, θ_v and turf firmness were investigated (Appendix Table C.7). Root diameter was the only root parameter to be positively correlated with above-ground response variables of visual turf quality, percent green cover, and turf firmness and also soil moisture (w and θ_v).

Past research has reported root diameters of 0.1 mm for C3 turfgrasses (Głąb and Szewczyk, 2015) and 0.3 to 0.4 mm for forage grasses (Głąb, 2013a, 2013b). In my study, mean root diameter of two C4 grasses and perennial ryegrass all measured greater than 0.2 mm, while mean root diameter for Kentucky bluegrass was 0.174 mm. Research in other plant species has indicated that a larger root diameter is the best indicator of a plant's ability to penetrate compacted soils (Clark et al., 2003). Therefore, buffalograss, zoysiagrass, and perennial ryegrass with a larger root diameter in my study may have been more resistant to soil compaction and more capable of exploring a large amount of soil, possibly at deeper depths.

Lipiec et al. (1991; 2003) reported a decrease in root length and root concentration with an increase ρ_b in the upper soil profile. Similarly, in my study, root biomass and root length density were lower in the C4 grasses, which had a higher ρ_b than C3 grasses (Tables 4.3 and 4.4). This same trend of lower root biomass and root length density with higher ρ_b occurred in traffic vs. non-traffic plots (Tables 4.3 and 4.4).

Głąb and Szewczyk (2014) reported root biomasses ranging from 5.04 to 9.61 mg cm^{-3} for trafficked grasses and 6.88 to 9.26 mg cm^{-3} for non-trafficked grasses, which was higher than in my study; however, their grasses were well-watered. Those authors reported perennial ryegrass had the highest root biomass at 0-15 cm compared to Kentucky bluegrass, tall fescue, and chewings fescue, which is similar to my results. Głąb and Szewczyk (2014) also reported greater root length densities than in my study, and traffic reduced root length density by 4 to 15 cm cm^{-3}. In Głąb and Szewczyk (2014), the greater root biomass and root length density values at 0-15 cm compared to my study at 0-30.5 cm would be expected because the turfgrasses were well-watered and also the density of roots in turfgrass is typically greater near the surface. The declines in root biomass and root length density due to traffic reported by Głąb and Szewczyk (2014) may have occurred because traffic was applied to turfgrass at well-watered conditions, whereas, in my study traffic had a negligible impact on root parameters most likely due to the low soil moisture from drought stress.

At four weeks and after 35 traffic passes on tall fescue, Boufford and Carrow (1980) reported differences in root biomass at 0-10 cm between trafficked (5.08 to 7.27 mg cm^{-3}) and non-trafficked plots (8.31 mg cm^{-3}). However, no statistical differences occurred at the 10-20 cm. At ten weeks after traffic application, there were no differences in root biomass among the traffic treatments at both depths (Boufford and Carrow, 1980). The study by Boufford and Carrow (1980) was conducted on turfgrass at various soil water contents, but not prolonged drought conditions. Carrow (1980) reported perennial ryegrass was the least impacted by soil compaction compared to tall fescue and Kentucky bluegrass. Furthermore, different turf species varied in their response to soil compaction, with the only adverse effects on perennial ryegrass being reduced root weight, whereas Kentucky bluegrass exhibited a reduction in verdure, shoot density, and root weight, and tall fescue a reduction in verdure. In my study, root biomass and ρ_b were similar between perennial ryegrass and Kentucky bluegrass in 2016. However, in Chapter 3 I reported that while both turf species performed similarly above-ground at fairway mowing height, percent green cover and visual quality were higher in perennial ryegrass than in Kentucky bluegrass at the rough mowing height. Therefore, although root parameters may be similar, above-ground responses may vary among turf species after a drought and/or traffic application period, possibly due to leaf morphology/physiology differences.

Głąb and Szewczyk (2015) reported turfgrasses with a higher root biomass, root surface area, and larger root diameters had improved wear tolerance, with root length density of perennial ryegrass cultivars being positively correlated to wear tolerance. This correlation between higher root parameter values and higher turf quality and green cover during the drought was not observed in my study. However, a moderate positive correlation between root diameter and visual turf quality and percent green cover was present ($r = 0.501$; $P < 0.001$; $n = 64$) (Appendix Table C.7). Similarly, in an irrigation deficit study, greater root length density and root surface area in the upper soil layer (0-30 cm) of ‘Thermal Blue’ hybrid bluegrass did not translate to better above-ground performance than other grasses during water deficit (Su et al., 2008).

As reported in Chapter 3, the C4 grasses maintained higher green cover and turf quality than C3 grasses during drought and traffic stresses. This occurred even though both C4 grasses had less root biomass, root length density, and root surface area than C3 grasses from 0 to 30.5 cm. The C4 grasses possibly had more roots than the C3 grasses at non-measured depths below 30.5-cm, which would have allowed them to extract more water during the drought. Differences in root distribution may contribute to different water uptake rates among species (Huang, 1999; Qian et al., 1997). Also, even though the C4 grasses had less root biomass and root length density at 0 to 30.5-cm, past turfgrass research has reported that C4 grasses generally have a more efficient photosynthetic pathway, lower ET rates, higher levels of osmotic adjustment, higher cell wall elasticity, and better tolerance to low leaf relative water content, all of which provide better drought resistance than C3 grasses (Beard, 1973; Beard and Kenna, 2008; Biran et al., 1981; Fu et al., 2004; Fry and Huang, 2004; Huang and Fry, 1999; Kim and Beard, 1988; Meyer and Gibeault, 1986; Qian and Fry, 1997). Regardless, future drought research should include turfgrass species and specific cultivars that exhibit deep rooting characteristics that help avoid drought conditions.

Not only has there been minimal research conducted addressing the effects on soil properties and roots in buffalograss and zoysiagrass subjected to traffic stress, but also the majority of past traffic research has been conducted on well-watered turfgrasses with little investigation into the effects of traffic on turfgrass during dry conditions. Therefore, comparisons of root responses to past research are difficult to make.

Conclusions

At the end of a 41-day drought, w at 0 to 6 cm depth was higher in buffalograss than the other turf species. However, the 41-day drought resulted in minor differences among turf species in soil compaction as estimated by ρ_b and SPR. Decreased soil moisture during drought may have diminished differences in ρ_b and SPR, especially between trafficked and non-trafficked plots. Therefore, during a drought, traffic may not increase ρ_b and SPR in turfgrass. However, after a period of drought stress, regardless of turf species, mowing height, or traffic, turf managers may likely see a change in ρ_b and/or SPR compared to pre-drought stress due to soil heterogeneity and temporal changes due to shrinking and swelling of the soil. After a 41-day drought, SPR was higher in all turf species across all depth x mowing height x traffic combinations, and SPR at lower depths exceeded the critical value of 2.0 MPa, more commonly at fairway mowing height, which could impede root growth. After a 40-day recovery with adequate soil moisture and no traffic, SPR generally returned to a similar range as the pre-drought period. After the drought, the C3 grasses had higher root biomass, root length density, and surface area, but not root diameter, than the C4 grasses in the upper profile of 0-30.5 cm. However, with respect to Chapter 3 results, the higher root biomass, root length density, and root surface area at 0-30.5 cm may not be a clear indicator of better above-ground turfgrass performance during drought and traffic stress. Turfgrasses such as buffalograss, zoysiagrass, and perennial ryegrass with a larger root diameter may be more resistant to soil compaction and more capable of exploring large volumes of soil, possibly at deeper depths. This would allow them to extract more water during the drought. Most differences measured within soil and root measurements were due to the effects of drought stress and not traffic stress, since the traffic main effect was not significant across all below-ground variables. Therefore, turf managers may see a minimal impact on soil and root characteristics from traffic application during a drought period. Investigating the combination of two stresses (e.g. drought and traffic stresses) can sometimes lead to confounding results. Further research is recommended to attain a better understanding on the combined effects of drought and traffic stress on soil and root responses of turfgrasses. More specifically, in this study, traffic was applied for a short duration during summer, future research should investigate the effects of traffic application during drought over a longer duration, such as cumulative years. Also, investigation into additional turf species and deeper root depth measurements should be conducted. Future investigation should include turf species and specific cultivars that exhibit deep rooting characteristics that help avoid drought conditions.

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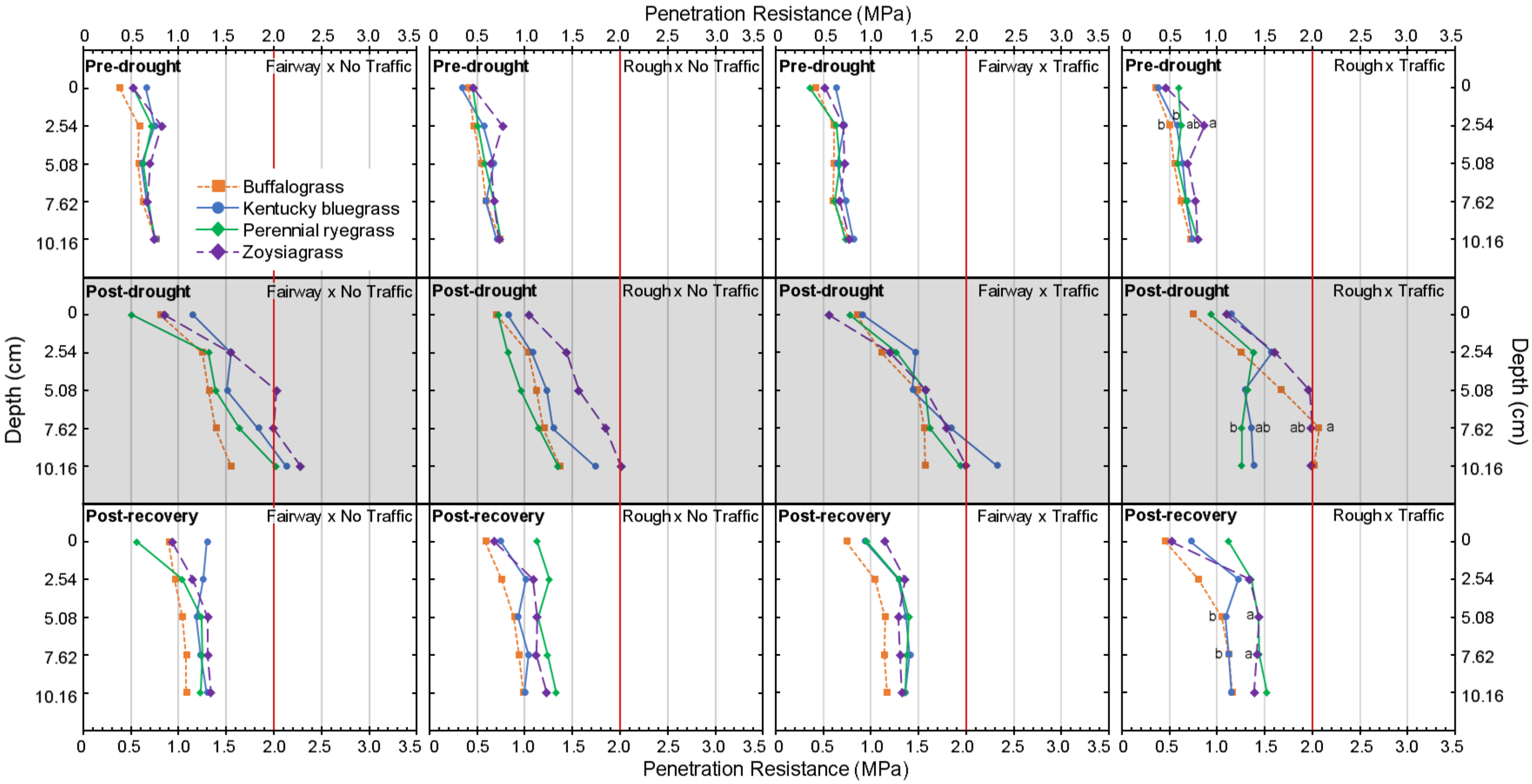

Figure 4.1. Comparison of soil penetration resistance among turfgrass species sliced by mowing height, traffic, and depth in 2015 for pre-drought, post-drought, and post-recovery periods, each was period separately analyzed. Soil penetration resistance (MPa) was measured in two locations per plot at 0, 2.54, 5.08, 7.6, and 10.16 cm depths. Vertical red line at 2.0 MPa represents critical value of soil penetration resistance that would limit root growth. At each depth by mowing height x traffic combination, turf species means with the same letter or no letters horizontally are not significantly different at $\alpha_{bon} = 0.00417$.

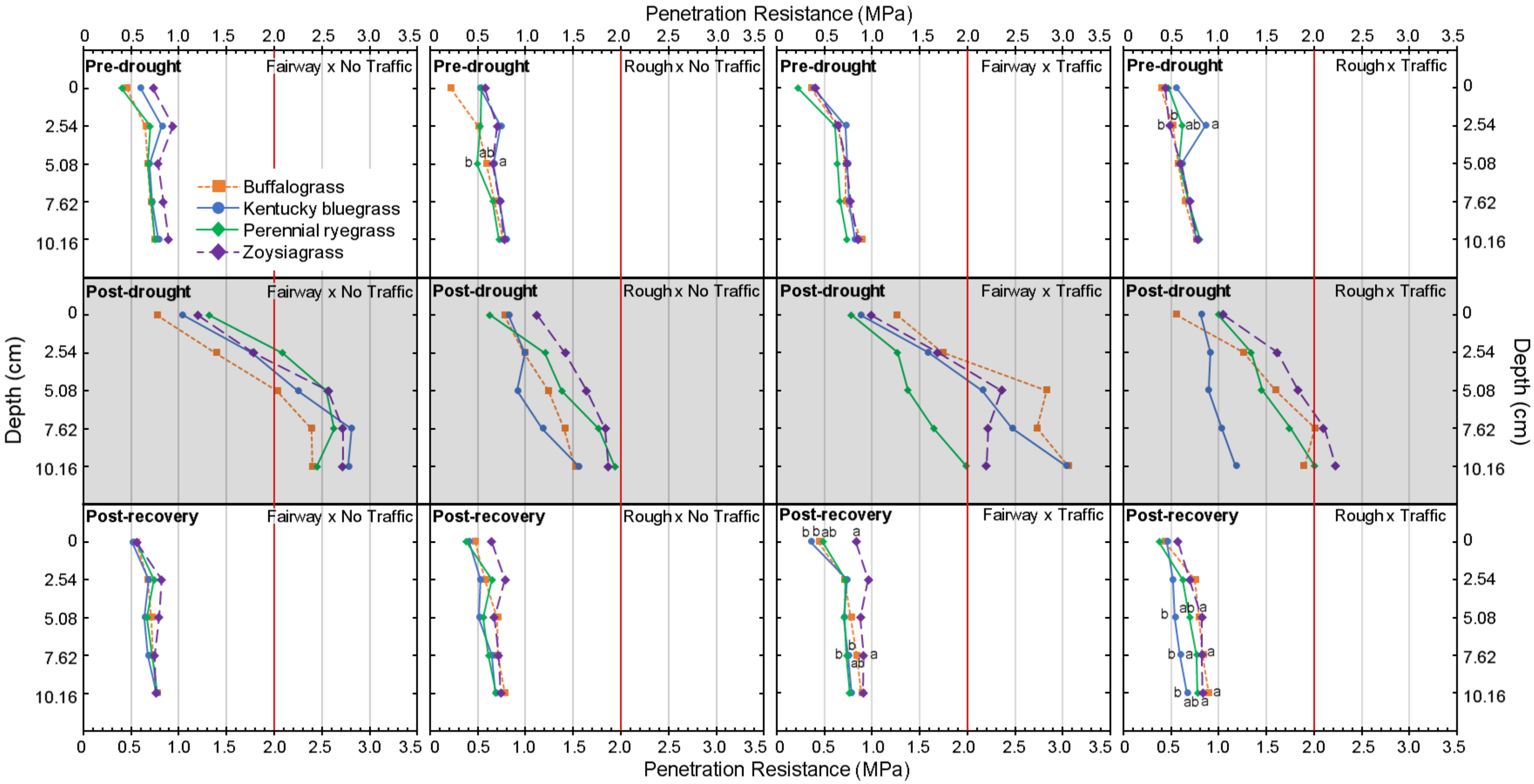

Figure 4.2. Comparison of soil penetration resistance among turfgrass species sliced by mowing height, traffic, and depth in 2016 for pre-drought, post-drought, and post-recovery periods, each period was separately analyzed. Soil penetration resistance (MPa) was measured in two locations per plot at 0, 2.54, 5.08, 7.6, and 10.16 cm depths. Vertical red line at 2.0 MPa represents critical value of soil penetration resistance that would limit root growth. At each depth by mowing height x traffic combination, turf species means with the same letter or no letters horizontally are not significantly different at $\alpha_{bon} = 0.00417$.

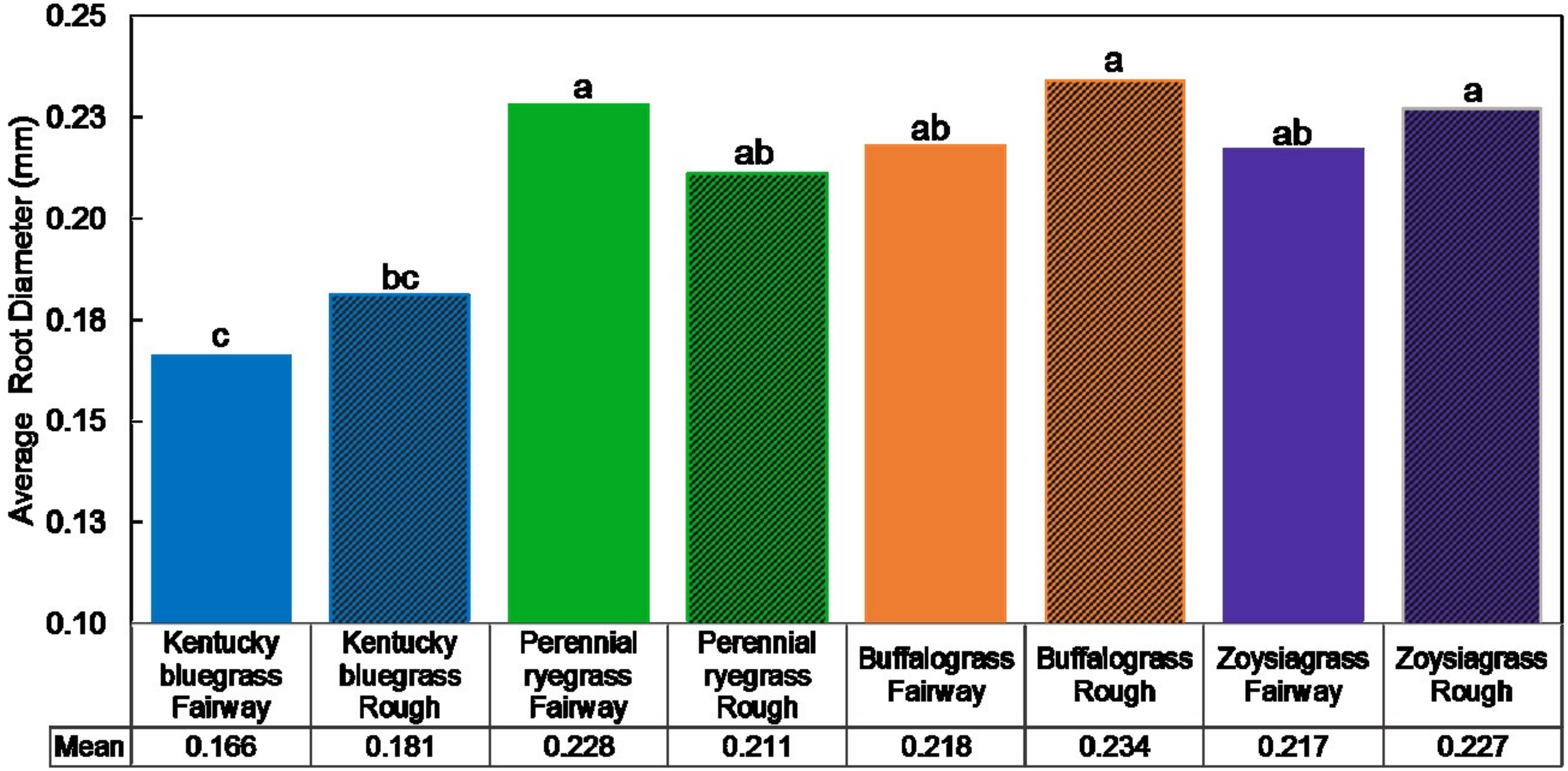

Figure 4.3. Effect of turf species x mowing height (fairway or rough) interaction on root diameter following a 41-day drought period with no precipitation or irrigation and averaged over traffic treatments of 0 or 96 cumulative golf cart traffic passes in 2016. Letter groupings above each bar with the same letter are not significantly different according to Tukey's Honestly Significant Difference test ($P \leq 0.05$).

Table 4.1. Mean monthly maximum, minimum, mean soil temperatures at 5.08-cm [bolded] and (10.16-cm) depths from August 2014 through September 2016 from an on-site weather station.

	Monthly Soil Temperature (°C)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2014												
Min	--	--	--	--	--	--	--	**23**[†] (23.3)[‡]	**18.5** (19.3)	**12.8** (13.8)	**3.4** (4.9)	**2.6** (3.5)
Max	--	--	--	--	--	--	--	**29** *(26.6)*	**24.2** (*22.6*)	**17.3** (16.6)	**7.6** (7.3)	**5** (5)
Mean	--	--	--	--	--	--	--	**26** (25)	**21.3** (21)	**15.1** (15.2)	**5.5** (6.1)	**3.8** (4.2)
2015												
Min	**-0.5** (0.2)	**0.5** (1.1)	**4.7** (5.4)	**11.3** (12)	**16.3** (16.6)	**22.2** (22.3)	**24.4** (24.5)	**22.6** (23.1)	**20.8** (21.2)	**13.9** (15)	**7.9** (9)	**3** (4)
Max	**1** (0.9)	**1.9** (2)	**10.2** (8.5)	**17.1** (15.3)	**21.6** (19.8)	**27.6** (25.7)	**29.5** (27.6)	**27.4** (25.8)	**24.9** (23.6)	**18.2** (17.3)	**11.4** (11.2)	**5.6** (5.5)
Mean	**0.3** (0.6)	**1.2** (1.6)	**7.4** (7)	**14.2** (13.6)	**18.9** (18.2)	**24.9** (24)	**26.9** (26)	**25** (24.5)	**22.8** (22.4)	**16.1** (16.1)	**9.6** (10.1)	**4.3** (4.7)
2016												
Min	**0.3** (1)	**2.6** (3.3)	**7.4** (8.1)	**11.6** (12.4)	**14.8** (15.4)	**22.6** (23)	**24.1** (24.4)	**23.4** (23.7)	**20.9** (21.5)	--	--	--
Max	**1.2** (1.6)	**5.7** (5.1)	**12.2** (11)	**18** (16.3)	**22.4** (20.2)	**32.4** (29)	**31.4** (28.8)	**28.9** (27.0)	**25.7** (24.2)	--	--	--
Mean	**0.8** (1.3)	**4.2** (4.2)	**9.8** (9.6)	**14.8** (14.3)	**18.6** (17.8)	**27.5** (26)	**27.7** (26.6)	**26.1** (25.4)	**23.3** (22.9)	--	--	--

[†] Bolded number are soil temperatures measured at the 5.08-cm depth.

[‡] Non-bolded numbers in parentheses are soil temperatures measured at the 10.16-cm depth.

Table 4.2. Analysis of variance for the fixed effects of turf species, mowing height, and traffic on gravimetric soil water content at 0-6 cm depth measured at pre-drought and post-drought in 2015 and 2016.

Source	2015 Pre-drought[‡]	2015 Post-drought	2016 Pre-drought	2016 Post-drought
	Gravimetric soil water content[†]			
Turf species (T)	NS[§]	***	NS	***
Mowing height (MH)	--[¶]	NS	NS	NS
T x MH	--	NS	NS	NS
Traffic (TR)	NS	NS	NS	NS
T x TR	NS	NS	NS	NS
MH x TR	--	NS	NS	NS
T x MH x TR	--	NS	NS	NS
Contrasts[#]				
C3 vs C4 Turf species	**	**	NS	***
C3 vs C4 @ Fairway MH	--	**	NS	***
C3 vs C4 @ Rough MH	--	*	NS	**
C3 vs C4 @ No Traffic	NS	**	NS	***
C3 vs C4 @ Traffic	NS	**	NS	***
Ls means[††]				
Turf species	%	%	%	%
Kentucky bluegrass	32.5	10.4 c[‡‡]	30.4	11.4 b
Perennial ryegrass	33.0	12.6 b	33.4	12.4 b
Buffalograss	34.7	14.5 a	31.7	15.2 a
Zoysiagrass	34.5	11.3 bc	30.4	12.3 b
Mowing height				
Fairway	33.7	12.1	30.6	12.6
Rough	--[¶]	12.4	32.3	13.1
Traffic				
No	33.7	11.9	30.9	12.6
Yes	33.6	12.5	32.1	13.1

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Gravimetric water content (w, g g^{-1}) at the 0-6 cm depth was determined by extracting a soil core from each plot, soil core was then weighed for moist soil weight, then dried in a forced-air oven for 48 h at 105 ºC, lastly weighed separately to determine dry weight.

[‡] In 2015 pre-drought period, measurements were conducted only in the fairway mowing height due to time restrictions, but measured in both mowing heights for all remaining periods in 2015 and 2016.

[§] Not significant (NS).

[¶] Not applicable, only measurements conducted on fairway mowing height (--).

[#] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass).

[††] Ls means for the main effect of turf species, mowing height, and traffic.

[‡‡] Within a column of the turf species main effect, means with the same letter or no letters are not significantly different according to Tukey's Honestly Significant Difference test ($P \leq 0.05$).

Table 4.3. Analysis of variance for the fixed effects of turf species, mowing height, and traffic on soil bulk density levels at 0-6 cm depth measured at pre-drought and post-drought in 2015 and 2016.

	Soil bulk density[†]			
Source	2015 Pre-drought[‡]	2015 Post-drought	2016 Pre-drought	2015 Post-drought
Turf species (T)	NS[§]	*	NS	NS
Mowing height (MH)	--[¶]	NS	NS	NS
T x MH	--	NS	NS	NS
Traffic (TR)	NS	NS	NS	NS
T x TR	NS	NS	NS	NS
MH x TR	--	NS	NS	NS
T x MH x TR	--	NS	NS	NS
	Contrasts[#]			
C3 vs C4 Turf species	NS	**	NS	*
C3 vs C4 @ Fairway MH	--	*	NS	*
C3 vs C4 @ Rough MH	--	*	NS	NS
C3 vs C4 @ No Traffic	NS	*	NS	NS
C3 vs C4 @ Traffic	NS	**	NS	*
	Ls means[††]			
Turf species	$g\ cm^{-3}$	$g\ cm^{-3}$	$g\ cm^{-3}$	$g\ cm^{-3}$
Kentucky bluegrass	1.27	1.33 b[‡‡]	1.26	1.33
Perennial ryegrass	1.29	1.36 b	1.26	1.34
Buffalograss	1.28	1.44 a	1.26	1.37
Zoysiagrass	1.28	1.38 ab	1.26	1.37
Mowing height				
Fairway	1.28	1.39	1.27	1.36
Rough	--[¶]	1.37	1.25	1.34
Traffic				
No	1.27	1.33	1.25	1.32
Yes	1.29	1.42	1.27	1.38

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Soil bulk density (ρ_b, $g\ cm^{-3}$) at the 0-6 cm depth was determined by extracting a soil core from each plot. Samples were then weighed and dried in a forced-air oven for 48 h at 105 ºC.

[‡] In 2015 pre-drought period, measurements were conducted only in the fairway mowing height due to time restrictions, but measured in both mowing heights for all remaining periods in 2015 and 2016.

[§] Not significant (NS).

[¶] Not applicable, only measurements conducted on fairway mowing height (--).

[#] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass).

[††] Ls means for the main effect of turf species, mowing height, and traffic.

[‡‡] Within a column of the turf species main effect, means with the same letter or no letters are not significantly different according to Tukey's Honestly Significant Difference test ($P \leq 0.05$).

Table 4.4. Analysis of variance for the fixed effects of turf species, mowing height, and traffic on root parameters at 0-30.5 cm depth measured at post-drought in 2016.

	Root parameters[†]			
Source	Root biomass[‡]	Root length density[‡]	Average root diameter	Root surface area
Turf species (T)	***	***	***	***
Mowing height (MH)	NS[¶]	NS	NS	NS
T x MH	NS	NS	*	NS
Traffic (TR)	NS	NS	NS	NS
T x TR	NS	NS	NS	NS
MH x TR	NS	NS	NS	NS
T x MH x TR	NS	NS	NS	NS
			Contrasts[#]	
C3 vs C4 Turf species	***	***	***	***
C3 vs C4 @ Fairway MH	***	***	*	***
C3 vs C4 @ Rough MH	***	***	***	***
C3 vs C4 @ No Traffic	***	***	***	***
C3 vs C4 @ Traffic	***	***	**	***
			Ls means[††]	
Turf species	mg cm^{-3}	cm cm^{-3}	mm	cm^{2}
Kentucky bluegrass	0.973 a[‡‡]	15.3 a	0.174 b	506.5 a
Perennial ryegrass	1.05 a	10.8 b	0.219 a	488.1 a
Buffalograss	0.617 b	3.9 c	0.226 a	168.8 b
Zoysiagrass	0.667 b	4.3 c	0.222 a	181.5 b
Mowing height				
Fairway	0.848	9.2	0.207	351.7
Rough	0.806	7.9	0.213	320.7
Traffic				
No	0.853	8.7	0.217	347.5
Yes	0.801	8.4	0.203	324.9

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] One soil core was collected from each plot at the end of the drought period. Roots were washed, dyed with methyl blue and water solution (5 g methyl blue L^{-1} water), scanned at 800 dpi, and analyzed with WinRHIZO to determine root length, average root diameter, and root surface area. Root length density was calculated as root length divided by the volume of soil core. Total root biomasses were then dried in a forced-air oven for 48 h at 105 ºC and weighed separately to determine dry root biomass.

[‡] Raw data were subjected to the log transformation to normalize. Means were separated using Tukey's HSD test, and transformed means were back-transformed for presentation

[¶] Not significant (NS).

[#] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass).

[††] Ls means for the main effect of turf species, mowing height, and traffic.

[‡‡] Within a column of the turf species main effect, means with the same letter are not significantly different according to Tukey's Honestly Significant Difference test ($P \leq 0.05$).

Chapter 5 - Summary

Nitrous oxide (N_2O) and carbon dioxide (CO_2) are important greenhouse gases (GHG) that are natural and anthropogenic by-products associated with global climate change. The turfgrass industry, which consists of home lawns, commercial properties, golf courses, parks, athletic fields, and roadsides, covers a substantial area of land in the United States. The turfgrass industry not only has a significant positive impact in the U.S. economy, but also provides a variety of environmental and human health benefits that improve the quality of life. However, turfgrasses sequester and emit CO_2, and emit N_2O when fertilized with nitrogen (N) and irrigated, with comparable annual N_2O emissions as other agricultural systems. The effects of N fertilizer sources on N_2O emissions have been investigated in other agricultural systems but minimal research has been conducted in turfgrass systems, especially pertaining to controlled-released N fertilizers. Further N_2O research is required in turfgrass to develop management practices, such as the use of controlled-release N fertilizers and/or deficit irrigation, which may potentially reduce N_2O emissions, but also affect carbon (C) sequestration in turf soils.

Results from Chapter 2 indicate that some management practices in turfgrass can reduce N_2O emissions. A higher irrigation amount [66% reference evapotranspiration (ET_o) replacement] resulted in 6.3% higher N_2O emissions than a lower irrigation amount (33% ET_o) applied to zoysiagrass during two years of summer periods (June, July, and August), indicating that a reduced irrigation amount has the potential to reduce N_2O emissions in turfgrass. Cumulative emissions of N_2O for the entire 2-year period were 38% higher in the quick-release N fertilizer (urea) than in the unfertilized no-N (UF) turf, and 25% greater in urea than the controlled-release N-fertilizer [polymer-coated urea (PCU)]. Cumulative emissions of N_2O over the 2-year period were 11% higher in PCU than in UF turf. Over the two years, cumulative N_2O emissions averaged 4.06 kg ha^{-1} in UF turf, 4.5 kg ha^{-1} in PCU treated turf, and 5.62 kg ha^{-1} in urea treated turf, each statistically different from one another ($P \leq 0.01$). These results indicate that the use of a controlled-release N fertilizer, such as PCU compared to the use of a quick-release fertilizer reduces N_2O emissions in turfgrass.

Soil of the zoysiagrass turf system increased in soil organic carbon (SOC) after a 3-year period. However, a higher input management schedule (urea + 66% ET_o irrigation treatment) in zoysiagrass did not increase C sequestration compared with a low input management schedule (no fertilizer + 33% ET_o irrigation treatment). A greater C sequestration rate occurred in the 0-10 cm soil layer compared to lower soil depths. Regardless of management input schedule or depth, after a 3-year period zoysiagrass exhibited enhanced SOC content and an average C sequestration rate of 0.952 Mg C ha^{-1} yr^{-1}, which may help mitigate climate change.

Anyone who manages turfgrass is a steward of the environment and shares the responsibility in providing better environmental quality practices for future generations. Turfgrass managers can be better stewards of the environment by using smarter fertilizer practices, such as controlled-release N fertilizers (polymer-coated urea) instead of quick-release (urea) fertilizer, and also using smarter irrigation practices, such as reducing irrigation amounts with deficit irrigation to reduce N_2O emissions.

Another issue in the turfgrass industry is the decreasing water availability for irrigation. Therefore, during periods of drought, watering restrictions may be imposed on turf managers with no regard for damage to turfgrass. During drought, turfgrass on golf courses continues to receive vehicular or foot traffic. Drought resistance and traffic tolerance in turfgrasses have been investigated separately. Therefore, the combined effects of drought and traffic stresses on turf species needs to be further investigated to understand how the shoot, soil, and root systems are affected to help develop possible management decisions.

Results from chapters 3 and 4 indicate that traffic during drought will have negative and accelerated impacts above-ground (shoots), but minimal impact below-ground (soil and roots), which will vary with turf species and mowing height.

In the turfgrass shoots, more differences occurred between non-traffic vs. traffic treatments within each mowing height of the warm-season (C4) grasses (buffalograss and zoysiagrass) than the cool-season (C3) grasses (Kentucky bluegrass and perennial ryegrass). This was due to the better drought tolerance of C4 grasses, which maintained high turf quality and percent green cover when no traffic was applied during the drought, while C3 grasses declined in turf quality and percent green cover at both traffic treatments during the drought. This does not imply the C4 grasses have lower traffic tolerance. Rather, when traffic occurs during drought stress, there is less chance for a decline in C3 grasses because they are already in poorer shape than C4 grasses, even before traffic stress is applied. Nevertheless, if traffic is applied to C3 grasses during drought stress, turf quality and green cover will decrease faster than if no traffic was applied. Also, trafficked C4 grass plots had higher turf quality and green cover than trafficked C3 grass plots and at times non-trafficked C3 grass plots. Across all four turf species, the higher rough mowing height was more negatively impacted by traffic during drought than the lower fairway mowing height. At both traffic treatments and both mowing heights, the C4 grasses had the fastest recovery times, as both C4 grasses were generally the slowest to lose green cover and turf quality during the drought.

As the soil water content decreased, the surface of the turf species became more firm, especially at the lower mowing height. This effect was enhanced by the application of traffic, especially at the higher mowing height. The influence of traffic on turf firmness will depend on a variety of soil factors such as soil moisture and turf species. The turf firmness may affect playability or the safety of the surface; therefore, it is an important factor to consider during times of drought. Therefore, turf managers will see negative and accelerated impacts on turfgrass shoots from traffic application during a drought period.

In soil compaction measurements, minimal and inconsistent differences occurred between turf species. Also, mowing height and traffic treatments resulted in no significant differences in soil bulk density at 0-6 cm and soil penetration resistance at 0 cm, 2.54 cm, 5.08 cm, 7.62 cm, and 10.16 cm depths. The decreased soil moisture during drought may have diminished differences in soil compaction measurements, especially between trafficked and non-trafficked plots. Therefore, during a drought, traffic may not increase soil bulk density or soil penetration resistance in turfgrass. Similar to soil compaction measurements, most of the differences in root measurements at 0-30.5 cm were due to turf species and/or mowing height, with no differences between traffic treatments. At the end of 41-day drought, the two C3 grasses had higher root biomass, surface area, and root length density in the upper soil profile than the two C4 grasses. However, buffalograss, zoysiagrass, and perennial ryegrass had larger root diameters, which may have led to better soil compaction resistance and greater capabilities of exploring deeper depths, thus better drought performance than Kentucky bluegrass. Based on the above-ground performance, the C4 grasses possibly had more roots than the C3 grasses at non-measured depths below 30.5-cm, which would have allowed them to extract more water during the drought. Most differences measured within soil and root measurements were due to the effects of drought stress and not traffic stress, since the traffic main effect was not significant across all below-ground variables. Therefore, turf managers may see a minimal impact on soil and root characteristics from traffic application during a drought period.

Although turfgrass managers may see minimal impact on below-ground variables, they still need to be aware of traffic application during periods of drought, especially pertaining to above-ground variables. During times of drought stress, turfgrass managers need to closely monitor trafficked areas and/or possibly restrict traffic as drought stress increases. During drought stress, trafficked areas compared to non-trafficked areas will be more noticeable on warm-season (C4) grasses than cool-season (C3) grasses, due to the good drought tolerance of C4 grasses. During drought, C3 grasses will likely decline in turf quality and percent green cover more quickly than C4 grasses, and traffic will accelerate this decline. Regardless of turf species, if traffic must be allowed on the turfgrass during times of drought stress, I would advise turfgrass managers to direct traffic to stay on the lower mowing height (fairway) and limit traffic on the higher mowing height (rough). Turfgrass managers can also direct traffic with stakes, ropes, signs, and, if severe drought, possibly only allow traffic on cart paths. Also, it’s important to keep the customers and turf users (homeowners, park users, etc.) informed during times of drought stress and the importance of limiting traffic or possibly changing the mowing patterns during times of stress. If traffic can be properly managed during a drought period, areas that are the slowest to lose green cover will typically be the faster to recover once the drought period has ended.

Appendix A - Additional Tables for Chapter 2

Table A.1. Minimum positive and negative detection limits for the Hutchinson and Mosier (1981) (H/M) and linear regression (LR) techniques and analytical precision (% coefficient of variation, CV) for each measurement date.

Minimum detection limit (µg N_2O-N m^{-2} h^{-1})†

Day of Year	302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200
Date	10/29/15	11/12/14	12/10/14	1/20/15	2/7/15	3/17/15	4/2/15	4/21/15	5/5/15	5/13/15	5/19/15	5/27/15	6/1/15	6/3/15	6/5/15	6/9/15	6/16/15	6/23/15	7/1/15	7/8/15	7/15/15	7/17/15	7/19/15
H/M	9.7	13.0	6.9	14.7	12.0	11.2	12.3	11.6	11.2	12.3	12.7	13.6	8.6	16.6	14.1	13.1	13.4	10.0	8.7	14.5	12.7	15.9	16.3
LR	2.4	3.2	1.7	3.7	3.0	2.8	3.1	2.9	2.8	3.1	3.2	3.4	2.1	4.1	3.5	3.3	3.3	2.5	2.2	3.6	3.2	4.0	4.1
% CV	1.9	3.0	1.6	3.2	2.7	2.4	3.1	2.4	2.6	2.8	2.6	3.1	1.8	3.1	2.8	2.6	3.1	1.9	2.1	2.9	2.2	2.8	3.0

Day of Year	203	211	216	223	231	238	252	265	278	299	326	339	352	14	44	74	96	112	124	131	139	143	153
Date	7/22/15	7/30/15	8/4/15	8/11/15	8/19/15	8/26/15	9/9/15	9/22/15	10/5/15	10/26/15	11/22/15	12/5/15	12/18/15	1/14/16	2/13/16	3/14/16	4/5/16	4/21/16	5/3/16	5/10/16	5/18/16	5/22/16	6/1/16
H/M	11.8	14.5	11.6	12.1	15.2	15.9	7.9	9.7	6.3	10.8	10.1	10.5	13.2	10.2	15.6	12.6	12.6	10.9	11.8	12.4	13.5	10.8	12.4
LR	2.9	3.6	2.9	3.0	3.8	4.0	2.0	2.4	1.6	2.7	2.5	2.6	3.3	2.5	3.9	3.1	3.1	2.7	2.9	3.1	3.4	2.7	3.1
% CV	2.0	2.9	2.3	2.6	2.7	2.9	1.8	3.1	2.1	2.7	3.0	3.2	2.7	2.4	2.9	2.8	2.4	2.5	2.6	2.5	2.8	3.1	2.5

Day of Year	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
Date	6/5/16	6/7/16	6/9/16	6/11/16	6/13/16	6/21/16	6/29/16	7/5/16	7/11/16	7/19/16	7/21/16	7/23/16	7/26/16	7/28/16	8/1/16	8/9/16	8/16/16	8/23/16	8/29/16	9/8/16	9/15/16	9/27/16	10/3/16
H/M	14.0	14.5	13.0	12.0	8.1	12.4	12.5	12.5	12.9	14.8	13.5	9.3	11.7	13.1	11.4	11.8	13.5	9.9	10.3	8.8	8.6	13.0	11.8
LR	3.5	3.6	3.2	3.0	2.0	3.1	3.1	3.1	3.2	3.7	3.4	2.3	2.9	3.3	2.8	2.9	3.4	2.5	2.6	2.2	2.2	3.2	2.9
% CV	2.5	2.3	2.1	2.1	1.2	2.3	2.3	2.2	2.3	2.6	2.3	1.6	2.0	2.0	1.9	2.6	2.6	2.0	1.8	1.8	1.6	2.5	2.2

† The detection limits for negative fluxes can be obtained by multiplying the positive values by -1.

Table A.2. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on daily nitrous oxide fluxes in ‘Meyer’ zoysiagrass in year 1, from October 2014 (DOY 302) to October 2015 (DOY 278).

ANOVA[†]																																	
		Day of Year (DOY)[‡]																															
Parameter	Source[§]	302	316	344	20	38	76	92	111	125	133	139	147	152[¶]	154	156	160	167	174	182	189	196	198*	200	203	211	216	223	231	238[¶]	252	265	278
N_2O-N Fluxes	Fertilizer	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	***	**	NS	NS	NS	NS	**	***	***	*	NS	**	NS	NS	NS	NS	NS	NS
	Irrigation	*	NS	NS	NS	*	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	**	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																															
Fertilizer		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
	UF	14.95	7.02	3.02	7.13	3.59	11.87	12.3	15.35	13.65	16.49	29.51	26.14	35.89	32.22 b	33.79 b	43.8 b	29.8	48.27	38.69	44.82	50.21 b	62.68 b	50.14 c	55.71 b	39.76	41.66 b	40.24	56.45	43.85	32.19	15.58	25.68
	PCU	18.25	7.36	5.91	6.10	4.33	8.85	12.2	16.83	13.43	17.48	30.23	31.94	39.84	34.76 b	38.24 b	44.11 b	38.3	57.82	40.60	49.18	66.8 a	67.53 b	65.49 b	62.49 ab	49.74	59.0 a	48.41	71.09	59.87	35.95	17.62	26.25
	Urea	18.72	6.86	5.54	8.58	3.9	13.32	14.43	17.15	14.36	19.89	27.37	28.33	37.43	498.3 a	127.74 a	54.22 a	39.0	58.2	43.94	45.74	55.81 b	881.48 a	94.09 a	68.43 a	49.74	48.98 ab	40.84	58.81	53.67	37.25	16.99	24.96
Irrigation		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
	33% ET_o	19.31 a[††]	7.14	4.69	7.21	2.95 b	11.81	13.35	16.78	13.04	20.12 a	28.63	29.37	39.55	202.31	62.78	46.89	39.38 a	54.56	41.91	45.85	59.98	314.12	64.87 b	61.2	43.06	49.36	39.89	58.76	48.26	34.04	17.22	24.7
	66% ET_o	15.30 b	7.02	4.96	7.33	4.92 a	10.88	12.6	16.11	14.58	15.79 b	29.44	28.24	35.89	174.54	70.4	47.86	32.01 b	54.97	40.24	47.31	55.23	360.34	74.95 a	63.22	49.77	50.4	46.44	65.48	56.66	36.22	16.24	26.56
FERT * IRR		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
	UF*33%	15.37	7.93	3.89	7.63	3.51	12.66	14.38	15.01	10.13	19.98	28.12	28.31	36.89 b	33.93	36.63	40.96 bc	29.67	54.06	38.89	43.79	50.01	68.48	49.78 e	58.64	36.38	44.21	38.3	56.7	39.82	27.95	16.52	23.02
	UF*66%	14.53	6.11	2.16	6.63	3.67	11.81	10.22	15.69	17.17	13.01	30.9	23.96	34.89 b	30.51	30.94	46.65 bc	29.94	42.48	38.49	45.84	50.41	56.89	50.5 de	52.78	43.13	39.1	42.18	56.19	47.87	36.42	14.64	28.34
	PCU*33%	21.14	7.98	4.43	5.74	2.56	9.28	9.22	17.59	13.95	18.95	29.05	32.39	45.97 a	35.07	33.08	39.04 c	42.31	51.93	39.08	45.83	69.42	65.73	63.66 cd	56.02	41.8	55.57	46.81	67.06	52.44	34.72	17.82	23.8
	PCU*66%	15.36	6.74	7.39	6.47	6.1	8.41	15.18	16.08	12.92	16.02	31.42	31.5	33.71 b	34.45	43.41	49.19 b	34.3	63.71	42.13	52.53	64.17	69.33	67.32 c	68.96	57.68	62.43	50.01	75.12	67.3	37.19	17.41	28.7
	UREA*33%	21.43	5.5	5.75	8.27	2.79	13.49	16.46	17.74	15.05	21.44	28.72	27.39	35.8 b	537.94	118.64	60.68 a	46.18	57.68	47.77	47.92	60.51	808.14	81.15 b	68.94	50.99	48.29	34.56	52.51	52.53	39.46	17.33	27.27
	UREA*66%	16.0	8.22	5.33	8.89	5.0	13.15	12.41	16.56	13.67	18.34	26.01	25.26	39.08 ab	458.67	136.85	47.76 bc	31.8	58.73	40.11	43.56	51.12	954.82	107.03 a	67.93	48.5	49.67	47.13	65.11	54.82	35.05	16.66	22.64

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for daily N_2O-N fluxes in Meyer zoysiagrass between October 2014, day of year (302) to October 2015 (278).

[‡] Day of Year (DOY), 302, 316, & 344 of year 2014, following day of year occurred in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of N_2O-N fluxes ($\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$)

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.3. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on daily nitrous oxide fluxes in ‘Meyer’ zoysiagrass in year 2, from October 2015 (DOY 299) to October 2016 (DOY 277).

		ANOVA[†]																																				
		Day of Year (DOY)[‡]																																				
Parameter	Source[§]	299	326	339	352	14	44	74	96	112	124	131	139	143	153[¶]	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242[¶]	252	259	271	277
N$_2$O-N Fluxes	Fertilizer	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	***	***	***	**	NS	*	NS	*	NS	***	***	NS	***	***	NS	NS	NS	NS	***	***	*	*
	Irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS	NS	NS	*	NS	**	*	NS	NS	NS	NS	*	**	**	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																																				
Fertilizer		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF		11.32	4.0 b[††]	4.11	1.63	3.3	4.25	13.3	9.65 b	16.2	17.55	32.45	32.36	23.66	38.87	53.27	62.16 b	66.55 b	63.86 b	49.92 b	63.89	65.07 b	67.19	70.37 ab	54.09	73.1 b	60.02 c	73.07	61.73 c	62.96 b	40.32	56.32	45.95	58.82	48.29 b	45.45 c	31.77 b	20.88 b
PCU		13.98	7.42 a	8.53	1.64	4.92	4.2	12.07	16.51 a	16.66	18.0	34.06	36.83	22.17	34.89	55.72	73.44 b	60.4 b	64.84 b	51.29 b	70.28	64.58 b	69.03	66.84 b	55.32	71.77 b	79.93 b	76.56	71.18 b	58.89 b	43.78	57.6	48.29	58.52	60.18 a	52.37 b	31.8 b	23.7 ab
Urea		13.39	4.57 ab	7.66	1.66	4.83	3.26	13.62	13.88 ab	15.25	18.71	28.3	35.12	23.81	37.52	51.52	318.14 a	111.2 a	91.55 a	64.06 a	68.07	77.32 a	76.63	77.32 a	64.51	300.9 a	96.47 a	87.2	97.91 a	83.39 a	45.81	58.7	51.86	60.65	66.44 a	60.14 a	37.62 a	27.41 a
Irrigation		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
33% ET$_o$		13.96	4.87	7.07	1.16	4.82	3.24	12.92	13.17	17.32	19.2	31.78	33.4	23.67	39.68	54.42	126.91 b	79.19	71.12	53.77	61.71 b	65.38	68.03	70.79	55.88	131.7	74.23 b	78.12	72.48 b	63.51 b	45.65	60.77	47.28	59.16	61.36 a	56.34 a	36.34 a	25.06
66% ET$_o$		11.83	5.8	6.46	2.13	3.88	4.57	13.08	13.52	14.81	16.97	31.43	36.14	22.75	34.5	52.58	175.59 a	79.57	75.73	56.41	73.12 a	72.6	73.88	72.23	60.07	165.5	83.38 a	79.76	81.4 a	73.32 a	40.95	54.31	50.12	59.51	55.24 b	48.96 b	31.12 b	22.93
FERT * IRR		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF*33%		11.58	3.09	4.15	1.08	3.03	4.72	12.99	8.6	19.69	17.2	28.78	32.44	24.34	44.23	53.04	65.04 c	66.58	61.22	52.47	58.19 b	60.03	62.8	72.01	50.71	70.78	62.34 b	69.18	60.25	61.65	44.5	61.75	44.25	60.39	51.96	48.2	31.73	22.05
UF*66%		11.05	4.92	4.07	2.18	3.58	3.79	13.6	10.71	12.9	17.91	36.13	32.28	22.98	33.5	53.51	59.29 c	66.53	66.5	47.37	69.58 ab	70.11	71.58	68.74	57.48	75.41	57.7 b	76.96	63.21	64.27	36.14	50.89	47.64	57.25	44.63	42.69	31.8	19.7
PCU*33%		14.38	8.22	9.11	0.84	5.25	3.63	13.17	17.65	17.9	17.93	35.41	36.31	22.77	34.47	58.1	75.8 c	59.87	64.08	44.23	57.15 b	56.14	64.45	65.13	52.14	71.01	67.74 b	78.45	66.62	50.04	48.8	58.25	48.76	55.18	59.21	55.98	34.82	24.53
PCU*66%		13.58	6.63	7.95	2.45	4.58	4.76	10.98	15.37	15.42	18.07	32.72	37.34	21.57	35.3	53.33	71.07 c	60.93	65.6	58.35	83.41 a	73.02	73.62	68.54	58.49	72.52	92.13 a	74.67	75.75	67.74	38.75	56.95	47.82	61.87	61.15	48.77	28.79	22.86
UREA*33%		15.92	3.3	7.95	1.57	6.18	1.36	12.59	13.27	14.3	22.49	31.16	31.46	23.92	40.34	52.13	239.89 b	111.12	88.03	64.62	69.8 ab	79.97	76.83	75.22	64.78	253.3	92.61 a	86.74	90.58	78.84	43.66	62.31	48.83	61.9	72.92	64.83	42.48	28.61
UREA*66%		10.86	5.85	7.37	1.76	3.49	5.17	14.65	14.48	16.1	14.93	25.43	38.79	23.7	34.7	50.9	396.4 a	111.3	95.08	63.5	66.34 b	74.68	76.43	79.41	64.25	348.6	100.3 a	87.66	105.23	87.94	47.96	55.09	54.89	59.4	59.96	55.44	32.76	26.22

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for daily N$_2$O-N fluxes (μg N m^{-2} h^{-1}) evaluated in ‘Meyer’ zoysiagrass between October 2015, day of year (299) to October 2016 (277).

[‡] Day of Year (DOY), 299, 326, 339, & 352 of year 2015, following day of year occurred in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET$_o$) replacement and 66% ET$_o$ replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of N$_2$O-N fluxes (μg N$_2$O-N m^{-2} h^{-1})

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.4. Analyses fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on cumulative nitrous oxide emissions in 'Meyer' zoysiagrass over a two-year period between October 2014 to October 2016.

Source of variation	Year 1	Year 2	Total
	Cumulative N_2O-N Emissions[†]		
	N_2O-N kg ha^{-1} yr^{-1}	N_2O-N kg ha^{-1} yr^{-1}	N_2O-N kg ha^{-1}
Fertilizer[‡]			
Unfertilized (UF)	1.82 c[‡]	2.24 c[‡]	4.06 c[‡]
Polymer-coated urea (PCU)	2.09 b	2.41 b	4.50 b
Urea	2.77 a	2.85 a	5.62 a
Irrigation			
33% ET_o	2.20	2.48	4.68
66% ET_o	2.25	2.52	4.77
Fertilizer x Irrigation			
UF*33%	1.82	2.25	4.07
UF*66%	1.81	2.23	4.04
PCU*33%	1.98	2.38	4.36
PCU*66%	2.19	2.46	4.64
UREA*33%	2.78	2.83	5.61
UREA*66%	2.76	2.88	5.63

ANOVA

Source	p-value		
Fertilizer	**<.0001**	**<.0001**	**<.0001**
Irrigation	0.3298	0.3890	0.2180
Fertilizer x Irrigation	0.2006	0.6493	0.2093

[†] Cumulative emissions measured in 'Meyer' zoysiagrass at the Rocky Ford Turfgrass Research Center, Manhattan, KS in year 1 [October 2014, day of year (302) to October 2015 (278)], year 2 [October 2015, (299) to October 2016 (277)], and total emissions over the 2-year period.

[‡] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.01$).

Table A.5. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on water-filled pore space (WFPS) in 'Meyer' zoysiagrass in year 1, from October 2014 (DOY 302) to October 2015 (DOY 278).

		ANOVA[†]																															
		Day of Year (DOY)[‡]																															
Parameter	Source[§]	302	316	344	20	38	76	92	111	125	133	139	147	152[¶]	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238[¶]	252	265	278
WFPS	Fertilizer	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*	*	NS	NS	NS	NS	NS	*	**	NS	NS	NS	NS	**	*
	Irrigation	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	**	***	***	***	*	NS	***	***	***	***	***	***	***	*	**	***
	FERT*IRR	NS	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	**	NS	*	*	NS	NS	NS
		LS Means[#]																															
Fertilizer		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF		73.9	55.4 b[††]	62.5	48.8	57.6	50.8	73.2	71.0	81.8	73.9	74.3	82.2	78.9	88.5	94.5	88.7	87.8 a	82.3 a	75.8 a	79.3	86.3	90.7	81.4	82.1	70.1 a	80.1 a	84.5	73.6	69.6	82.9	92.4 a	74.2 a
PCU		72.7	60.7 a	63.5	46.3	57.6	51.8	72.3	70.4	80.1	73.2	73.4	81.4	77.7	87.4	94.0	88.1	87.1 ab	82.8 a	72.2 b	78.4	85.3	91.6	80.8	81.6	67.2 ab	75.1 b	83.1	72.3	69.6	82.5	91.7 a	72.0 ab
Urea		73.5	57.5 ab	64.3	45.7	57.2	51.1	71.8	69.2	80.2	72.7	73.7	81.5	77.5	89.4	94.1	86.5	85.8 b	77.8 b	71.2 b	75.5	83.8	92.5	80.9	78.4	64.8 b	71.7 b	79.4	70.6	66.7	80.7	89.1 b	71.1 b
Irrigation		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
33% ET_o		72.9	56.4	62.6	48.4	58.5 a	51.0	72.5	69.9	81.2	72.9	73.8	81.5	77.8	88.0	94.3	87.0 b	85.9 b	75.4 b	66.6 b	73.3 b	82.9 b	90.2	78.3 b	77.9 b	59.5 b	62.0 b	73.1 b	64.4 b	61.5 b	80.6 b	89.6 b	69.8 b
66% ET_o		73.8	59.3	64.3	45.6	56.4 b	51.4	72.4	70.5	80.2	73.6	73.9	81.9	78.3	88.9	94.1	88.5 a	87.8 a	86.5 a	79.5 a	82.1 a	87.3 a	92.9	83.8 a	83.4 a	75.3 a	89.3 a	91.6 a	80.0 a	75.8 a	83.5 a	92.6 a	75.1 a
FERT * IRR		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF*33%		71.3	56.1 b	62.9	50.3	60.1	49.9 b	72.8	70.6	81.7	73.8	74.5	81.9	79.2	87.5	94.2	87.7	86.7	78.3	70.9	75.3	82.8	89.0	78.1	80.4	65.4 b	71.6 b	77.8	68.9 b	64.5 c	81.8	91.6	72.4
UF*66%		76.5	54.7 b	62.1	47.4	55.2	51.7 ab	73.6	71.3	81.8	74.0	74.2	82.6	78.6	89.6	94.9	89.6	89.0	86.1	80.7	83.3	89.9	92.4	84.7	83.7	74.8 a	88.5 a	91.2	78.3 a	74.8 b	84.0	93.2	76.0
PCU*33%		73.0	56.3 b	61.5	47.6	57.2	51.0 ab	72.6	70.2	81.1	73.0	73.1	81.3	76.7	87.5	94.1	87.9	86.5	77.0	64.7	74.0	83.7	90.5	78.9	78.1	58.0 c	58.4 c	72.9	62.9 c	60.3 d	81.2	89.2	69.1
PCU*66%		72.4	65.2 a	65.4	45.1	57.9	52.5 a	72.1	70.6	79.0	73.4	73.7	81.5	78.8	87.4	94.0	88.3	87.7	88.6	79.7	82.8	86.9	92.6	82.7	85.0	76.5 a	91.8 a	93.2	81.8 a	79.0 a	83.9	94.2	74.9
UREA*33%		74.5	56.9 b	63.2	47.2	58.3	52.3 ab	72.1	68.8	80.7	72.0	73.8	81.3	77.4	89.1	94.8	85.3	84.7	70.9	64.3	70.7	82.4	91.2	77.8	75.3	55.0 c	55.9 c	68.5	61.6 c	59.7 d	78.7	88.0	67.7
UREA*66%		72.4	58.1 b	65.4	44.3	56.1	50.0 b	71.5	69.5	79.8	73.5	73.7	81.7	77.6	89.8	93.5	87.7	86.9	84.6	78.1	80.3	85.2	93.8	84.0	81.6	74.7 a	87.5 a	90.2	79.7 a	73.7 b	82.6	90.3	74.4

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for water-filled pore space in 'Meyer' zoysiagrass between October 2014, day of year (302) to October 2015 (278).

[‡] Day of Year (DOY), 302, 316, & 344 of year 2014, following day of year occurred in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of water-filled pore space (v v^{-1}) calculated from volumetric soil water content (cm^3/cm^3) at a 7.6 cm depth using a Field Scout TDR 300 (5 measurements per plot) [100 * volumetric water content / total pore space (0.480 cm^3 cm^{-3})].

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.05$).

Table A.6. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on water-filled pore space (WFPS) in 'Meyer' zoysiagrass in year 2, from October 2015 (DOY 299) to October 2016 (DOY 277).

		ANOVA[†]																																				
		Day of Year (DOY)[‡]																																				
Parameter	Source[§]	299	326	339	352	14	44	74	96	112	124	131	139	143	153[¶]	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242[¶]	252	259	271	277
WFPS	Fertilizer	*	NS	*	*	NS	*	NS	*	*	*	NS	NS	NS	*	NS	NS	*	*	NS	NS	*	*	**	*	NS	NS	*	*	**	*	***	*	***	NS	*	NS	NS
	Irrigation	**	*	**	NS	NS	*	***	*	NS	NS	NS	NS	*	*	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	**	**
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	**	NS	NS
		LS Means[#]																																				
Fertilizer		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF		86.4 a[††]	75.1	74.8 a	65.5 a	46.5	55.2 a	70.4	62.9 a	74.1 a	69.8 a	63.1	77.0	71.8	77.7 a	64.9	73.4	64.9 a	79.8 a	67.2	74.9	78.4 a	79.7 a	63.6 a	66.3 a	75.0	78.1	69.1 a	72.8 a	70.8 a	83.0 a	80.6 a	73.6 a	71.5 a	80.5	88.2 a	78.5	78.6
PCU		83.9 ab	73.2	72.3 b	63.0 ab	46.4	53.9 ab	69.5	61.8 a	71.7 ab	69.2 ab	63.1	74.2	70.2	75.3 ab	61.2	71.2	59.7 b	76.0 ab	63.4	70.1	72.5 b	73.3 b	57.7 b	62.4 ab	72.7	74.4	63.6 b	66.7 b	64.5 b	75.7 b	73.6 b	67.7 b	64.1 b	78.2	84.0 b	76.4	76.4
Urea		83.0 b	72.7	72.2 b	61.3 b	44.8	52.6 b	68.1	58.1 b	70.5 b	67.2 b	61.5	74.5	69.8	73.7 b	61.8	69.7	58.3 b	73.0 b	62.9	68.8	72.0 b	75.1 b	57.2 b	59.6 b	71.2	72.3	63.8 b	67.2 b	63.1 b	77.9 ab	71.4 b	67.2 b	61.0 b	77.8	84.7 b	78.0	75.5
Irrigation		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
33% ET_o		83.0 b	72.3 b	72.0 b	62.5	46.1	53.2 b	67.8 b	59.7 b	71.6	68.0	61.6	75.2	69.1 b	74.4 b	59.5 b	63.9 b	54.5 b	66.3 b	55.8 b	60.2 b	62.6 b	63.2 b	48.7 b	54.0 b	63.2 b	63.5 b	55.2 b	57.2 b	53.4 b	64.5 b	60.2 b	57.3 b	53.5 b	70.3 b	80.1 b	75.7 b	74.2 b
66% ET_o		85.9 a	75.1 a	74.2 a	64.1	45.8	54.6 a	70.9 a	62.2 a	72.6	69.5	63.6	75.2	72.1 a	76.8 a	65.8 a	79.0 a	67.4 a	86.2 a	73.2 a	82.4 a	86.0 a	88.9 a	70.3 a	71.5 a	82.6 a	86.4 a	75.8 a	80.6 a	78.9 a	93.2 a	90.2 a	81.7 a	77.5 a	87.4 a	91.1 a	79.5 a	79.4 a
FERT * IRR		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF*33%		85.0	73.3	73.7	65.4	46.0	54.2	68.1	60.7	73.3	68.5	61.8	76.5	70.4	76.8	61.9	66.7	59.6	70.8	60.4	66.5	68.9	69.3	53.9	57.0	66.6	67.1	60.1	63.5	60.4	71.9	68.3	64.2	62.5 c	73.3	84.9 b	76.3	77.3
UF*66%		87.8	77.0	76.0	65.5	47.1	56.2	72.7	65.2	74.9	71.1	64.4	77.5	73.1	78.5	67.8	80.1	70.2	88.8	73.9	83.3	87.9	90.0	73.3	75.5	83.3	89.1	78.0	82.0	81.2	94.0	92.8	83.1	80.4 a	87.8	91.5 a	80.7	79.8
PCU*33%		81.9	72.2	71.0	60.8	46.6	53.0	68.1	60.9	70.9	68.9	62.2	73.4	68.9	73.4	58.0	63.3	54.3	65.5	55.1	58.2	60.6	58.8	46.7	53.4	62.9	63.7	52.2	54.1	50.2	59.5	57.9	55.1	49.6 d	68.0	76.1 c	74.1	73.3
PCU*66%		85.9	74.3	73.7	65.2	46.2	54.7	71.0	62.6	72.5	69.5	64.0	75.0	71.6	77.3	64.4	79.0	65.1	86.5	71.7	82.0	84.4	87.8	68.7	71.3	82.4	85.1	75.0	80.3	78.9	91.9	89.2	80.2	78.6 ab	88.4	91.8 a	78.7	79.4
UREA*33%		82.2	71.5	71.4	61.2	45.5	52.4	67.2	57.4	70.7	66.6	60.7	75.8	68.1	73.0	58.6	61.5	49.7	62.7	51.8	55.9	58.3	61.4	45.5	51.5	60.2	59.6	53.2	54.1	49.6	62.2	54.4	52.6	48.3 d	69.5	79.4 c	76.8	71.9
UREA*66%		83.9	73.9	73.0	61.5	44.2	52.8	69.0	58.9	70.4	67.8	62.3	73.2	71.5	74.5	65.1	77.8	66.9	83.2	74.0	81.7	85.8	88.8	68.9	67.6	82.2	85.0	74.5	79.4	76.6	93.6	88.5	81.8	73.6 b	86.0	90.0 a	79.1	79.1

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for volumetric water content in 'Meyer' zoysiagrass between October 2015, day of year (299) to October 2016 (277).

[‡] Day of Year (DOY), 299, 326, 339, & 352 of year 2015, following day of year occurred in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of water-filled pore space (v v^{-1}) calculated from volumetric soil water content (cm^3/cm^3) at a 7.6 cm depth using a Field Scout TDR 300 (5 measurements per plot) [100 * volumetric water content / total pore space (0.480 cm^3 cm^{-3})].

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.05$).

Table A.7. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on soil temperature (°C) in ‘Meyer’ zoysiagrass in year 1, from October 2014 (DOY 302) to October 2015 (DOY 278).

		ANOVA[†]																															
		Day of Year (DOY)[‡]																															
Parameter	Source[§]	302	316	344	20	38	76	92	111	125	133	139	147	152[¶]	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238[¶]	252	265	278
Soil Temp	Fertilizer	*	*	***	NS	NS	NS	*	**	NS	NS	*	NS	**	***	*	NS	**	***	**	**	***	***	***	***	***	**	***	**	**	**	NS	NS
	Irrigation	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	***	NS	NS	*	NS	**	**	NS	NS	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

	LS Means[#]																														
Fertilizer	302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF	12.1 b	3.0 b	2.7 b	-0.2	0.1	9.4	13.4 a	10.4 b	17.2	15.5	17.2 b	18.2	18.9 b	21.1 c	20.9 b	22.9	21.9 b	25.2 b	25.7 b	22.1 b	27.0 b	27.6 b	28.1 b	24.6 b	24.7 b	27.5 b	25.6 c	21.9 b	21.3 b	23.7 b	21.3	17.0
PCU	12.6 a	3.9 a	3.1 a	-0.2	0.2	9.3	13.3 b	10.9 a	17.2	15.7	17.5 a	18.3	19.1 a	21.2 b	21.0 ab	23.1	22.1 a	25.5 a	26.0 a	22.4 a	27.2 a	27.9 a	28.3 a	25.0 a	25.2 a	27.7 a	26.0 a	22.4 a	21.6 a	23.9 a	21.4	17.2
Urea	12.4 ab[††]	3.5 a	3.0 a	-0.3	0.1	9.4	13.37 ab	10.7 a	17.2	15.5	17.5 a	18.2	19.0 a	21.3 a	21.1 a	23.0	22.1 a	25.5 a	25.9 ab	22.4 a	27.2 a	27.9 a	28.3 a	25.0 a	25.2 a	27.7 a	25.8 b	22.2 a	21.5 a	23.9 a	21.4	17.1
Irrigation	302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
33% ET_o	12.4	3.5	2.9	-0.1	0.3	9.5 a	13.4	10.6	17.2	15.6	17.4	18.2	19.0	21.2	21.0	23.0	22.0	25.3	25.9	22.3	27.1 b	27.7	28.2 b	24.8	25.0	27.5 b	25.7	22.0 b	21.4 b	23.8	21.4	17.1
66% ET_o	12.3	3.4	2.9	-0.4	0.1	9.3 b	13.4	10.6	17.2	15.5	17.4	18.2	19.0	21.3	21.1	22.9	22.0	25.4	25.9	22.3	27.2 a	27.8	28.3 a	24.9	25.0	27.7 a	25.9	22.3 a	21.6 a	23.9	21.3	17.1
FERT * IRR	302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF*33%	12.2	3.1	2.7	0.05	0.3	9.5	13.4	10.4	17.2	15.5	17.1	18.2	18.9	21.2	20.9	22.9	21.9	25.2	25.8	22.1	27.0	27.6	28.0	24.5	24.7	27.4	25.5	21.9	21.3	23.7	21.3	17.0
UF*66%	12.0	2.9	2.6	-0.4	-0.03	9.3	13.5	10.3	17.2	15.4	17.3	18.2	18.9	21.2	21.0	22.9	21.9	25.2	25.8	22.2	27.1	27.6	28.1	24.6	24.7	27.6	25.6	22.1	21.4	23.7	21.2	17.0
PCU*33%	12.6	3.7	3.0	-0.2	0.3	9.4	13.3	10.8	17.3	15.7	17.5	18.3	19.1	21.2	21.0	23.1	22.1	25.4	26.0	22.4	27.2	27.8	28.2	24.9	25.2	27.7	25.9	22.2	21.5	23.9	21.4	17.2
PCU*66%	12.5	4.0	3.2	-0.3	0.2	9.3	13.3	10.9	17.2	15.6	17.6	18.3	19.1	21.3	21.1	23.0	22.1	25.5	26.0	22.5	27.3	28.0	28.5	25.1	25.2	27.7	26.1	22.5	21.7	23.9	21.3	17.2
UREA*33%	12.5	3.7	3.0	-0.3	0.2	9.5	13.4	10.7	17.2	15.6	17.6	18.2	19.0	21.3	21.1	23.0	22.1	25.5	25.9	22.4	27.1	27.9	28.3	25.0	25.2	27.7	25.7	22.1	21.4	23.9	21.4	17.2
UREA*66%	12.3	3.4	2.9	-0.4	0.1	9.2	13.4	10.7	17.2	15.4	17.4	18.3	19.0	21.3	21.1	22.9	22.1	25.5	26.0	22.4	27.3	27.9	28.4	25.0	25.1	27.8	25.9	22.3	21.6	23.9	21.3	17.0

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for soil temperature at a 7.6 cm soil depth in ‘Meyer’ zoysiagrass between October 2014, day of year (302) to October 2015 (278).

[‡] Day of Year (DOY), 302, 316, & 344 of year 2014, following day of year occurred in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of soil temperature (°C) at a 7.6 cm depth.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.8. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on soil temperature (°C) in ‘Meyer’ zoysiagrass in year 2, from October 2015 (DOY 299) to October 2016 (DOY 277).

		ANOVA[†]																																				
		Day of Year (DOY)[‡]																																				
Parameter	Source[§]	299	326	339	352	14	44	74	96	112	124	131	139	143	153[¶]	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242[¶]	252	259	271	277
Soil Temp	Fertilizer	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	***	*	***	*	***	**	**	NS	NS	***	*	***
	Irrigation	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	***	NS	*	*	NS	**	NS	***	***	***	***	NS	NS	***	***	NS	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																																				
Fertilizer		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF		11.4	5.6	5.3	0.9	-0.3	0.5	10.7	10.5	14.5	12.9	17.7	14.5	17.4	20.9	21.3	21.4	23.7	24.7	25.3	27.5	25.7	25.4	27.7	27.5	28.0 c	28.6 b	25.4 b	26.8 b	26.9 b	24.8 b	24.19 b	24.5 b	25.6	25.7	21.9 b	17.7 b	18.2 b
PCU		11.6	5.9	5.4	1.0	-0.3	0.5	10.7	10.5	14.6	12.8	17.7	14.6	17.4	20.9	21.3	21.5	23.7	24.8	25.3	27.5	25.7	25.5	27.7	27.5	28.1 b	28.7 a	25.5 a	27.0 a	27.0 a	25.0 a	24.44 a	24.7 a	25.7	25.8	22.0 a	18.1 a	18.5 a
Urea		11.6	5.8	5.4	0.9	-0.3	0.5	10.7	10.5	14.5	12.8	17.7	14.5	17.4	20.9	21.3	21.5	23.7	24.8	25.3	27.5	25.8	25.5	27.8	27.5	28.2 a	28.8 a	25.5 a	27.0 a	27.0 a	25.1 a	24.45 a	24.7 a	25.7	25.8	22.0 a	18.0 a	18.5 a
Irrigation		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
33% ET$_o$		11.6	5.7	5.4	1.0	-0.3	0.5	10.7 b[††]	10.5	14.5	12.8	17.7	14.5	17.4	20.9	21.3	21.5	23.7	24.8	25.2 b	27.4	25.6	25.5	27.7 b	27.5 b	28.1	28.6 b	25.4	26.9 b	26.9 b	24.9 b	24.2 b	24.6	25.6	25.7 b	21.9 b	17.9	18.4
66% ET$_o$		11.5	5.8	5.4	0.9	-0.3	0.5	10.8 a	10.5	14.6	12.8	17.7	14.5	17.4	20.9	21.3	21.5	23.7	24.8	25.3 a	27.5	25.8	25.5	27.8 a	27.6 a	28.1	28.7 a	25.5	27.1 a	27.0 a	25.1 a	24.5 a	24.6	25.7	25.8 a	22.0 a	18.0	18.4
FERT * IRR		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF*33%		11.4	5.5	5.3	0.9	-0.3	0.5	10.7	10.5	14.5	12.9	17.7	14.5	17.4	20.9	21.3	21.4	23.7	24.7	25.2	27.4	25.7	25.4	27.7	27.4	28.0	28.6	25.3	26.8 d	26.8	24.8	24.1	24.5	25.6	25.7	21.9	17.7	18.2
UF*66%		11.4	5.7	5.3	0.9	-0.3	0.5	10.7	10.4	14.5	12.8	17.7	14.5	17.4	20.9	21.3	21.4	23.7	24.8	25.3	27.5	25.8	25.5	27.7	27.5	28.0	28.6	25.4	26.9 c	26.9	24.9	24.3	24.6	25.6	25.8	21.9	17.8	18.2
PCU*33%		11.7	5.9	5.4	1.0	-0.3	0.5	10.7	10.5	14.6	12.8	17.7	14.6	17.4	20.9	21.3	21.6	23.7	24.7	25.2	27.5	25.6	25.5	27.7	27.5	28.2	28.7	25.5	26.9 c	27.0	24.9	24.3	24.6	25.7	25.7	22.0	18.0	18.5
PCU*66%		11.6	5.9	5.4	1.0	-0.3	0.5	10.8	10.5	14.6	12.8	17.7	14.5	17.4	21.0	21.3	21.5	23.7	24.8	25.3	27.5	25.8	25.5	27.8	27.6	28.1	28.7	25.5	27.1 b	27.1	25.1	24.6	24.7	25.7	25.8	22.1	18.1	18.5
UREA*33%		11.7	5.7	5.4	1.0	-0.3	0.5	10.7	10.5	14.5	12.8	17.7	14.6	17.4	21.0	21.2	21.5	23.8	24.8	25.3	27.4	25.7	25.5	27.7	27.5	28.2	28.7	25.5	26.9 c	26.9	24.9	24.2	24.6	25.6	25.7	22.0	17.9	18.6
UREA*66%		11.5	5.8	5.3	0.8	-0.3	0.5	10.8	10.5	14.5	12.7	17.7	14.4	17.4	20.9	21.3	21.5	23.7	24.8	25.3	27.5	25.9	25.6	27.8	27.6	28.2	28.9	25.6	27.2 a	27.1	25.2	24.7	24.7	25.7	25.8	22.1	18.0	18.5

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for soil temperature at a 7.6 cm soil depth in ‘Meyer’ zoysiagrass between October 2015, day of year (299) to October 2016 (277).

[‡] Day of Year (DOY), 299, 326, 339, & 352 of year 2015, following day of year occurred in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET$_o$) replacement and 66% ET$_o$ replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of soil temperature (°C) at a 7.6 cm depth.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.9. Spearman correlation coefficients of variables measured in a stand of 'Meyer' zoysiagrass over a two-year period from October 2014 to October 2016.

	Spearman Correlation Coefficients[†]			
	N_2O-N[‡]	**Soil Temp[§]**	**WFPS[¶]**	**NO_3^- [#]**
N_2O-N	-			
Soil Temp	**0.834*****	-		
WFPS	**0.229*****	**0.295*****	-	
NO_3^-	**0.163*****	**0.118*****	**0.066*****	-
NH_4^+ [††]	-0.021	-0.004	**0.072*****	0.016

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] N = 2484

[‡] N_2O-N fluxes (µg N m^{-2} h^{-1}).

[§] Soil temperature (°C) at a 7.6 cm depth.

[¶] Water-filled pore space (WFPS) (v v^{-1}) at a 7.6 cm depth [100 * volumetric water content / total pore space (0.480 cm^3 cm^{-3})].

[#] Soil nitrate content (NO_3^-) (mg kg^{-1} of soil) from 0 to 12.7 cm depth.

[††] Soil ammonium (NH_4^+) (mg kg^{-1} of soil) from 0 to 12.7 cm depth.

Table A.10. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on soil nitrate (NO_3^-) content in 'Meyer' zoysiagrass in year 1, from October 2014 (DOY 302) to October 2015 (DOY 278).

		ANOVA[†]																															
		Day of Year (DOY)[‡]																															
Parameter	Source[§]	302	316	344	20	38	76	92	111	125	133	139	147	152[¶]	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238[¶]	252	265	278
Soil NO_3^-	Fertilizer	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	***	***	**	NS	*	***	*	NS	**	NS	*	NS	NS	*	NS	NS	*	***	*
	Irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	***	NS	NS	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS
		LS Means[#]																															
Fertilizer		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF		1.15	1.63	1.27	1.93	2.68	1.90	1.61	1.05 b[††]	1.33	1.84	1.81	1.12	1.28	0.94 b	0.66 b	1.10 b	0.87	1.13 b	1.50 b	1.26 b	1.50	1.71 b	2.23	1.38 b	1.39	1.32	1.18 b	1.17	1.62	1.33 b	1.50 c	0.94 b
PCU		1.21	1.63	1.30	2.20	2.92	2.19	1.60	1.06 b	1.31	1.84	2.03	1.00	1.24	0.91 b	0.59 b	1.07 b	0.87	1.26 ab	2.43 a	1.53 a	1.63	1.89 b	2.99	1.56 b	1.72	1.40	1.52 ab	1.36	1.81	1.62 a	1.70 b	1.03 ab
Urea		1.33	1.74	1.42	2.34	3.44	2.78	1.72	1.22 a	1.53	2.01	1.89	1.13	1.40	1.83 a	1.27 a	1.37 a	0.95	1.50 a	1.41 b	1.54 a	1.61	4.16 a	4.59	2.64 a	1.76	1.68	1.62 a	1.55	1.74	1.63 a	1.92 a	1.18 a
Irrigation		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
33% ET_o		1.27	1.74	1.34	2.18	3.12	2.32	1.66	1.14	1.40	1.96	2.06 a	1.13	1.32	1.23	0.72 b	1.26 a	0.91	1.31	1.59	1.36	1.56	2.61	3.09	1.81	1.47	1.31	1.28 b	1.28	1.50 b	1.55	1.74	1.06
66% ET_o		1.19	1.60	1.32	2.13	2.91	2.26	1.63	1.08	1.38	1.83	1.75 b	1.04	1.29	1.22	0.95 a	1.10 b	0.88	1.29	1.98	1.52	1.61	2.56	3.44	1.92	1.78	1.61	1.61 a	1.44	1.95 a	1.50	1.67	1.03
FERT * IRR		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF*33%		1.16	1.76	1.21	1.96	2.83	2.20	1.70	1.05	1.28	1.85	1.92	1.10	1.26	0.86	0.67 b	1.12	0.84	1.10	1.30	1.17	1.43	1.78	2.11	1.31	1.30	1.16	0.99	1.05	1.45	1.22	1.44 c	0.92
UF*66%		1.13	1.50	1.33	1.91	2.53	1.60	1.52	1.06	1.38	1.82	1.70	1.15	1.29	1.02	0.65 b	1.08	0.90	1.16	1.71	1.35	1.58	1.65	2.35	1.45	1.47	1.47	1.37	1.29	1.79	1.44	1.56 bc	0.95
PCU*33%		1.26	1.65	1.24	2.19	2.83	1.72	1.76	1.11	1.42	1.87	2.33	1.05	1.22	0.96	0.59 b	1.13	0.88	1.24	2.04	1.48	1.61	1.97	3.29	1.51	1.62	1.27	1.32	1.15	1.59	1.66	1.64 bc	1.01
PCU*66%		1.15	1.61	1.36	2.22	3.02	2.66	1.45	1.02	1.21	1.81	1.73	0.95	1.25	0.86	0.59 b	1.01	0.87	1.28	2.82	1.57	1.65	1.81	2.69	1.62	1.82	1.53	1.73	1.57	2.02	1.58	1.76 b	1.04
UREA*33%		1.38	1.81	1.56	2.24	3.70	3.04	1.51	1.27	1.51	2.15	1.94	1.24	1.48	1.88	0.90 b	1.53	1.02	1.58	1.42	1.44	1.63	4.10	3.89	2.60	1.49	1.51	1.52	1.65	1.44	1.76	2.15 a	1.25
UREA*66%		1.28	1.68	1.28	2.43	3.18	2.53	1.93	1.17	1.55	1.86	1.83	1.02	1.32	1.78	1.63 a	1.21	0.89	1.42	1.41	1.63	1.59	4.22	5.29	2.68	2.04	1.83	1.73	1.46	2.04	1.50	1.69 b	1.10

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance on soil nitrate (NO_3^-) content in 'Meyer' zoysiagrass between October 2014, day of year (302) to October 2015 (278).

[‡] Day of Year (DOY), 302, 316, & 344 of year 2014, following day of year occurred in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of soil nitrate content (mg kg^{-1} of soil) from 0 to 12.7 cm depth.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.05$).

Table A.11. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on soil nitrate (NO$_3^-$) content in 'Meyer' zoysiagrass in year 2, from October 2015 (DOY 299) to October 2016 (DOY 277).

		ANOVA[†]																																				
		Day of Year (DOY)[‡]																																				
Parameter	Source[§]	299	326	339	352	14	44	74	96	112	124	131	139	143	153[¶]	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242[¶]	252	259	271	277
Soil NO$_3^-$	Fertilizer	**	NS	*	NS	**	*	*	NS	*	NS	NS	*	NS	*	NS	*	*	**	NS	NS	**	NS	NS	NS	***	*	NS	NS	NS	**	NS	NS	NS	*	*	NS	NS
	Irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*	NS	**	***	***	**	NS	NS	**	**	NS	**	NS	NS	*	**	NS	NS	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																																				
Fertilizer		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF		0.82 b[††]	0.63	0.97 b	0.99	0.90 b	1.39 b	1.36 b	0.89	1.39 b	1.45	1.47	1.18 b	1.82	1.78 b	3.16	1.83 b	1.29 b	2.36 b	1.16	1.66	1.34 b	1.22	0.90	1.17	1.47 b	2.5 b	1.53	1.02	1.44	1.66 b	1.32	1.6	1.15	1.31 b	1.61 b	1.6	1.83
PCU		1.01 a	0.61	1.14 ab	1.24	1.04 b	1.6 ab	1.47 ab	0.99	2.03 a	1.53	1.59	1.52 a	2.02	1.84 b	3.64	1.82 b	1.56 b	2.69 b	1.24	1.87	1.56 b	1.28	1.01	1.32	2.25 b	3.28 ab	1.5	1.15	1.96	1.69 b	1.5	1.78	1.23	1.59 ab	2.02 ab	1.88	2.15
Urea		1.18 a	0.75	1.20 a	1.24	1.27 a	2.06 a	1.66 a	1.12	2.04 a	1.81	1.82	1.58 a	2.04	2.2 a	3.6	6.19 a	3.27 a	3.81 a	2.27	2.22	2.34 a	1.51	1.06	1.29	10.9 a	4.62 a	1.64	1.19	2.33	2.49 a	2.0	1.8	1.46	1.85 a	2.38 a	2.03	2.35
Irrigation		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
33% ET$_o$		1.02	0.75	1.16	1.24	1.06	1.82	1.57	1.01	1.8	1.7	1.7	1.47	2.0	1.97	3.66	2.18	1.85	2.49 b	1.09 b	1.75	1.36 b	1.03 b	0.79 b	0.99 b	4.06	3.12	1.39 b	0.94 b	1.61	1.57 b	1.48	1.59	1.07 b	1.35 b	1.86	1.77	2.18
66% ET$_o$		0.99	0.58	1.05	1.08	1.08	1.55	1.42	0.99	1.84	1.48	1.56	1.39	1.93	1.91	3.27	4.38	2.24	3.41 a	2.03 a	2.08	2.13 a	1.64 a	1.2 a	1.53 a	5.7	3.81	1.72 a	1.3 a	2.21	2.32 a	1.73	1.87	1.49 a	1.82 a	2.14	1.9	2.04
FERT * IRR		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF*33%		0.78	0.72	0.97	1.0	0.87	1.47	1.37	0.84	1.48	1.48	1.33	1.12	1.77	1.72 b	3.38	1.61	1.27	2.33	1.05	1.35	1.19	0.93	0.65	0.91	1.51	2.44	1.35	0.91	1.31	1.48	1.21	1.41	0.95	1.23	1.42	1.47	1.66
UF*66%		0.85	0.54	0.97	0.98	0.92	1.31	1.34	0.94	1.3	1.41	1.6	1.23	1.87	1.85 b	2.94	2.05	1.31	2.39	1.27	1.96	1.48	1.51	1.16	1.42	1.44	2.56	1.71	1.14	1.56	1.84	1.44	1.79	1.34	1.38	1.8	1.72	2.0
PCU*33%		0.96	0.72	1.18	1.33	1.06	1.65	1.57	1.02	1.78	1.64	1.6	1.44	2.04	1.71 b	3.72	2.04	1.09	2.25	1.07	1.73	1.56	0.91	0.69	0.87	1.93	2.54	1.32	0.97	2.01	1.82	1.13	1.6	0.94	1.26	1.73	1.75	2.18
PCU*66%		1.06	0.51	1.1	1.15	1.02	1.56	1.36	0.96	2.3	1.41	1.58	1.6	2.0	1.97 b	3.56	1.6	2.03	3.13	1.42	2.01	3.12	1.66	1.34	1.76	2.58	4.02	1.68	1.33	1.91	2.2	1.87	1.96	1.51	1.93	2.31	2.0	2.12
UREA*33%		1.31	0.80	1.33	1.39	1.24	2.33	1.76	1.16	2.18	2.0	2.16	1.84	2.19	2.48 a	3.87	2.88	3.18	2.91	1.15	2.18	1.34	1.27	1.03	1.19	8.73	4.39	1.52	0.95	1.51	2.05	2.09	1.76	1.33	1.56	2.43	2.08	2.7
UREA*66%		1.06	0.70	1.07	1.11	1.31	1.79	1.56	1.09	1.91	1.62	1.48	1.33	1.9	1.93 b	3.32	9.5	3.37	4.71	3.4	2.26	1.56	1.76	1.1	1.39	13.1	4.85	1.77	1.44	3.15	2.93	1.89	1.85	1.6	2.14	2.33	1.98	2.0

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance on soil nitrate (NO$_3^-$) content in 'Meyer' zoysiagrass between October 2015, day of year (299) to October 2016 (277).

[‡] Day of Year (DOY), 299, 326, 339, & 352 of year 2015, following day of year occurred in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET$_o$) replacement and 66% ET$_o$ replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of soil nitrate content (mg kg^{-1} of soil) from 0 to 12.7 cm depth.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.05$).

Table A.12. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on soil ammonium (NH_4^+) content in 'Meyer' zoysiagrass in year 1, from October 2014 (DOY 302) to October 2015 (DOY 278).

		ANOVA[†]																															
		Day of Year (DOY)[‡]																															
Parameter	Source[§]	302	316	344	20	38	76	92	111	125	133	139	147	152[¶]	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238[¶]	252	265	278
Soil NH_4^+	Fertilizer	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	*	NS	*	**	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
	Irrigation	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																															
Fertilizer		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF		6.65	8.95	5.51	8.17	6.76	10.00	7.67	10.16	7.65	7.36	6.21	11.49	9.49	11.01 b	11.30	9.02	13.08	6.91	10.43 b	8.22	6.82 b	7.26 b	8.90	10.35	8.88 b	9.72	8.98	7.91	9.74	7.91	9.08	8.24
PCU		7.63	9.36	5.93	8.58	7.24	9.92	8.32	9.94	7.49	7.85	7.04	11.80	10.02	11.09 b	11.24	10.57	14.94	7.43	12.39 a	8.89	8.31 a	8.03 b	9.67	10.17	10.75 a	10.18	9.37	8.69	10.95	8.59	9.45	8.71
Urea		7.18	9.55	5.61	8.40	7.06	9.53	8.14	10.96	6.90	7.51	6.67	11.63	9.98	14.93 a	12.33	9.52	13.43	8.28	11.84 a	8.19	6.95 b	10.83 a	9.16	10.52	9.71 ab	9.86	9.38	8.32	10.68	8.59	8.28	8.62
Irrigation		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
33% ET$_o$		7.58 a[††]	9.31	5.67	8.41	6.91	9.93	8.22	10.47	7.50	7.75	6.54	11.51	9.69	12.68	11.80	10.17	13.90	7.98	11.63	8.52	7.36	9.09	9.40	10.65	10.25	9.67	9.14	8.52	11.13	8.44	8.66	8.66
66% ET$_o$		6.73 b	9.26	5.69	8.36	7.13	9.70	7.87	10.23	7.19	7.39	6.74	11.77	9.97	12.01	11.45	9.24	13.74	7.10	11.48	8.35	7.35	8.32	9.09	10.05	9.31	10.17	9.35	8.10	9.78	8.29	9.21	8.39
FERT * IRR		302	316	344	20	38	76	92	111	125	133	139	147	152	154	156	160	167	174	182	189	196	198	200	203	211	216	223	231	238	252	265	278
UF*33%		6.90	8.77	5.53	8.17	6.70	10.11	8.33	10.02	7.72	7.37	5.57	11.20	9.27	11.49	11.61	9.24	12.65	7.17 b	9.95	8.25	7.04	7.30	8.52	10.58	9.45	9.20	9.45	7.95	10.46	7.95	8.85	8.26
UF*66%		6.41	9.13	5.48	8.18	6.82	9.88	7.02	10.31	7.58	7.35	6.86	11.78	9.70	10.53	10.99	8.81	13.52	6.65 b	10.90	8.20	6.61	7.22	9.28	10.12	8.32	10.23	8.51	7.88	9.03	7.86	9.30	8.22
PCU*33%		7.84	9.08	5.84	8.58	6.77	9.86	8.56	10.41	7.84	8.19	6.99	11.52	10.23	11.49	11.03	11.00	15.35	7.17 b	12.71	8.72	7.89	8.52	10.30	10.38	10.75	9.80	9.01	9.04	12.12	8.85	8.89	8.93
PCU*66%		7.42	9.65	6.02	8.58	7.71	9.98	8.07	9.46	7.14	7.51	7.09	12.08	9.81	10.70	11.44	10.14	14.54	7.69 b	12.07	9.06	8.72	7.53	9.04	9.96	10.76	10.55	9.74	8.33	9.79	8.33	10.01	8.49
UREA*33%		8.00	10.08	5.65	8.47	7.24	9.83	7.78	10.98	6.95	7.70	7.07	11.81	9.57	15.07	12.75	10.27	13.72	9.60 a	12.23	8.60	7.16	11.44	9.38	10.99	10.55	10.00	8.96	8.56	10.83	8.52	8.25	8.78
UREA*66%		6.37	9.02	5.57	8.34	6.87	9.23	8.51	10.93	6.85	7.32	6.28	11.44	10.40	14.80	11.90	8.76	13.15	6.97 b	11.46	7.79	6.73	10.22	8.94	10.05	8.87	9.73	9.81	8.08	10.53	8.67	8.30	8.46

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance on soil ammonium (NH_4^+) content in 'Meyer' zoysiagrass between October 2014, day of year (302) to October 2015 (278).

[‡] Day of Year (DOY), 302, 316, & 344 of year 2014, following day of year occurred in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET$_o$) replacement and 66% ET$_o$ replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of soil ammonium (NH_4^+) (mg kg^{-1} of soil) from 0 to 12.7 cm depth.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.05$).

Table A.13. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on soil ammonium (NH_4^+) content in 'Meyer' zoysiagrass in year 2, from October 2015 (DOY 299) to October 2016 (DOY 277).

		ANOVA[†]																																				
		Day of Year (DOY)[‡]																																				
Parameter	Source[§]	299	326	339	352	14	44	74	96	112	124	131	139	143	153[¶]	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242[¶]	252	259	271	277
Soil NH_4^+	Fertilizer	NS	NS	NS	*	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	*	**	NS	NS	NS	*	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
	Irrigation	NS	NS	NS	*	NS	NS	*	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																																				
Fertilizer		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF		10.46	3.9	9.26	7.61 b[††]	9.1	10.24	6.77 b	9.38	8.9	10.15	8.17	7.3	6.33	7.9	12.84 ab	3.61	6.62	6.67	6.71	8.94 b	8.89 b	7.47	5.07	12.23	8.74 b	7.78 b	5.15	8.6	4.14	5.58 b	9.5	5.71	4.19	6.95	4.16	5.4	5.22
PCU		10.61	4.27	9.54	7.8 ab	9.67	9.97	7.57 a	9.65	9.97	10.28	8.52	7.55	6.49	8.17	13.89 a	4.8	7.41	6.72	6.88	10.42 a	10.91 a	7.87	5.4	12.87	9.46 b	9.02 ab	5.66	9.05	4.44	6.68 a	9.52	6.63	4.85	8.28	4.32	5.55	5.46
Urea		10.21	3.99	9.66	8.3 a	9.94	9.88	6.66 b	9.78	10.06	10.62	8.09	8.26	6.04	8.37	12.13 b	5.82	10.73	7.33	7.21	9.08 b	9.28 b	7.28	5.08	12.73	11.29 a	9.83 a	5.5	9.89	4.55	5.74 b	9.42	5.49	4.45	8.99	3.68	4.89	4.87
Irrigation		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
33% ET_o		10.34	4.08	9.68	8.17 a	9.48	10.36	7.4 a	10.04 a	9.65	10.29	8.56	7.66	6.12	8.42	13.0	4.97	9.41	7.02	7.12	9.43	9.79	7.58	5.0	12.47	10.91 a	8.22 b	5.73	9.55	4.57	5.81	9.75	6.25	4.27	8.6	3.83	5.36	4.62 b
66% ET_o		10.51	4.03	9.29	7.64 b	9.66	9.7	6.6 b	9.16 b	9.64	10.4	7.95	7.74	6.45	7.87	12.91	4.51	7.1	6.81	6.74	9.53	9.59	7.5	5.36	12.75	8.75 b	9.55 a	5.15	8.81	4.17	6.2	9.2	5.64	4.72	7.55	4.28	5.2	5.75 a
FERT * IRR		299	326	339	352	14	44	74	96	112	124	131	139	143	153	157	159	161	163	165	173	181	187	193	201	203	205	208	210	214	222	229	236	242	252	259	271	277
UF*33%		10.5	3.98	9.54	7.66	8.89	11.03	6.99	9.77	8.81	9.71	7.81	7.03	6.13	7.9	12.58	3.5	6.54	6.96	6.83	9.12	8.97	7.29	4.97	11.82	9.28	7.48	5.43	8.8	3.99	5.49	9.93	5.63	4.04	7.11	4.2	5.8	4.22
UF*66%		10.42	3.83	8.98	7.56	9.32	9.44	6.54	8.99	9.0	10.59	8.53	7.57	6.53	7.9	13.11	3.72	6.71	6.39	6.59	8.76	8.81	7.64	5.17	12.65	8.21	8.1	4.88	8.39	4.28	5.67	9.07	5.79	4.34	6.79	4.12	5.0	6.22
PCU*33%		10.49	4.42	9.65	7.92	9.71	10.5	8.14	9.8	9.93	10.36	8.96	7.03	5.92	8.68	14.15	5.56	7.57	6.49	7.15	9.72	11.18	7.85	5.04	12.54	9.89	7.96	5.88	9.11	4.69	6.33	10.01	6.92	4.49	8.11	3.83	5.5	4.63
PCU*66%		10.73	4.12	9.42	7.69	9.63	9.44	7.01	9.49	10.01	10.19	8.07	8.06	7.05	7.66	13.63	4.04	7.25	6.96	6.61	11.12	10.64	7.9	5.75	13.2	9.04	10.09	5.45	9.0	4.18	7.04	9.03	6.35	5.2	8.45	4.82	5.61	6.3
UREA*33%		10.04	3.83	9.84	8.92	9.83	9.54	7.08	10.57	10.21	10.82	8.93	8.92	6.31	8.69	12.28	5.85	14.13	7.59	7.39	9.46	9.23	7.6	5.0	13.06	13.57	9.21	5.89	10.74	5.04	5.61	9.32	6.19	4.28	10.57	3.45	4.79	5.02
UREA*66%		10.38	4.15	9.47	7.68	10.05	10.22	6.24	9.0	9.9	10.43	7.25	7.6	5.78	8.05	11.99	5.78	7.34	7.08	7.03	8.71	9.32	6.95	5.16	12.4	9.0	10.45	5.12	9.05	4.05	5.88	9.51	4.79	4.63	7.41	3.9	4.98	4.73

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance on soil ammonium (NH_4^+) content in 'Meyer' zoysiagrass between October 2015, day of year (299) to October 2016 (277).

[‡] Day of Year (DOY), 299, 326, 339, & 352 of year 2015, following day of year occurred in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of soil ammonium (NH_4^+) ($mg\ kg^{-1}$ of soil) from 0 to 12.7 cm depth.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \le 0.05$).

Table A.14. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on visual quality in ‘Meyer’ zoysiagrass in year 1 (2015).

		ANOVA[†]																
		Day of Year (DOY)[‡]																
Parameter	Source[§]	147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
Visual Quality	Fertilizer	NS	*	***	***	***	***	***	***	***	***	**	**	NS	NS	NS	NS	**
	Irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	*	**	***	*	*
	FERT*IRR	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																
Fertilizer		147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
UF		7.7	7.6 b[††]	7.4 c	7.3 b	7.7 c	7.4 b	7.6 b	7.4 c	6.8 c	7.1 b	7.4 b	7.5 b	8.1	8.3	8.3	8.7	8.4 b
PCU		8.1	8.2 a	8.2 b	8.6 a	8.5 b	9.0 a	8.9 a	9.0 a	8.8 a	8.8 a	8.7 a	8.8 a	8.3	8.1	8.3	8.8	8.9 a
Urea		7.9	7.8 ab	8.6 a	8.8 a	8.9 a	8.8 a	8.6 a	7.9 b	8.3 b	8.8 a	8.2 a	8.2 a	8.0	8.0	7.8	8.4	8.8 a
Irrigation		147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
33% ET_o		7.9	7.8	8.1	8.1	8.4	8.3	8.3	8.1	7.8	8.2	7.8 b	7.9	7.8 b	7.7 b	7.6 b	8.3 b	8.6 b
66% ET_o		7.8	7.9	8.1	8.3	8.3	8.4	8.4	8.2	8.2	8.2	8.4 a	8.4	8.5 a	8.6 a	8.7 a	8.9 a	8.8 a
FERT * IRR		147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
UF*33%		7.7	7.5	7.5	7.0 c	7.8	7.2	7.3	7.3	6.5	6.8	7.2	7.2	7.7	8.0	7.8	8.3	8.3
UF*66%		7.7	7.7	7.3	7.5 c	7.5	7.7	7.8	7.5	7.2	7.3	7.7	7.8	8.5	8.7	8.7	9.0	8.5
PCU*33%		8.2	8.0	8.0	8.3 b	8.5	9.0	9.0	9.0	8.7	9.0	8.3	8.5	7.8	7.7	7.7	8.5	8.8
PCU*66%		8.0	8.3	8.3	8.8 ab	8.5	9.0	8.8	9.0	9.0	8.7	9.0	9.0	8.8	8.5	8.8	9.0	9.0
UREA*33%		8.0	7.8	8.7	9.0 a	9.0	8.8	8.7	7.8	8.3	8.8	7.8	8.0	7.8	7.3	7.2	8.2	8.5
UREA*66%		7.8	7.7	8.5	8.7 ab	8.8	8.7	8.5	8.0	8.3	8.7	8.5	8.3	8.2	8.7	8.5	8.7	9.0

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for visual quality evaluated in ‘Meyer’ zoysiagrass at the Rocky Ford Turfgrass Research Center, Manhattan, KS between May (DOY 147) to September 2015 (259)

[‡] Day of Year (DOY) in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of visual quality on a 1 to 9 scale where 1 = poorest color, uniformity, and density; 6 = acceptable quality, and 9 = optimum color, uniformity, and density.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.15. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on visual quality in ‘Meyer’ zoysiagrass in year 2 (2016).

		ANOVA[†]																		
		Day of Year (DOY)[‡]																		
Parameter	Source[§]	139	146	153[¶]	160	167	174	181	188	195	202	209	216	223	230	237	244[¶]	251	258	265
Visual Quality	Fertilizer	NS	NS	NS	***	***	***	***	**	***	***	***	**	***	***	*	***	***	***	***
	Irrigation	NS	NS	NS	NS	*	***	***	***	***	***	***	***	***	***	***	***	***	***	*
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		LS Means[#]																		
Fertilizer		139	146	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265
UF		6.2	6.4	6.2	6.4 b[††]	6.9 c	7.5 b	7.4 b	7.5 b	7.0 b	6.3 c	6.7 b	7.5 b	7.3 b	7.5 b	7.3 b	7.3 b	7.5 b	7.7 b	8.1 b
PCU		6.4	6.6	6.5	6.8 b	7.5 b	7.8 b	8.2 a	8.4 a	8.3 a	8.4 a	8.4 a	8.4 a	8.6 a	8.3 a	8.3 a	8.4 a	8.5 a	8.8 a	9.0 a
Urea		6.3	6.4	6.5	7.3 a	8.4 a	8.5 a	8.4 a	8.4 a	7.9 a	7.5 b	7.9 a	8.3 a	8.4 a	8.4 a	8.0 a	8.0 a	8.3 a	8.7 a	8.8 a
Irrigation		139	146	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265
33% ET_o		6.3	6.4	6.3	6.7	7.3 b	7.6 b	7.5 b	7.6 b	6.9 b	6.7 b	6.8 b	7.6 b	7.6 b	7.4 b	7.0 b	7.2 b	7.4 b	8.1 b	8.5 b
66% ET_o		6.3	6.6	6.5	6.9	7.9 a	8.3 a	8.5 a	8.6 a	8.5 a	8.1 a	8.5 a	8.6 a	8.7 a	8.7 a	8.7 a	8.7 a	8.7 a	8.7 a	8.8 a
FERT * IRR		139	146	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265
UF*33%		6.2	6.5	6.2	6.2	6.7	7.2	7.0	7.0	6.3	5.7	5.8	7.0	6.7	7.0	6.5	6.7	6.8	7.2	7.8
UF*66%		6.2	6.3	6.2	6.7	7.2	7.8	7.8	8.0	7.8	6.8	7.5	8.0	8.0	8.0	8.2	8.0	8.2	8.2	8.3
PCU*33%		6.3	6.5	6.5	6.5	7.2	7.3	7.5	7.8	7.5	7.8	7.8	8.0	8.2	7.5	7.5	7.8	8.0	8.7	9.0
PCU*66%		6.5	6.7	6.5	7.0	7.8	8.2	8.8	9.0	9.0	9.0	9.0	8.8	9.0	9.0	9.0	9.0	9.0	9.0	9.0
UREA*33%		6.3	6.2	6.2	7.5	8.2	8.2	8.0	8.0	7.0	6.5	6.8	7.7	7.8	7.8	7.0	7.0	7.5	8.3	8.7
UREA*66%		6.3	6.7	6.8	7.2	8.7	8.8	8.8	8.8	8.8	8.5	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for visual quality evaluated in ‘Meyer’ zoysiagrass at the Rocky Ford Turfgrass Research Center, Manhattan, KS between May (DOY 139) to September (265) 2016.

[‡] Day of Year (DOY) in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of visual quality on a 1 to 9 scale where 1 = poorest color, uniformity, and density; 6 = acceptable quality, and 9 = optimum color, uniformity, and density.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.16. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on percent green cover in ‘Meyer’ zoysiagrass in year 1 (2015).

		ANOVA[†]																
		Day of Year (DOY)[‡]																
Parameter	Source[§]	147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
Percent Green Cover	Fertilizer	***	***	***	***	*	**	***	***	***	***	NS	NS	***	***	**	NS	NS
	Irrigation	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	**	*	***	***	***	**
	FERT*IRR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
		LS Means[#]																
Fertilizer		147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
UF		77.2 b[††]	74.7 b	81.8 b	89.7 c	91.9 b	92.5 b	92.9 b	91.9 b	93.3 c	92.4 b	95.6	93.5	91.9 a	92.1 a	88.0 a	91.7	88.4
PCU		85.8 a	81.9 a	88.8 a	93.0 b	94.3 a	95.6 a	96.2 a	95.2 a	96.7 a	95.6 a	96.5	94.0	87.6 b	86.1 b	84.7 b	89.4	89.0
Urea		83.6 a	80.2 a	90.9 a	94.6 a	93.9 a	94.1 ab	92.3 b	91.7 b	95.5 b	95.7 a	96.1	93.8	87.6 b	82.8 b	83.2 b	89.2	89.0
Irrigation		147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
33% ET$_o$		81.4	78.7	86.8	92.1	93.4	93.6	93.8	92.7	95.1	94.3	95.5 b	92.9 b	87.9 b	84.1 b	82.7 b	88.1 b	87.5 b
66% ET$_o$		83.0	79.1	87.5	92.7	93.3	94.5	94.5	93.2	95.3	94.8	96.6 a	94.6 a	90.2 a	89.9 a	87.9 a	92.1 a	90.0 a
FERT * IRR		147	152[¶]	159	166	173	180	187	194	201	208	215	222	229	236[¶]	243	250	257
UF*33%		76.5	75.2	81.1	89.6	91.7	92.3	92.5	91.6	93.3	92.1	95.0	92.6	91.0	91.4 a	87.0	91.2	87.3
UF*66%		77.9	74.1	82.5	89.9	92.1	92.6	93.4	92.2	93.3	92.6	96.1	94.5	92.9	92.7 a	89.0	92.2	89.4
PCU*33%		85.1	81.6	88.1	92.4	94.2	95.0	95.9	95.1	96.6	95.0	96.1	93.4	86.4	83.7 b	81.5	86.9	87.5
PCU*66%		86.5	82.3	89.5	93.5	94.4	96.2	96.4	95.2	96.9	96.2	96.8	94.7	88.8	88.6 a	87.9	92.0	90.5
UREA*33%		82.7	79.4	91.1	94.4	94.3	93.4	92.9	91.4	95.2	95.7	95.5	92.9	86.2	77.2 c	79.5	86.3	87.9
UREA*66%		84.6	80.9	90.7	94.7	93.5	94.8	93.6	92.0	95.8	95.8	96.8	94.7	89.1	88.4 ab	86.9	92.2	90.1

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for green cover percentage evaluated in ‘Meyer’ zoysiagrass at the Rocky Ford Turfgrass Research Center, Manhattan, KS between May (DOY 147) to September 2015 (259).

[‡] Day of Year (DOY) in 2015.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ETo) replacement and 66% ETo replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 238. Fertilization events occurred DOY 155 (urea & PCU) and DOY 197 (urea only).

[#] LS Means of green cover percentage (0 to 100%) were calculated using a lightbox and digital camera.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher’s Protected LSD ($P \leq 0.05$).

Table A.17. Analyses of fertilizer main effect, irrigation main effect, and fertilizer*irrigation interaction on percent green cover in 'Meyer' zoysiagrass in year 2 (2016).

		ANOVA[†]																		
		Day of Year (DOY)[‡]																		
Parameter	Source[§]	139	146	153[¶]	160	167	174	181	188	195	202	209	216	223	230	237	244[¶]	251	258	265
Percent Green Cover	Fertilizer	NS	NS	NS	*	***	***	***	***	**	***	**	**	**	*	NS	**	***	***	***
	Irrigation	NS	NS	NS	NS	*	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	FERT*IRR	NS	NS	NS	NS	*	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	**

	LS Means[#]																		
Fertilizer	139	146	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265
UF	76.6	80.9	81.1	83.8 b[††]	82.5 b	86.7 b	90.1 b	90.8 b	89.8 b	89.4 b	89.5 b	89.5 b	89.9 b	91.7 b	87.1	88.1 b	91.7 b	95.7 b	94.1 b
PCU	78.4	81.6	81.6	84.6 b	83.0 b	85.3 b	90.4 b	94.2 a	94.0 a	95.1 a	94.1 a	93.1 a	93.6 a	94.5 a	89.7	91.8 a	95.5 a	97.7 a	97.6 a
Urea	76.5	80.6	81.6	86.8 a	90.2 a	92.7 a	94.0 a	95.4 a	93.6 a	94.0 a	95.0 a	95.5 a	94.0 a	95.5 a	90.7	91.1 a	94.7 a	97.3 a	96.8 a
Irrigation	139	146	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265
33% ET_o	76.8	81.3	82.3	84.9	84.5 b	86.3 b	89.4 b	91.7 b	89.6 b	90.1 b	89.2 b	89.0 b	89.0 b	90.3 b	84.5 b	86.5 b	91.8 b	96.1 b	95.2 b
66% ET_o	77.6	80.7	80.5	85.3	85.9 a	90.2 a	93.6 a	95.2 a	95.3 a	95.6 a	96.5 a	96.3 a	96.0 a	97.5 a	93.8 a	94.1 a	96.2 a	97.7 a	97.0 a
FERT * IRR	139	146	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265
UF*33%	76.4	81.0	83.0	83.7	82.2 c	84.9	88.3 c	89.2	87.2	86.8	85.7	85.6	86.2	87.7	83.2	84.4	89.0	94.5 c	92.3 d
UF*66%	76.9	80.8	79.3	84.0	82.9 bc	88.5	91.9 b	92.4	92.4	92.1	93.2	93.4	93.5	95.8	90.9	91.8	94.5	97.0 b	95.8 c
PCU*33%	79.1	81.5	81.3	84.3	81.0 c	82.6	86.8 c	91.7	90.2	92.2	89.9	88.3	89.5	90.3	83.8	88.1	93.5	97.4 ab	97.1 ab
PCU*66%	77.7	81.7	81.8	84.9	84.9 b	88.0	93.9 ab	96.8	97.9	98.1	98.3	98.0	97.6	98.7	95.5	95.6	97.5	98.1 a	98.0 a
UREA*33%	74.9	81.4	82.6	86.7	90.4 a	91.4	93.0 ab	94.3	91.4	91.3	91.9	93.2	91.3	93.0	86.5	87.2	92.9	96.6 b	96.2 bc
UREA*66%	78.2	79.7	80.6	87.0	90.0 a	94.1	95.1 a	96.5	95.8	96.7	98.0	97.7	96.7	98.0	94.9	95.0	96.6	98.0 a	97.3 ab

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively, and not significant (NS).

[†] Analysis of variance for green cover percentage evaluated in 'Meyer' zoysiagrass at the Rocky Ford Turfgrass Research Center, Manhattan, KS between May (DOY 139) to September (265) 2016.

[‡] Day of Year (DOY) in 2016.

[§] Source of variation, Fertilizer main effect (FERT) includes unfertilized (UF); polymer-coated urea (PCU); and urea, Irrigation main effect (IRR) includes 33% reference evapotranspiration (ET_o) replacement and 66% ET_o replacement, FERT*IRR is interaction of fertilizer and irrigation.

[¶] Rain-out shelter period (irrigation treatments applied) from DOY 152 to DOY 245. Fertilization events occurred DOY 158 (urea & PCU) and DOY 202 (urea only).

[#] LS Means of percent green cover (0 to 100%) were calculated using a lightbox and digital camera.

[††] Within each source of variation, means in column with different letters are significantly different according Fisher's Protected LSD ($P \leq 0.05$).

Table A.18. Spearman correlation coefficients for visual quality and percent green cover measured in a stand of ‘Meyer’ zoysiagrass from May to September in 2015 and 2016.

Spearman Correlation Coefficients[†]	
	Percent Green Cover[‡]
Visual Quality[§]	**0.64*****

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] N = 1296

[‡] Percent green cover (0 to 100%) were calculated using a lightbox and digital camera.

[§] Visual quality on a 1 to 9 scale where 1 = poorest color, uniformity, and density; 6 = acceptable quality, and 9 = optimum color, uniformity, and density.

Table A.19. Analysis of variance for the fixed effects of management schedule (MS), year, and depth on soil bulk density (ρ_b), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N), and average annual change in soil organic carbon (ΔSOC).

Source of variation	ρ_b	SOC	SON	C/N	ΔSOC
	p-values[†]				
Management schedule (MS)	0.0845	**0.0273**	**0.0324**	0.3472	0.4455
Year	0.8526	**<.0001**	**0.0436**	**0.0005**	--
MS x Year	0.8526	0.548	0.3814	0.3763	--
Depth	**0.0002**	**<.0001**	**<.0001**	0.5758	**0.0005**
MS x Depth	0.7456	0.2852	0.3932	0.1258	0.5231
Year x Depth	0.7408	**0.0018**	0.3521	0.2184	--
MS x Year x Depth	0.8627	0.6712	0.3218	0.1495	--

[†] P-values bolded are significant at either the 0.05, 0.01, and 0.001 probability level, respectively.

Table A.20. Analyses of test of slice effects of management schedule (MS), year, and depth on soil bulk density (ρ_b), soil organic carbon (SOC), soil organic nitrogen (SON), soil carbon/nitrogen ratio (C/N), and average annual change in soil organic carbon (ΔSOC).

	Tests of Slice Effects				
	ρ_b	SOC	SON	C/N	ΔSOC
	p-values				
Cell means sliced by Year x Depth[†]					
2013 x 0-10 cm	0.9546	0.8049	0.6298	0.9096	--
2013 x 10-20 cm	0.284	0.0329	0.5246	0.9407	--
2013 x 20-30 cm	0.3657	0.2808	0.6116	0.9761	--
2016 x 0-10 cm	0.5327	0.8363	0.131	0.5488	0.6812
2016 x 10-20 cm	0.4964	0.4215	0.763	0.2316	0.2161
2016 x 20-30 cm	0.284	0.1485	0.0145	**0.0069**	0.729
Cell means sliced by MS x Depth[†]					
High x 0-10 cm	0.9546	**<.0001**	0.5878	0.3818	--
High x 10-20 cm	0.8645	0.0406	0.4972	0.2675	--
High x 20-30 cm	0.5704	0.0638	0.021	**0.0005**	--
Low x 0-10 cm	0.5327	**<.0001**	0.6116	0.6954	--
Low x 10-20 cm	0.8201	0.4777	0.1113	0.0298	--
Low x 20-30 cm	0.6908	0.0279	0.7239	0.3292	--
MS x Year sliced by Year[‡]					
2013	0.2686	0.0471	0.3497	0.9681	--
2016	0.1739	0.2372	0.0343	0.1997	0.4455
MS x Year sliced by MS[‡]					
High	0.7929	**<.0001**	0.0423	**0.0019**	--
Low	1.000	**<.0001**	0.3998	0.0424	--
Year x Depth sliced by Year[‡]					
2013	**0.0035**	**<.0001**	**0.0035**	0.7768	**--**
2016	**0.0139**	**<.0001**	**<.0001**	0.1655	**0.0005**
Year x Depth sliced by Depth[§]					
0-10 cm	0.6879	**<.0001**	0.9805	0.3715	--
10-20 cm	0.9679	0.0522	0.1099	**0.0110**	--
20-30 cm	0.4956	**0.0053**	0.058	**0.0017**	--

[†] Test of slice effects indicate significant p-value according to α_{bon} = 0.0083, bolded if significant.

[‡] Test of slice effects indicate significant p-value according to α_{bon} = 0.025, bolded if significant.

[§] Test of slice effects indicate significant p-value according to α_{bon} = 0.016, bolded if significant.

Appendix B - Additional Figures and Tables for Chapter 3

Figure B.1. Field plots at Rocky Ford Turfgrass Research Center, Manhattan KS on 24 June 2016 (baseline period, pre-drought with no traffic applied).

Figure B.2. Field plots at Rocky Ford Turfgrass Research Center, Manhattan KS on 6 Aug. 2016 (41 days of simulated drought with no irrigation and a total of 96 golf cart traffic passes applied inside the white lines).

Figure B.3. Field plots at Rocky Ford Turfgrass Research Center, Manhattan KS on 15 Sept. 2016 (40 days of recovery with no simulated golf traffic applied since 6 Aug. 2016).

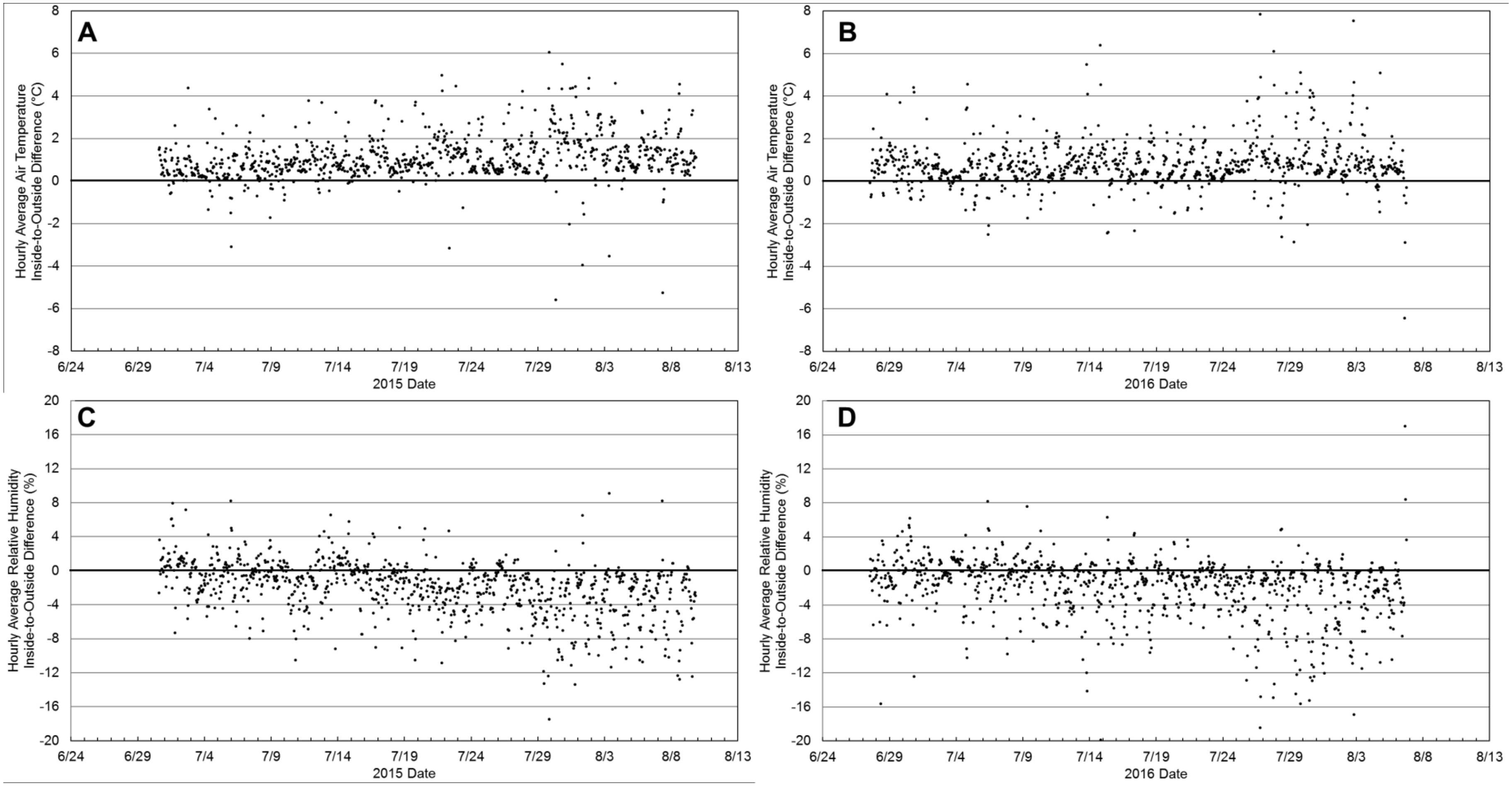

Figure B.4. Differences of inside-to-outside the shelter of recorded hourly average air temperature (°C) in 2015 (A) and 2016 (B); and hourly average relative humidity (%) in 2015 (C) and 2016 (D). Hourly averages of air temperature and relative humidity were monitored inside and outside of the rainout shelter during the drought period in both years. The mentioned weather variables were automatically logged every hour using a shaded, ventilated sensor placed at 15 cm above the ground.

Table B.1. Fungicide applications under the rainout shelter from 2014 through 2016.

Application date	Active ingredient (trade name)[†]	FRAC code[‡]	Application rate
	Zoysiagrass plots		
2014			
14 Sept.	Flutolanil (Prostar 70WG, Bayer Environmental Science, Research Triangle Park, NC)	7	4.69 kg a.i. ha^{-1}
2015			
19 Sept.	Flutolanil	7	4.69 kg a.i. ha^{-1}
	Perennial ryegrass and Kentucky bluegrass plots[§]		
2015			
29 May[¶]	Chlorothalonil (Lesco Manicure 6FL, Lesco Inc., Cleveland, OH)	M	4.6 kg a.i. ha^{-1}
	Boscalid (Emerald, BASF Corp., Research Triangle Park, NC)	7	0.32 kg a.i. ha^{-1}
12 June	Triticonazole (Triton FLO, Bayer Environmental Science)	3	1.14 kg a.i. ha^{-1}
	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
20 June	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
15 July	Propiconazole (Lesco Spectator Ultra 1.3, Lesco Inc.)	3	0.99 kg a.i. ha^{-1}
	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
28 July	Triticonazole	3	1.14 kg a.i. ha^{-1}
13 Aug.	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
	Boscalid	7	0.32 kg a.i. ha^{-1}
1 Sept.	Triticonazole	3	1.14 kg a.i. ha^{-1}
2016			
25 May	Triticonazole	3	1.14 kg a.i. ha^{-1}
8 June	Trifloxystrobin (Compass 50 WG, Bayer Environmental Science)	11	0.31 kg a.i ha^{-1}
	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
28 June	Propiconazole	3	0.99 kg a.i. ha^{-1}
	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
13 July	Trifloxystrobin	11	0.31 kg a.i ha^{-1}
	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
3 Aug.	Propiconazole	3	0.99 kg a.i. ha^{-1}
	Isofetamid (Kabuto Fungicide SC, PBI/Gordon Corporation, Kansas City, MO).	7	0.64 kg a.i ha^{-1}
12 Aug.	Tebuconazole (Mirage Stressgard, Bayer Environmental Science)	3	1.53 kg a.i ha^{-1}
27 Aug.	Trifloxystrobin	11	0.31 kg a.i ha^{-1}
	Chlorothalonil	M	4.6 kg a.i. ha^{-1}
8 Sept.	Triticonazole	3	1.14 kg a.i. ha^{-1}

[†] If the same active ingredient is listed with no trade name on a following date then the trade name is the same as listed for active ingredient at a previous date.

[‡] Fungicide Resistance Action Committee (FRAC) codes indicate the biochemical target site of action. M indicates multisite inhibitor, with no significant risk of fungicide resistance.

[§] Fungicide applications were applied on all dates listed below on perennial ryegrass, and most, but not all dates for Kentucky bluegrass.

[¶] If more than one chemical is listed for an application date, then fungicides were tank mixed.

Table B.2. Model specification for each parameter in each study period in 2015 and 2016.

	Model specifications[†]					
	2015			2016		
Parameter	Baseline[‡]	Drought[§]	Recovery[¶]	Baseline	Drought	Recovery
Percent green cover	Full DDF specification Group: buffalograss	AR(1) Group: C3 (perennial ryegrass & Kentucky bluegrass) vs. C4 (buffalograss & zoysiagrass) Outliers removed	AR(1) Group: (perennial ryegrass vs Kentucky bluegrass vs C4 species) Outliers removed	Full DDF specification Group: buffalograss	ARH(1) Group:C3 vs. C4	ARH(1) Group:C3 vs. C4 Outliers removed
Visual turf quality	Full DDF specification Group: none	ARH(1) Group: none	TOEP Group: Buffalograss	Full DDF specification Group: Kentucky bluegrass	ARH(1) Group: C3 vs C4	TOEP Group: perennial ryegrass
Turf firmness	--	ARH(1) Group: none	ARH(1) Group: none	Full DDF specification Group: buffalograss	ARH(1) Group: none	ARH(1) Group: none
Volumetric water content	Full DDF specification Group: none	TOEP Group: buffalograss	AR(1) Group: date (12 & 13)	Full DDF specification Group: none	TOEP Group: none	AR(1) Group: date (10,11,13) vs (8,9,12)

[†] A several step process was used to assure proper "best" model specification. First non-estimable covariance parameters were removed and appropriate denominator degrees of freedom (DDF) were specified. Next, different variance-covariance structures {compound symmetry [CS], autoregressive [AR(1)], toeplitz [TOEP], heterogenous compound symmetry [CSH], heterogeneous autoregressive [ARH(1)], and heterogeneous toeplitz [TOEPH]} were investigated to find the best fitting model. AIC = Akaike's Information Criteria and BIC = Bayesian Information Criteria were utilized to assess best fitting model (lower is better). Furthermore, studentized residuals were investigated to check assumptions of normal distribution and homogeneous variance properties. If necessary, additional variance group arrangements were specified. Significant outliers were also detected utilizing conservative Bonferroni adjustment and removed from the dataset.

[‡] Baseline period occurred 4 days prior to the drought period and traffic application consisted of only one rating and therefore did not include date treatment factor to be analyzed as a repeated measure. There was no baseline period for turf firmness in year 1 due to the instrument was not available.

[§] Drought period consisted of 41-days with no precipitation or irrigation with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. All four parameters were measured weekly.

[¶] Recovery period consisted of 40-days with no golf cart traffic applied and turfgrasses kept well-watered. All four parameters were measured weekly.

Table B.3. Analysis of variance for the fixed effects of turf species (T), mowing height (MH), traffic (TR), and date (D) on volumetric water content evaluated in 2015 and 2016.

	Volumetric water content					
Source of variation	2015 Baseline[†]	2015 Drought[‡]	2015 Recovery[§]	2016 Baseline	2016 Drought	2016 Recovery
Turf species (T)	***	**	***	***	***	***
Mowing height (MH)	NS[¶]	NS	NS	NS	NS	NS
T x MH	*	NS	NS	NS	*	**
Traffic (TR)	NS	NS	*	NS	*	*
T x TR	NS	NS	*	NS	NS	**
MH x TR	NS	NS	NS	NS	NS	NS
T x MH x TR	NS	NS	NS	NS	NS	NS
Date (D)	--[#]	***	***	--	***	***
T x D	--	***	***	--	***	***
MH x D	--	NS	NS	--	NS	***
T x MH x D	--	NS	NS	--	NS	***
TR x D	--	***	NS	--	***	NS
T x TR x D	--	NS	NS	--	NS	NS
MH x TR x D	--	NS	NS	--	NS	NS
T x MH x TR x D	--	NS	NS	--	NS	NS
	Contrasts[††]					
C3 vs C4 Turf species	***	NS	***	***	NS	***
C3 vs C4 @ Fairway MH	***	NS	***	***	NS	***
C3 vs C4 @ Rough MH	***	NS	***	***	NS	***
C3 vs C4 @ No TR	***	NS	***	***	NS	***
C3 vs C4 @ Yes TR	***	NS	***	***	NS	***
C3 vs C4 @ Week 2 (D) / 8(R)	--	**	***	--	***	***
C3 vs C4 @ Week 3 (D) / 9 (R)	--	NS	**	--	NS	***
C3 vs C4 @ Week 4 (D) / 10 (R)	--	NS	***	--	NS	***
C3 vs C4 @ Week 5 (D) / 11 (R)	--	NS	NS	--	NS	***
C3 vs C4 @ Week 6 (D) / 12 (R)	--	NS	***	--	*	***
C3 vs C4 @ Week 7 (D) / 13 (R)	--	NS	NS	--	**	***

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Baseline period occurred 4 days prior to the drought period with no traffic applied.

[‡] Drought period consisted of 41-days with no precipitation or irrigation with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Volumetric water content was measured weekly.

[§] Recovery period consisted of 40-days with no golf cart traffic applied and turfgrasses kept well-watered. Volumetric water content was measured weekly.

[¶] Not significant (NS).

[#] Not applicable (--).

[††] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass) overall, at each mowing height, traffic treatment, and individual rating date.

Table B.4. Effect of date on volumetric water content of turfgrass species evaluated during baseline, drought, and recovery periods in 2015.

		Volumetric water content[†]			
		Turf species[‡]			
Date[§]	**P-Value¶**	Kentucky bluegrass	Perennial ryegrass	Buffalograss	Zoysiagrass
26 June	**0.0002**	49.5 a[#]	51.0 a	46.6 b	47.5 b
3 July	**0.0011**	41.6 ab[††]	43.5 a	40.4 b	40.9 ab
10 July	**0.0012**	26.7 b	29.6 a	29.3 a	27.7 ab
17 July	**<.0001**	20.9 b	24.3 a	25.8 a	20.5 b
24 July	**<.0001**	19.1 b	22.3 a	22.0 a	17.9 b
31 July	**<.0001**	15.1 bc	17.7 ab	18.6 a	14.8 c
9 Aug.	**0.0011**	14.6 b	16.9 a	17.1 a	14.6 b
14 Aug.	**<.0001**	38.6 a	40.0 a	30.9 b	32.2 b
21 Aug.	**0.0032**	30.4 ab	31.5 a	30.1 ab	28.1 b
28 Aug.	**<.0001**	39.0 ab	40.2 a	36.4 bc	35.4 c
4 Sept.	0.0173	34.1	35.6	34.5	32.7
11 Sept.	**<.0001**	39.3 a	41.5 a	36.2 b	36.5 b
18 Sept.	0.9759	34.6	35.0	34.8	34.8

[†] Volumetric water content (θ_v) was measured weekly at a 7.6 cm depth (averaged from 4 measurements per plot) with time domain reflectometry.

[‡] Turf species was assigned to column or “whole-plot” treatment factor.

[§] Date was assigned to sub-cell treatment factor as a repeated measure of time. Date 26 June is the baseline period, which occurred four days prior to start of drought period. Dates 3 July through 9 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 14 Aug. through 18 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses kept well-watered. Each period was analyzed separately. Baseline, drought, and recovery periods were each analyzed separately.

[¶] P-values for dates 3 July through 18 Sept. indicate significant difference for the test of slice effects for date according to the Bonferroni adjustment test ($P \leq 0.0083$), bolded if significant.

[#] Within the row of date 26 June (baseline period), means with the same letter are not significantly different according to Tukey’s Honestly Significant Difference test ($P \leq 0.05$).

[††] Within each row for dates 3 July through 18 Sept., means with the same letter are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.001389$).

Table B.5. Effect of date on volumetric water content of turfgrass species evaluated during baseline, drought, and recovery periods in 2016.

		Volumetric water content[†]			
		Turf species[‡]			
Date[§]	**P-Value[¶]**	Kentucky bluegrass	Perennial ryegrass	Buffalograss	Zoysiagrass
23 June	**0.0009**	48.4 ab[#]	50.0 a	46.1 bc	45.4 c
30 June	**<.0001**	38.7 bc[††]	43.1 a	39.9 ab	36.0 c
7 July	**<.0001**	26.7 b	30.2 a	30.8 a	25.8 b
14 July	**0.0011**	20.8 b	23.5 a	24.1 a	20.8 b
21 July	**<.0001**	17.6 b	20.1 ab	22.4 a	18.2 b
28 July	**<.0001**	16.9 b	19.9 ab	22.8 a	17.1 b
6 Aug.	**<.0001**	14.6 b	16.9 b	21.0 a	15.1 b
11 Aug.	**<.0001**	35.1 a	33.1 a	27.4 b	22.7 c
18 Aug.	**<.0001**	39.1 a	37.5 a	29.8 b	27.4 b
25 Aug.	**<.0001**	43.5 a	43.1 a	34.2 b	35.9 b
1 Sept.	**<.0001**	44.4 a	44.9 a	39.5 b	40.1 b
8 Sept.	**<.0001**	38.4 a	34.2 ab	33.4 b	31.8 b
15 Sept.	**<.0001**	44.7 a	45.7 a	40.1 b	40.0 b

[†] Volumetric water content (θ_v) was measured weekly at a 7.6 cm depth (averaged from 4 measurements per plot) with time domain reflectometry.

[‡] Turf species was assigned to column or "whole-plot" treatment factor.

[§] Date was assigned to sub-cell treatment factor as a repeated measure of time. Date 23 June is the baseline period, which occurred four days prior to start of drought period. Dates 30 June through 6 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought period. Dates 11 Aug. through 15 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses kept well-watered. Baseline, drought, and recovery periods were each analyzed separately.

[¶] P-values for dates 30 June through 15 Sept. indicate significant difference for the test of slice effects for date according to the Bonferroni adjustment test ($P \leq 0.0083$), bolded if significant.

[#] Within the row of date 23 June (baseline period), means with the same letter are not significantly different according to Tukey's Honestly Significant Difference test ($P \leq 0.05$).

[††] Within each row for dates 30 June through 15 Sept., means with the same letter are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.001389$).

Table B.6. Analysis of variance for the fixed effects of turf species (T), mowing height (MH), traffic (TR), and date (D) on percent green cover evaluated during baseline, drought, and recovery periods in 2015 and 2016.

	Percent green cover					
Source	2015 Baseline[†]	2015 Drought[‡]	2015 Recovery[§]	2016 Baseline	2016 Drought	2016 Recovery
Turf species (T)	***	***	***	***	***	***
Mowing height (MH)	NS[¶]	NS	NS	*	*	**
T x MH	**	*	***	***	***	***
Traffic (TR)	NS	*	NS	NS	**	NS
T x TR	NS	NS	***	NS	**	**
MH x TR	NS	NS	NS	NS	*	NS
T x MH x TR	NS	**	NS	NS	NS	NS
Date (D)	--[#]	***	***	--	***	***
T x D	--	***	***	--	***	***
MH x D	--	NS	***	--	***	***
T x MH x D	--	**	***	--	***	***
TR x D	--	***	***	--	***	***
T x TR x D	--	***	NS	--	***	***
MH x TR x D	--	NS	NS	--	**	NS
T x MH x TR x D	--	NS	NS	--	***	NS
	Contrasts[††]					
C3 vs C4 Turf species	***	NS	*	**	***	***
C3 vs C4 @ Fairway MH	***	NS	NS	***	***	NS
C3 vs C4 @ Rough MH	***	NS	**	NS	***	***
C3 vs C4 @ No TR	***	NS	NS	***	***	***
C3 vs C4 @ Yes TR	***	NS	**	***	***	***
C3 vs C4 @ Week 2 (D) / 8(R)	--	***	***	--	***	NS
C3 vs C4 @ Week 3 (D) / 9 (R)	--	***	***	--	*	***
C3 vs C4 @ Week 4 (D) / 10 (R)	--	***	**	--	***	***
C3 vs C4 @ Week 5 (D) / 11 (R)	--	**	NS	--	***	***
C3 vs C4 @ Week 6 (D) / 12 (R)	--	***	NS	--	***	***
C3 vs C4 @ Week 7 (D) / 13 (R)	--	***	NS	--	***	***

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Baseline period occurred 4 days prior to the drought period with no traffic applied.

[‡] Drought period consisted of 41-days with no precipitation or irrigation with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Percent green cover was measured weekly.

[§] Recovery period consisted of 40-days with no golf cart traffic applied and turfgrasses kept well-watered. Percent green cover was measured weekly.

[¶] Not significant (NS).

[#] Not applicable (--).

[††] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass) overall, at each mowing height, traffic treatment, and individual rating date.

Table B.7. Analysis of variance for the fixed effects of turf species (T), mowing height (MH), traffic (TR), and date (D) on visual turf quality evaluated during baseline, drought, and recovery periods.

Source	2015 Baseline[†]	2015 Drought[‡]	2015 Recovery[§]	2016 Baseline	2016 Drought	2016 Recovery
	Visual turf quality					
Turf species (T)	***	***	***	*	***	***
Mowing height (MH)	NS[¶]	NS	NS	NS	*	*
T x MH	NS	NS	NS	**	***	***
Traffic (TR)	NS	**	*	NS	**	NS
T x TR	NS	*	NS	NS	***	***
MH x TR	NS	NS	NS	NS	**	*
T x MH x TR	NS	*	NS	NS	**	NS
Date (D)	--[#]	***	***	--	***	***
T x D	--	***	***	--	***	***
MH x D	--	***	*	--	***	***
T x MH x D	--	NS	*	--	***	***
TR x D	--	***	***	--	***	***
T x TR x D	--	***	***	--	***	***
MH x TR x D	--	NS	NS	--	***	***
T x MH x TR x D	--	NS	NS	--	***	***
	Contrasts[††]					
C3 vs C4 Turf species	**	***	***	**	***	***
C3 vs C4 @ Fairway MH	**	***	***	NS	***	***
C3 vs C4 @ Rough MH	*	***	***	***	***	***
C3 vs C4 @ No TR	***	***	***	**	***	***
C3 vs C4 @ Yes TR	*	***	***	*	***	***
C3 vs C4 @ Week 2 (D) / 8(R)	--	**	***	--	***	***
C3 vs C4 @ Week 3 (D) / 9 (R)	--	**	***	--	***	***
C3 vs C4 @ Week 4 (D) / 10 (R)	--	***	***	--	***	***
C3 vs C4 @ Week 5 (D) / 11 (R)	--	***	***	--	***	***
C3 vs C4 @ Week 6 (D) / 12 (R)	--	***	***	--	***	***
C3 vs C4 @ Week 7 (D) / 13 (R)	--	***	***	--	***	***

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Baseline period occurred 4 days prior to the drought period with no traffic applied.

[‡] Drought period consisted of 41-days with no precipitation or irrigation with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Visual turf quality was measured weekly.

[§] Recovery period consisted of 40-days with no golf cart traffic applied and turfgrasses kept well-watered. Visual turf quality was measured weekly.

[¶] Not significant (NS).

[#] Not applicable (--).

[††] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass) overall, at each mowing height, traffic treatment, and individual rating date.

Table B.8. Comparison of percent green turfgrass cover between traffic treatments sliced by turf species, mowing height, and date in 2015.

			Percent green cover[†]												
			2015 Date[‡]												
	Treatment		26 June	3 July	10 July	17 July	24 July	31 July	9 Aug.	14 Aug.	21 Aug.	28 Aug.	4 Sept.	11 Sept.	18 Sept.
Kentucky bluegrass	Fairway	**P-value[§]**	0.2378	.09231	0.875	0.113	**<.0001**	**0.0002**	0.0126	0.0585	0.2688	0.7237	0.8239	0.9034	0.9964
	No traffic		98.6	99.0	98.3	94.4	78.8 a[¶]	63.3 a	42.0	51.3	77.6	85.1	94.7	90.5	92.8
	Traffic		97.9	98.2	97.1	81.7	34.5 b	33.5 b	22.0	29.3	64.7	81.0	92.1	91.9	92.7
	Rough	**P-value**	0.9809	0.9877	0.8797	0.3527	**<.0001**	**0.0007**	0.0055	0.0869	0.7554	0.4824	0.463	0.5669	0.8682
	No traffic		96.7	97.3	96.7	93.1	78.3 a	64.2 a	40.2	40.7	46.7	69.6	83.7	81.0	83.6
	Traffic		96.6	97.2	95.5	85.7	41.8 b	36.7 b	17.9	20.8	43.1	61.4	75.2	74.4	81.7
Perennial ryegrass	Fairway	**P-value**	0.1992	0.9985	0.9141	0.5925	0.003	0.0093	0.0141	**0.0009**	0.0251	0.5195	0.7482	0.8719	0.9447
	No traffic		96.6	98.6	97.5	96.7	90.2	80.4	82.1	79.8 a	93.3	94.7	97.7	96.0	95.3
	Traffic		96.0	98.6	96.7	92.4	66.3	59.5	62.5	68.7 b	86.3	92.7	96.7	95.5	95.1
	Rough	**P-value**	0.9350	0.9815	0.6752	0.4045	0.0024	0.0149	**0.0002**	**<.0001**	**0.0001**	0.766	0.8094	0.7932	0.9171
	No traffic		92.0	95.6	94.3	93.0	84.0	72.1	80.9 a	78.9 a	88.0 a	90.3	95.2	94.2	92.4
	Traffic		92.0	95.4	91.0	86.3	59.6	52.6	50.8 b	49.2 b	76.1 b	89.4	96.0	95.0	92.8
Buffalograss	Fairway	**P-value**	0.5981	0.8129	**0.0006**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0004**	0.7916	0.0664	0.5666	0.0035	0.0335
	No traffic		81.4	85.5	81.8 a	73.3 a	69.7 a	82.5 a	78.8 a	71.2 a	75.0	80.1	84.6	77.2	75.7
	Traffic		82.6	84.9	73.0 b	61.5 b	56.2 b	67.0 b	57.3 b	64.6 b	75.2	83.5	85.7	82.6	79.6
	Rough	**P-value**	0.3349	**0.0003**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0316	0.0914	0.0688	0.0525	0.2624
	No traffic		81.5	81.5 a	78.3 a	83.1 a	74.2 a	81.6 a	84.9 a	82.1 a	82.2	84.9	86.1	85.5	81.2
	Traffic		79.2	72.2 b	52.0 b	44.5 b	40.2 b	48.1 b	46.7 b	67.5 b	78.2	88.1	89.5	89.1	83.3
Zoysiagrass	Fairway	**P-value**	0.4381	0.543	0.0994	0.0059	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0043	0.5226	0.9223	0.7698	0.5795
	No traffic		93.1	95.0	96.2	95.6	93.7 a	88.8 a	86.5 a	91.6 a	94.7	94.9	95.5	96.0	94.8
	Traffic		92.6	93.5	92.0	88.5	79.4 b	64.6 b	58.7 b	74.4 b	89.4	93.8	95.7	96.5	95.9
	Rough	**P-value**	0.7374	0.713	0.0024	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.1467	0.4922	0.6095	0.7205
	No traffic		94.7	96.1	97.0	96.9 a	95.8 a	93.2 a	93.6 a	93.0 a	93.6 a	94.6	95.2	94.6	93.9
	Traffic		94.9	95.2	89.2	85.4 b	74.9 b	56.0 b	48.0 b	64.0 b	79.7 b	91.9	93.9	95.5	94.5

[†] Percent green cover (%) was measured weekly from the average of two digital photographs under a lightbox from two locations per plot taken. Images were analyzed with SigmaScan Pro 5.0 for estimation of green pixels that represented green turf relative to non-green green turf.

[‡] Date was assigned to sub-cell treatment factor as a repeated measure of time. Date 26 June is the baseline period, which occurred four days prior to start of drought period. Dates 3 July through 9 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 14 Aug. through 18 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses were well-watered. Baseline, drought, and recovery periods were each analyzed separately.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.00625$) for date 26 June (baseline period) and ($P \leq 0.001$) for dates 3 July through 18 Sept. (drought and recovery periods), bolded if significant.

[¶] At each date, within each mowing height of each turf species, means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00625$) for date 26 June (baseline period) and ($P \leq 0.001$) for dates 3 July through 18 Sept. (drought and recovery periods).

Table B.9. Comparison of percent green turfgrass cover between traffic treatments sliced by turf species, mowing height, and date in 2016.

	Treatment		23 June	30 June	7 July	14 July	21 July	28 July	6 Aug.	11 Aug.	18 Aug.	25 Aug.	1 Sept.	8 Sept.	15 Sept.
			Percent green cover[†]												
			2016 date[‡]												
Kentucky bluegrass	Fairway	**P-value[§]**	0.7213	0.745	0.741	0.1486	0.0013	0.0684	0.3028	0.5279	0.4833	0.5985	0.496	0.4295	0.8152
	No traffic		97.8	98.4	94.6	82.0	54.4	28.6	19.2	31.3	60.2	69.9	81.5	81.1	87.3
	Traffic		98.1	97.5	92.4	70.2	24.4	16.5	13.0	26.4	67.1	74.3	85.2	85.7	86.1
	Rough	**P-value**	0.2886	0.0445	0.0649	0.0211	0.4952	0.9023	0.9849	0.9229	0.8172	0.8093	0.5071	0.3141	0.0543
	No traffic		82.3	82.9	61.0	24.7	7.0	0.9	0.2	0.8	4.3	5.1	6.1	14.1	20.4
	Traffic		83.2	77.0	48.8	5.7	0.8	0.1	0.1	0.1	2.0	3.1	2.5	8.3	10.9
Perennial ryegrass	Fairway	**P-value**	0.6662	0.8637	0.9505	0.1278	0.0359	0.2137	0.2735	0.9208	0.9685	0.846	0.6231	0.5933	0.6622
	No traffic		95.9	94.7	87.7	78.0	49.8	26.3	15.5	21.8	61.2	76.7	86.2	86.3	90.7
	Traffic		96.3	94.2	87.3	65.5	30.4	18.1	9.0	21.0	60.8	75.1	88.9	89.3	92.9
	Rough	**P-value**	0.1385	0.2847	0.8377	0.142	**0.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0007**	0.0048	0.0851	0.4022	0.9635
	No traffic		93.6	93.5	88.2	81.6	73.1 a[¶]	53.2 a	44.0 a	50.7 a	75.6 a	83.4	89.6	87.1	89.8
	Traffic		92.3	90.4	86.8	69.5	37.0 b	22.3 b	8.4 b	15.6 b	41.9 b	59.9	80.2	82.3	89.6
Buffalograss	Fairway	**P-value**	0.0579	0.4281	0.0011	**<.0001**	**0.0003**	**<.0001**	**<.0001**	0.0023	0.9373	0.77	0.3778	0.1606	0.4093
	No traffic		85.3	81.8	72.0	71.4 a	74.6 a	74.1 a	76.7 a	78.0	80.6	84.7	85.4	82.2	81.2
	Traffic		82.3	80.7	63.3	55.5 b	58.4 b	58.0 b	57.7 b	66.8	80.8	85.2	87.2	84.8	82.5
	Rough	**P-value**	0.8996	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0011	0.8191	0.0617	**<.0001**	**<.0001**	**0.0009**
	No traffic		80.6	83.7 a	76.5 a	71.2 a	81.4 a	74.9 a	84.5 a	78.6	80.2	81.2	77.4 b	78.6 b	79.3 b
	Traffic		80.4	72.5 b	45.0 b	39.8 b	49.2 b	47.5 b	48.8 b	66.5	79.5	84.7	86.8 a	85.9 a	84.4 a
Zoysiagrass	Fairway	**P-value**	0.9449	0.3389	0.0028	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0006**	0.0063	0.8528	0.6823	0.83
	No traffic		97.9	98.8	97.0	94.1 a	89.9 a	80.6 a	75.6 a	83.8 a	90.2 a	95.3	96.3	98.0	98.2
	Traffic		98.0	97.5	89.1	81.0 b	63.4 b	45.5 b	41.0 b	51.3 b	80.7 b	90.3	96.7	98.7	98.5
	Rough	**P-value**	0.1756	0.0041	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0019	0.9387	0.1246	0.0277	0.0105
	No traffic		91.5	96.0	94.9 a	91.5 a	86.8 a	73.3 a	77.6 a	85.7 a	92.2	91.8	92.1	91.5	92.3
	Traffic		92.7	91.9	77.8 b	62.4 b	45.0 b	25.1 b	25.7 b	52.0 b	83.6	91.7	95.1	95.6	96.2

[†] Percent green cover (%) was measured weekly from the average of two digital photographs under a lightbox from two locations per plot taken. Images were analyzed with SigmaScan Pro 5.0 for estimation of green pixels that represented green turf relative to non-green green turf.

[‡] Date was assigned to sub-cell treatment factor as a repeated measure of time. Date 23 June is the baseline period, which occurred four days prior to start of drought period. Dates 30 June through 6 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 11 Aug. through 15 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses kept well-watered. Baseline, drought, and recovery periods were each analyzed separately.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.00625$) for date 23 June (baseline period) and ($P \leq 0.001$) for dates 3 July through 18 Sept. (drought and recovery periods), bolded if significant.

[¶] At each date, within each mowing height of each turf species, means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00625$) for date 23 June (baseline period) and ($P \leq 0.001$) for dates 30 June through 15 Sept. (drought and recovery periods).

Table B.10. Comparison of visual turf quality ratings between traffic treatments sliced by turf species, mowing height, and date in 2015.

			Visual turf quality[†]												
			2015 date[‡]												
	Treatment		26 June	3 July	10 July	17 July	24 July	31 July	9 Aug.	14 Aug.	21 Aug.	28 Aug.	4 Sept.	11 Sept.	18 Sept.
Kentucky bluegrass	Fairway	**P-value[§]**	1.0	0.425	0.1054	0.0294	**<.0001**	**0.0004**	0.0065	0.0059	0.3132	0.8007	0.3132	0.8007	0.8007
	No traffic		9.0	9.0	9.0	7.0	6.4 a[¶]	5.5 a	3.7	4.0	4.5	5.0	6.3	6.3	7.9
	Traffic		9.0	8.9	8.6	6.3	5.0 b	3.6 b	2.4	2.6	4.0	5.1	5.8	6.4	7.8
	Rough	**P-value**	1.0	0.425	0.0013	0.7155	**0.0001**	0.0548	0.1181	0.4492	0.6138	0.4492	0.8007	1.0	0.8007
	No traffic		9.0	9.0	9.0	6.6	6.4 a	5.5	3.0	3.0	3.4	4.0	5.4	5.4	6.5
	Traffic		9.0	8.9	8.3	6.5	5.1 b	4.5	2.3	2.6	3.6	4.4	5.3	5.4	6.4
Perennial ryegrass	Fairway	**P-value**	0.0592	0.425	0.0072	0.0112	0.0073	0.63	0.0375	0.3132	0.0027	0.0059	0.4492	0.3132	0.4492
	No traffic		9.0	9.0	9.0	7.3	6.9	5.9	4.8	4.9	6.4	7.5	7.6	8.3	8.6
	Traffic		8.8	8.9	8.4	6.4	6.0	5.6	3.8	4.4	4.9	6.1	7.3	7.8	8.3
	Rough	**P-value**	0.3273	0.0172	**<.0001**	0.0692	0.0545	0.1492	0.0044	0.0027	0.2076	0.2076	0.8007	1.0	0.4492
	No traffic		8.9	9.0	8.8 a	7.0	6.4	6.0	4.9	4.6	5.0	6.5	7.3	7.9	8.5
	Traffic		8.8	8.6	7.8 b	6.4	5.8	5.3	3.5	3.1	4.4	5.9	7.1	7.9	8.1
Buffalograss	Fairway	**P-value**	0.3273	0.425	**<.0001**	0.0112	0.1236	0.1492	0.0095	**<.0001**	0.0076	0.0014	0.2827	0.2827	1.0
	No traffic		8.9	8.9	9.0 a	7.8	7.3	7.6	7.3	7.6 a	8.0	8.9	8.8	9.0	8.9
	Traffic		9.0	8.8	8.0 b	6.9	6.8	6.9	6.1	6.5 b	7.4	8.1	8.5	8.8	8.9
	Rough	**P-value**	1.0	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.0014	0.5909
	No traffic		9.0	9.0 a	8.9 a	8.0 a	7.8 a	8.1 a	7.9 a	8.9 a	8.5 a	8.9 a	9.0 a	9.0	9.0
	Traffic		9.0	8.3 b	6.8 b	5.5 b	5.8 b	5.8 b	5.2 b	6.1 b	6.6 b	7.0 b	7.9 b	8.3	8.9
Zoysiagrass	Fairway	**P-value**	1.0	1.0	**0.0002**	**<.0001**	0.0073	0.0926	**0.0003**	**<.0001**	0.0027	0.6138	0.8007	1.0	1.0
	No traffic		8.5	8.6	9.0 a	8.1 a	7.6	7.3	6.9 a	8.6 a	8.6	8.6	9.0	9.0	9.0
	Traffic		8.5	8.6	8.1 b	6.8 b	6.8	6.4	5.1 b	6.4 b	7.1	8.4	8.9	9.0	9.0
	Rough	**P-value**	1.0	0.425	**<.0001**	**<.0001**	**<.0001**	**0.0004**	**<.0001**	**<.0001**	0.0059	0.1308	0.8007	0.6138	0.8007
	No traffic		8.5	8.6	8.6 a	7.9 a	7.5 a	7.6 a	6.7 a	7.9 a	7.5	8.3	8.8	9.0	9.0
	Traffic		8.5	8.5	7.6 b	6.5 b	6.1 b	5.8 b	4.3 b	5.5 b	6.1	7.5	8.6	8.8	8.9

[†] Visual turf quality was rated and averaged from two locations per plot on a 1 to 9 scale (1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality) according to color, texture, density, and uniformity.

[‡] Date was assigned to sub-cell treatment factor as a repeated measure of time. Date 26 June is the baseline period, which occurred four days prior to start of drought period. Dates 3 July through 9 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 14 Aug. through 18 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses kept well-watered. Baseline, drought, and recovery periods were each analyzed separately.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.00625$) for date 26 June (baseline period) and ($P \leq 0.001$) for dates 3 July through 18 Sept. (drought and recovery periods), bolded if significant.

[¶] At each date, within each mowing height of each turf species, means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00625$) for date 26 June (baseline period) and ($P \leq 0.001$) for dates 3 July through 18 Sept. (drought and recovery periods).

Table B.11. Comparison of visual turf quality ratings between traffic treatments sliced by turf species, mowing height, and date in 2016.

			Visual turf quality[†]												
			2016 date[‡]												
	Treatment		23 June	30 June	7 July	14 July	21 July	28 July	6 Aug.	11 Aug.	18 Aug.	25 Aug.	1 Sept.	8 Sept.	15 Sept.
Kentucky bluegrass	Fairway	**P-value[§]**	1.0	0.7382	1.0	0.6655	0.0632	0.2961	0.4386	0.0638	**<.0001**	0.2157	1.0	1.0	0.2157
	No traffic		8.9	8.9	8.3	7.3	5.3	4.1	3.0	3.3	3.9 a[¶]	4.8	6.0	6.0	6.5
	Traffic		8.9	8.8	8.3	7.0	4.3	3.6	2.8	3.6	4.8 b	5.0	6.0	6.0	6.8
	Rough	**P-value**	0.7919	1.0	0.4239	0.0099	0.1038	0.6011	0.6984	0.5355	0.5355	0.2157	0.2157	0.0638	0.5355
	No traffic		7.4	6.9	4.9	3.5	1.9	1.3	1.1	1.1	1.1	1.3	1.4	1.4	1.3
	Traffic		7.5	6.9	4.5	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	1.1
Perennial ryegrass	Fairway	**P-value**	0.2338	0.504	0.7897	0.3875	0.2447	0.6011	0.6984	1.0	0.7188	0.7188	0.4717	0.5893	0.3684
	No traffic		8.9	8.9	7.8	7.1	5.0	3.8	2.9	3.3	3.8	4.6	5.8	5.9	6.9
	Traffic		9.0	8.6	7.9	6.6	4.4	3.5	2.8	3.3	4.0	4.9	6.3	6.3	7.5
	Rough	**P-value**	0.2338	0.3164	0.4239	0.018	0.0027	**0.0008**	**<.0001**	0.0073	0.0199	0.0013	0.0122	0.0073	0.0199
	No traffic		8.9	8.8	8.4	8.5	6.0	5.4 a	4.5 a	4.8	5.1	6.0	6.9	7.1	7.8
	Traffic		8.8	8.4	8.0	7.1	4.4	3.8 b	2.6 b	2.9	3.5	3.8	5.1	5.3	6.1
Buffalograss	Fairway	**P-value**	1.0	0.3701	**0.0006**	**<.0001**	0.0054	**<.0001**	**0.0004**	0.5355	0.0638	0.5355	0.5355	0.5355	0.5355
	No traffic		8.9	8.9	8.9 a	8.8 a	9.0	8.9 a	8.8 a	9.0	8.9	8.9	8.9	8.9	8.9
	Traffic		8.9	8.8	8.3 b	7.3 b	8.3	7.6 b	7.5 b	8.9	8.5	8.8	8.8	9.0	9.0
	Rough	**P-value**	0.2338	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	1.0	0.5355	1.0
	No traffic		9.0	9.0 a	9.0 a	9.0 a	9.0 a	8.9 a	8.9 a	9.0 a	8.9 a	8.8 a	8.9	8.9	9.0
	Traffic		8.9	7.6 b	5.9 b	6.4 b	5.1 b	6.1 b	5.8 b	6.4 b	7.8 b	7.9 b	8.9	9.0	9.0
Zoysiagrass	Fairway	**P-value**	1.0	1.0	**0.0006**	**<.0001**	**<.0001**	**<.0001**	**0.0004**	**<.0001**	0.0021	0.5355	1.0	1.0	1.0
	No traffic		9.0	9.0	9.0 a	9.0 a	8.1 a	7.9 a	6.8 a	6.6 a	8.5	9.0	9.0	9.0	9.0
	Traffic		9.0	9.0	8.4 b	7.4 b	6.8 b	6.0 b	5.5 b	5.8 b	7.9	8.9	9.0	9.0	9.0
	Rough	**P-value**	0.2338	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0002**	0.5355	1.0	0.5355
	No traffic		8.6	8.9 a	8.9 a	9.0 a	8.1 a	7.4 a	6.3 a	8.8 a	9.0 a	9.0 a	8.9	8.9	8.9
	Traffic		8.8	8.1 b	6.8 b	6.5 b	4.9 b	4.8 b	4.4 b	6.0 b	7.8 b	8.3 b	8.8	8.9	9.0

[†] Visual turf quality was rated and averaged from two locations per plot on a 1 to 9 scale (1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality) according to color, texture, density, and uniformity.

[‡] Date was assigned to sub-cell treatment factor as a repeated measure of time. Date 23 June is the baseline period, which occurred four days prior to start of drought period. Dates 30 June through 6 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 11 Aug. through 15 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses kept well-watered. Baseline, drought, and recovery periods were each analyzed separately.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.00625$) for date 23 June (baseline period) and ($P \leq 0.001$) for dates 3 July through 18 Sept. (drought and recovery periods), bolded if significant.

[¶] At each date, within each mowing height of each turf species, means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00625$) for date 23 June (baseline period) and ($P \leq 0.001$) for dates 30 June through 15 Sept. (drought and recovery periods).

Table B.12. Analysis of variance for the fixed effects of turf species (T), mowing height (MH), traffic (TR), and date (D) on turf firmness evaluated during baseline, drought, and recovery periods.

Source	2015 Drought[†]	2015 Recovery[‡]	2016 Baseline[§]	2016 Drought	2016 Recovery
Turf species (T)	***	***	***	***	***
Mowing height (MH)	*	**	*	**	**
T x MH	NS[¶]	**	NS	**	***
Traffic (TR)	*	NS	NS	NS	NS
T x TR	**	**	NS	***	*
MH x TR	NS	*	NS	***	***
T x MH x TR	**	*	NS	*	NS
Date (D)	***	***	--[#]	***	***
T x D	**	***	--	***	***
MH x D	NS	*	--	**	***
T x MH x D	NS	NS	--	NS	NS
TR x D	NS	NS	--	*	***
T x TR x D	*	NS	--	NS	NS
MH x TR x D	NS	NS	--	*	*
T x MH x TR x D	NS	NS	--	NS	NS
Contrasts[††]					
C3 vs C4 Turf species	*	***	NS	***	***
C3 vs C4 @ Fairway MH	*	**	NS	***	**
C3 vs C4 @ Rough MH	*	***	NS	***	***
C3 vs C4 @ No TR	**	***	NS	***	***
C3 vs C4 @ Yes TR	NS	***	NS	***	***
C3 vs C4 @ Week 2 (D) / 8(R)	--	NS	--	*	**
C3 vs C4 @ Week 3 (D) / 9 (R)	NS	***	--	**	***
C3 vs C4 @ Week 4 (D) / 10 (R)	**	***	--	***	***
C3 vs C4 @ Week 5 (D) / 11 (R)	NS	***	--	***	***
C3 vs C4 @ Week 6 (D) / 12 (R)	**	***	--	***	***
C3 vs C4 @ Week 7 (D) / 13 (R)	***	***	--	***	***

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Baseline period occurred 4 days prior to the drought period with no traffic applied.

[‡] Drought period consisted of 41-days of no precipitation or irrigation with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Turf firmness was measured weekly.

[§] Recovery period consisted of 40-days with no golf cart traffic applied and turfgrasses kept well-watered. Turf firmness was measured weekly.

[¶] Not significant (NS).

[#] Not applicable (--).

[††] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass) overall, at each mowing height, traffic treatment, and individual rating date.

Table B.13. Comparison of turf firmness measurements between mowing height x traffic treatments sliced by turf species and date in 2015.

		Turf firmness[†]										
		2015 date[‡]										
Treatment		10 July	17 July	24 July	31 July	9 Aug.	14 Aug.	21 Aug.	28 Aug.	4 Sept.	11 Sept.	18 Sept.
Kentucky bluegrass	**P-value[§]**	0.0048	**<.0001**	**0.0005**	**<.0001**	**0.0003**	**<.0001**	**<.0001**	**0.0001**	**<.0001**	**0.0003**	**0.0003**
Fairway*no traffic		13.8	9.8 a[¶]	10.7 ab	9.5 ab	10.9 ab	13.5 a	12.8 a	15.3 ab	13.7 a	16.6 ab	14.1 ab
Fairway*traffic		11.2	9.8 a	8.5 a	7.6 a	7.7 a	14.4 a	11.6 a	14.2 a	12.9 a	13.7 a	13.6 a
Rough*no traffic		15.7	13.9 b	12.8 b	12.9 b	13.1 b	18.6 b	17.8 b	18.5 b	17.6 ab	18.6 b	18.7 b
Rough*traffic		13.6	12.1 ab	11.8 ab	11.8 b	12.5 b	16.3 ab	16.5 b	17.6 ab	18.7 b	17.6 ab	17.1 ab
Perennial ryegrass	**P-value**	0.0073	**<.0001**	**0.0017**	0.0141	0.1564	0.0071	**<.0001**	**<.0001**	**0.0002**	**0.0002**	0.0037
Fairway*no traffic		12.7	10.2 a	9.5 ab	8.3	8.6	12.1	11.2 a	12.7 a	10.6 a	13.3 a	12.2
Fairway*traffic		12.2	9.2 a	9.0 a	8.0	8.2	13.0	12.3 ab	13.9 a	12.6 ab	14.7 ab	12.4
Rough*no traffic		16.1	15.7 b	12.8 b	11.4	10.9	15.4	14.5 b	18.8 b	15.2 ab	17.7 b	16.2
Rough*traffic		13.4	11.7 a	10.9 ab	10.1	9.7	14.0	15.2 b	15.0 ab	15.9 b	17.5 ab	15.6
Buffalograss	**P-value**	0.1144	**<.0001**	**0.0014**	0.008	0.0737	**<.0001**	**<.0001**	**<.0001**	**0.0005**	**0.0018**	**0.0001**
Fairway*no traffic		12.0	10.2 a	8.4 a	9.4	10.4	10.4 a	12.2 a	14.4 ab	13.2 a	13.9 ab	13.6 ab
Fairway*traffic		10.6	9.5 a	8.5 a	7.9	8.2	11.6 a	11.2 a	13.1a	13.0 a	13.1 a	11.2 a
Rough*no traffic		13.7	13.6 b	12.1 b	11.9	11.5	15.8 b	16.6 b	18.0 b	17.7 b	16.8 b	17.3 b
Rough*traffic		11.9	11.7 ab	10.4 ab	10.4	10.9	12.8 ab	14.2 ab	17.0 b	16.3 ab	16.5 b	15.3 ab
Zoysiagrass	**P-value**	0.0973	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fairway*no traffic		14.1	13.4 a	11.5 a	12.4 a	14.5 a	16.6 a	15.9 a	18.3 a	18.1 a	20.0 a	19.6 ab
Fairway*traffic		14.4	12.2 a	10.6 a	10.8 a	10.9 a	15.0 a	15.7 a	17.5 a	18.2 a	19.3 a	19.0 a
Rough*no traffic		16.9	17.3 b	18.4 b	16.9 b	19.5 b	22.4 b	23.1 c	25.4 b	27.2 b	28.3 b	28.8 c
Rough*traffic		14.9	14.8 ab	12.1 a	12.5 a	13.5 a	17.8 a	19.7 b	21.2 a	21.6 a	24.7 b	24.0 bc

[†] Turf firmness, depth of travel (mm) was measured and averaged from four locations per plot using a turf firmness meter.

[‡] Date was assigned as a repeated measure of time. Measurements from 10 July through 9 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 14 Aug. through 18 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses were well-watered. Drought and recovery periods were each analyzed separately.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.0025$) for drought period dates (10 July through 9 Aug) and ($P \leq 0.00208$) for recovery period dates (14 Aug. through 18 Sept), bolded if significant.

[¶] At each date, within each turf species, means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.000417$) for drought period dates (10 July through 9 Aug.) and ($P \leq 0.000347$) for recovery period dates (14 Aug. through 18 Sept.)

Table B.14. Comparison of turf firmness measurements between mowing height x traffic treatments sliced by turf species and date in 2016.

		Turf firmness[†]												
		2016 date[‡]												
Treatment		23 June	30 June	7 July	14 July	21 July	28 July	6 Aug.	11Aug.	18 Aug.	25 Aug	1 Sept.	8 Sept.	15 Sept.
Kentucky bluegrass	**P-value[§]**	**.0002**	**<.0001**	**<.0001**	0.0044	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.2454	0.0265	**<.0001**	0.4543
Fairway*no traffic		18.7 ab[¶]	15.1 a	13.6 a	12.6	11.2 a	11.1 a	10.4 a	12.7 a	13.9 a	15.4	16.7	12.6 a	13.6
Fairway*traffic		18.2 a	13.7 a	11.7 a	11.0	10.2 a	9.3 a	9.2 a	13.0 a	13.0 a	14.1	14.4	13.6 ab	13.7
Rough*no traffic		22.7 c	18.3 b	17.9 b	14.3	16.6 b	13.9 b	12.8 b	17.0 b	16.7 b	15.3	14.0	16.5 b	14.8
Rough*traffic		21.9 bc	15.8 ab	13.7 a	10.9	11.1 a	10.1 a	9.3 a	14.4 ab	14.3 ab	13.7	13.2	13.5 a	13.4
Perennial ryegrass	**P-value**	**.0007**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0001**	**<.0001**	**<.0001**
Fairway*no traffic		16.2 ab	12.2 ab	11.2 a	9.9 a	9.0 ab	8.7 a	8.8 ab	12.3 ab	12.0 ab	13.1 a	12.6 a	11.5 a	13.4 ab
Fairway*traffic		16.1 a	12.1 a	10.6 a	9.6 a	8.2 a	8.7 a	7.7 a	11.2 a	11.2 a	12.4 a	12.3 a	11.5 a	13.5 a
Rough*no traffic		19.8 c	16.9 c	16.6 b	14.9 b	14.9 c	14.7 b	12.9 c	18.1 c	16.6 c	16.9 b	17.0 b	15.5 b	17.2 b
Rough*traffic		19.7 bc	15.1 bc	12.4 a	11.6 ab	11.2 b	10.3 a	10.2 bc	15.4 bc	14.6 bc	14.1 ab	15.0 ab	13.5 ab	16.8 bc
Buffalograss	**P-value**	**.0015**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0002**	**<.0001**	**<.0001**
Fairway*no traffic		13.6 a	12.2 ab	10.7 a	9.9 a	9.6 a	9.1 a	9.9 a	11.0 a	11.9 ab	11.2 a	13.1 a	11.9 ab	12.8 a
Fairway*traffic		13.5 a	10.7 a	9.7 a	8.3 a	9.0 a	8.7 a	8.4 a	10.5 a	10.1 a	11.3 a	12.7 a	11.9 a	12.3 a
Rough*no traffic		20.1 b	16.2 c	15.5 b	14.6 b	14.2 b	13.9 b	14.2 b	17.7 b	18.6 c	16.8 b	17.4 b	16.1 c	16.6 b
Rough*traffic		18.0 ab	14.4 bc	12.3 ab	10.7 a	10.8 ab	10.2 a	10.5 a	13.3 a	13.8 b	13.9 ab	15.5 ab	14.9 bc	14.8 ab
Zoysiagrass	**P-value**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Fairway*no traffic		19.2 a	16.1 ab	15.6 a	15.2 a	14.7 a	14.7 a	14.4 a	14.9 ab	16.8 ab	17.3 a	19.0 a	17.4 ab	18.3 ab
Fairway*traffic		19.3 a	15.0 a	13.6 a	13.6 a	13.1 a	12.6 a	12.5 a	13.7 a	15.0 a	16.5 a	17.0 a	16.4 a	17.9 a
Rough*no traffic		23.2 b	22.3 c	21.6 b	21.9 b	21.0 b	20.7 b	19.5 b	24.0 c	23.7 c	23.1 b	24.4 b	22.3 c	22.6 c
Rough*traffic		24.1 b	17.6 b	16.2 a	15.6 a	14.2 a	13.9 a	13.4 a	17.2 b	19.3 b	20.7 b	21.7 ab	19.9 bc	21.2 bc

[†] Turf firmness, depth of travel (mm) was measured and averaged from four locations per plot using a turf firmness meter.

[‡] Date was assigned as a repeated measure of time. Date 23 June is the baseline period, which occurred four days prior to start of drought period. Dates 30 June through 6 Aug. consisted of weekly ratings during the 41-day drought with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a total of 0 or 96 golf cart traffic passes by the end of the drought. Dates 11 Aug. through 15 Sept. consisted of weekly ratings during the 40-day recovery with no golf cart traffic applied and turfgrasses kept well-watered. Baseline, drought, and recovery periods were each analyzed separately.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.0125$) for baseline period date (23 June) and ($P \leq 0.00208$) for drought and recovery period dates (30 June through 15 Sept), bolded if significant.

[¶] At each date, within each turf species, means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00208$) for baseline period date (23 June) and ($P \leq 0.000347$) for drought and recovery period dates (30 June through 15 Sept.)

Appendix C - Additional Tables for Chapter 4

Table C.1. Model specifications for soil penetration resistance, soil bulk density, and gravimetric soil water content in 2015 and 2016.

	Model specification[†]					
Parameters	**2015**			**2016**		
	Pre-drought	Post-drought	Post-recovery	Pre-drought	Post-drought	Post-recovery
Soil penetration resistance[‡]	ARH(1) Group: none	ARH(1) Group: none	ARH(1) Group: none	ARH(1) Group: none	ARH(1) Group: none	ARH(1) Group: none

	2015		**2016**	
	Pre-drought[§]	Post-drought	Pre-drought	Post-drought
Soil bulk density[¶]	*Fairway only* Full DDF specification Group: none	Full DDF specification Group: none	Full DDF specification Group: none	Full DDF specification Group: none
Gravimetric soil water content[#]	*Fairway only* Full DDF specification Group: none	Full DDF specification Group: none	Full DDF specification Group: none	Full DDF specification Group: none

[†] A several step process was used to assure proper "best" model specification. First non-estimable covariance parameters were removed and appropriate denominator degrees of freedom (DDF) were specified. Next, different variance-covariance structures {compound symmetry [CS], autoregressive [AR(1)], toeplitz [TOEP], heterogenous compound symmetry [CSH], heterogeneous autoregressive [ARH(1)], and heterogeneous toeplitz [TOEPH]} variance groupings (Group) were investigated to find the best fitting model. AIC and BIC were utilized to assess best fitting model (lower is better). Furthermore, studentized residuals were investigated to check assumptions of normal distribution and homogeneous variance properties. If necessary, additional variance group arrangements were specified.

[‡] Soil penetration resistance (MPa) was measured and averaged from two locations per plot at 5 depth levels (repeated measures); using a digital cone penetrometer at three time events each year (pre- and post-drought period, and post recovery period).

[§] In year 1 pre-drought period, soil bulk density measurements were conducted only in the fairway mowing height due to time restrictions, but measured in both mowing heights for all other periods in year 1 and year 2.

[¶] Soil bulk density (ρ_b, g cm^{-3}) at the 0-6 cm depth was determined by extracting a soil core with the volume of 137.26 cm^3 from each plot pre- and post-drought. Samples were then weighed and dried in a forced-air oven for 48 h at 105 ºC.

[#] Gravimetric water content (w, g g^{-1}) at 0-6 cm depth is weight of soil water per unit of dry soil weight. This was determined from the soil bulk density sample.

Table C.2. Models for root parameters measured during post-drought period in 2016.

	Root parameters[†]			
	Root biomass	Root length density	Average root diameter	Root surface area
Model specification[‡] 2016	*Log Transformation* Full DDF specification Group: traffic	*Log Transformation* Full DDF specification Group: (zoysiagrass & buffalograss)	Full DDF specification Group: perennial ryegrass	Full DDF specification Group: zoysiagrass

[†] One soil core (5.08 diam. x 30.5 cm depth) was collected from each plot at the end of the drought period using a hand-held soil core sampler (SST SCS #404.67, AMS Inc., American Falls, ID). Roots were washed, dyed with methyl blue [acid blue 93 ($C_{37}H_{27}N_3O_9S_3Na_2$), Sigma Chemical Co., St. Louis, MO] and water solution (5 g methyl blue L-1 water), scanned at 800 dpi, and analyzed with WinRHIZO (version 2003 b, Regent Instruments, Quebec City, Canada) to determine root length (cm), average root diameter (mm), and root surface area (cm^2). Root length density ($cm\ cm^{-3}$) was calculated as root length divided by the volume of soil core. Total root biomasses were then dried in a forced-air oven for 48 h at 105 ºC and weighed separately to determine dry root biomass ($mg\ cm^{-3}$). Drought period consisted of 41-days of no precipitation or irrigation with a cumulative total of 0 or 96 golf cart traffic passes applied.

[‡] A several step process was used to assure proper “best” model specification. First non-estimable covariance parameters were removed and appropriate denominator degrees of freedom (DDF) were specified. Next, different variance groupings (Group) were investigated to find the best fitting model. AIC = Akaike’s Information Criteria and BIC = Bayesian Information Criteria were utilized to assess best fitting model (lower is better). Furthermore, studentized residuals were investigated to check assumptions of normal distribution and homogeneous variance properties. If necessary, additional variance group arrangements were specified. Significant outliers were also detected utilizing conservative Bonferroni adjustment and removed from the dataset.

Table C.3. Pearson correlation coefficients among soil bulk density (ρ_b), soil penetration resistance (SPR), gravimetric soil water content (w), volumetric soil water content (θ_v), and turf firmness (FIRM). Analyses were performed across all pre-drought and post-drought periods in 2015 and 2016.

Variables	N	ρ_b	SPR	w	θ_v
ρ_b	224	-			
SPR	256	**0.472*****	-		
w	224	**-0.497*****	**-0.746*****	-	
θ_v	225	**-0.502*****	**-0.771*****	**0.973*****	-
FIRM	192	**-0.514*****	**-0.525*****	**0.688*****	**0.693*****

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

Table C.4. Analysis of variance for the fixed effects of turf species (T), mowing height (MH), traffic (TR), and depth (D) on soil penetration resistance in 2015 and 2016.

	Soil penetration resistance[†]					
	2015			2016		
Source of variation	Pre-drought	Post-drought	Post-recovery	Pre-drought	Post-drought	Post-recovery
Turf species (T)	**	*	*	**	NS	**
Mowing height (MH)	NS	NS	NS	NS	*	NS
T x MH	NS	NS	*	NS	NS	NS
Traffic (TR)	NS	NS	NS	NS	NS	NS
T x TR	NS	NS	NS	*	NS	NS
M x TR	NS	NS	NS	NS	NS	NS
T x MH x TR	NS	NS	NS	NS	NS	NS
Depth (D)	***	***	***	***	***	***
T x D	*	**	NS	*	NS	NS
MH x D	NS	*	NS	***	***	NS
T x MH x D	**	NS	NS	NS	NS	NS
TR x D	NS	NS	NS	*	NS	NS
T x TR x D	NS	NS	NS	NS	NS	NS
MH x TR x D	NS	NS	NS	NS	NS	NS
T x MH x TR x D	NS	NS	NS	NS	NS	NS
	Contrasts[¶]					
C3 vs C4 Turf species	NS	NS	*	NS	NS	***
C3 vs C4 @ Fairway MH	NS	NS	NS	NS	NS	*
C3 vs C4 @ Rough MH	NS	*	*	NS	NS	**
C3 vs C4 @ No Traffic	NS	NS	NS	NS	NS	*
C3 vs C4 @ Traffic	NS	NS	NS	NS	*	***
C3 vs C4 @ Depth 0	NS	NS	*	NS	NS	*
C3 vs C4 @ Depth 1	NS	NS	*	*	NS	*
C3 vs C4 @ Depth 2	NS	*	NS	NS	*	***
C3 vs C4 @ Depth 3	NS	*	NS	NS	NS	***
C3 vs C4 @ Depth 4	NS	NS	NS	*	NS	***

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.

[†] Soil penetration resistance (MPa) was measured and averaged from two locations per plot at 5 depth levels (repeated measure); 0, 2.54, 5.08, 7.6, and 10.16 cm using a hand-held digital cone penetrometer. Drought period consisted of a 41-days with no precipitation or irrigation and with 0 or 16 golf cart traffic passes per week for a cumulative total of 0 or 96 golf cart traffic passes by the end of the drought. Recovery period consisted of a 40-days with no golf cart traffic applied and turfgrasses were kept well-watered.

[‡] Not significant (NS).

[¶] Contrasts among C3 turfgrass species (Kentucky bluegrass and perennial ryegrass) vs. C4 turfgrass species (buffalograss and zoysiagrass) overall, at each mowing height, traffic treatment, and individual measurement depth.

Table C.5. Comparison of soil penetration resistance between turfgrass species sliced by mowing height, traffic, and depth for each period in 2015.

		Soil penetration resistance[†]														
		Pre-drought[‡]					Post-drought					Post-recovery				
		Depth (cm)					Depth (cm)					Depth (cm)				
Treatment		0	2.54	5.08	7.62	10.16	0	2.54	5.08	7.62	10.16	0	2.54	5.08	7.62	10.16
Fairway*No traffic	P-value[§]	0.091	0.070	0.267	0.517	0.988	0.227	0.659	0.007	0.124	0.170	0.025	0.503	0.120	0.183	0.123
Kentucky bluegrass		0.660	0.750	0.616	0.664	0.763	1.15	1.55	1.51	1.84	2.13	1.30	1.26	1.19	1.23	1.30
Perennial ryegrass		0.530	0.720	0.634	0.685	0.750	0.509	1.32	1.39	1.64	2.02	0.565	1.04	1.24	1.25	1.23
Buffalograss		0.384	0.586	0.577	0.625	0.763	0.806	1.25	1.32	1.39	1.55	0.896	0.961	1.04	1.08	1.08
Zoysiagrass		0.526	0.823	0.702	0.672	0.746	0.853	1.55	2.03	2.00	2.28	0.935	1.15	1.31	1.31	1.34
Rough*No traffic	P-value	0.639	0.004	0.189	0.034	0.927	0.661	0.209	0.047	0.031	0.172	0.115	0.114	0.056	0.051	0.005
Kentucky bluegrass		0.340	0.569	0.672	0.590	0.707	0.823	1.08	1.23	1.30	1.74	0.746	1.01	0.931	1.04	1.00
Perennial ryegrass		0.457	0.509	0.582	0.677	0.746	0.724	0.823	0.961	1.15	1.35	1.13	1.26	1.14	1.24	1.33
Buffalograss		0.410	0.465	0.547	0.590	0.737	0.702	1.04	1.12	1.20	1.37	0.586	0.758	0.888	0.939	0.983
Zoysiagrass		0.465	0.771	0.646	0.681	0.733	1.05	1.44	1.57	1.85	2.01	0.685	1.09	1.13	1.12	1.23
Fairway*Traffic	P-value	0.066	0.557	0.344	0.007	0.604	0.685	0.649	0.906	0.658	0.190	0.398	0.442	0.142	0.069	0.298
Kentucky bluegrass		0.634	0.720	0.646	0.737	0.819	0.914	1.47	1.44	1.84	2.33	0.939	1.29	1.37	1.41	1.36
Perennial ryegrass		0.362	0.638	0.681	0.621	0.737	0.780	1.27	1.57	1.62	1.94	0.957	1.30	1.40	1.38	1.36
Buffalograss		0.422	0.612	0.612	0.603	0.771	0.853	1.11	1.49	1.56	1.57	0.746	1.04	1.15	1.14	1.17
Zoysiagrass		0.521	0.711	0.724	0.677	0.776	0.560	1.20	1.58	1.80	2.00	1.15	1.36	1.29	1.31	1.33
Rough*Traffic	P-value	0.103	**0.0005**	0.143	0.003	0.444	0.558	0.570	0.006	**0.002**	0.046	0.026	0.026	**0.0004**	**0.0017**	0.0028
Kentucky bluegrass		0.379	0.577 b[¶]	0.638	0.681	0.737	1.15	1.58	1.29	1.36 ab	1.38	0.724	1.22	1.09 b	1.12 b	1.15
Perennial ryegrass		0.595	0.625ab	0.590	0.677	0.797	0.935	1.38	1.32	1.26 b	1.26	1.12	1.36	1.43 a	1.44 a	1.53
Buffalograss		0.349	0.500 b	0.552	0.621	0.720	0.746	1.25	1.68	2.07 a	2.02	0.457	0.802	1.05 b	1.12 b	1.16
Zoysiagrass		0.465	0.866 a	0.694	0.776	0.797	1.10	1.61	1.97	2.00 ab	2.00	0.526	1.34	1.44 a	1.42 a	1.39

[†] Soil penetration resistance (MPa) was measured and averaged from two locations per plot at 5 depth levels (repeated measure); 0 cm, 2.54 cm, 5.08 cm, 7.6 cm, 10.16 cm. Drought period consisted of 41-days of no precipitation or irrigation with a cumulative total of 0 or 96 golf cart traffic passes applied and recovery period consisted of 40-days with no traffic applied and turfgrasses kept well-watered to promote recovery.

[‡] Model specification and statistical analysis was conducted separately for pre-drought, post-drought, and post-recovery periods.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.0025$) for each depth, bolded if significant.

[¶] At each depth within each mowing height x traffic interaction, turf species means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00417$).

Table C.6. Comparison of soil penetration resistance between turfgrass species sliced by mowing height, traffic, and depth for each period in 2016.

		Soil penetration resistance[†]														
		Pre-drought[‡]					Post-drought					Post-recovery				
		Depth (cm)					Depth (cm)					Depth (cm)				
Treatment		0	2.54	5.08	7.62	10.16	0	2.54	5.08	7.62	10.16	0	2.54	5.08	7.62	10.16
Fairway*No traffic	P-value[§]	0.059	0.007	0.030	0.003	0.010	0.165	0.190	0.531	0.738	0.746	0.980	0.629	0.185	0.600	0.996
Kentucky bluegrass		0.599	0.827	0.694	0.720	0.789	1.04	1.77	2.25	2.81	2.78	0.513	0.685	0.642	0.677	0.771
Perennial ryegrass		0.405	0.702	0.677	0.715	0.754	1.32	2.09	2.55	2.63	2.45	0.560	0.741	0.668	0.720	0.776
Buffalograss		0.453	0.651	0.672	0.707	0.746	0.771	1.39	2.03	2.39	2.40	0.556	0.672	0.715	0.728	0.771
Zoysiagrass		0.733	0.939	0.784	0.840	0.892	1.20	1.79	2.57	2.72	2.72	0.560	0.819	0.793	0.746	0.763
Rough*No traffic	P-value	0.025	0.015	**0.0002**	0.191	0.477	0.269	0.494	0.385	0.311	0.658	0.195	0.168	0.028	0.153	0.242
Kentucky bluegrass		0.530	0.741	0.668a[¶]	0.733	0.797	0.823	0.995	0.914	1.18	1.56	0.409	0.526	0.513	0.651	0.690
Perennial ryegrass		0.543	0.530	0.496 b	0.659	0.724	0.629	1.21	1.38	1.77	1.94	0.384	0.651	0.560	0.616	0.694
Buffalograss		0.220	0.504	0.590 ab	0.681	0.771	0.780	0.987	1.24	1.41	1.52	0.474	0.577	0.707	0.711	0.784
Zoysiagrass		0.577	0.707	0.659 a	0.733	0.780	1.12	1.42	1.64	1.84	1.87	0.646	0.789	0.672	0.720	0.741
Fairway*Traffic	P-value	0.511	0.624	0.044	0.053	0.020	0.281	0.474	0.008	0.050	0.014	**0.0025**	0.139	0.059	**0.002**	0.013
Kentucky bluegrass		0.388	0.728	0.746	0.758	0.823	0.879	1.59	2.16	2.47	3.04	0.362 b	0.741	0.707	0.754 b	0.784
Perennial ryegrass		0.224	0.616	0.638	0.668	0.741	0.784	1.27	1.38	1.65	1.99	0.487 ab	0.720	0.711	0.733 b	0.767
Buffalograss		0.362	0.638	0.728	0.728	0.888	1.26	1.74	2.83	2.73	3.06	0.444 b	0.711	0.780	0.84 ab	0.888
Zoysiagrass		0.405	0.646	0.737	0.776	0.853	0.991	1.69	2.36	2.22	2.20	0.836 a	0.961	0.883	0.914 a	0.909
Rough*Traffic	P-value	0.669	**0.0002**	0.774	0.611	0.872	0.203	0.190	0.148	0.032	0.073	0.524	0.267	**0.0007**	**<.0001**	**0.0005**
Kentucky bluegrass		0.556	0.862 a	0.616	0.685	0.771	0.814	0.914	0.892	1.03	1.18	0.461	0.517	0.543b	0.599 b	0.672 b
Perennial ryegrass		0.474	0.621 ab	0.590	0.690	0.802	1.00	1.34	1.46	1.75	2.01	0.379	0.625	0.698 ab	0.771 a	0.780 ab
Buffalograss		0.396	0.521 b	0.573	0.646	0.763	0.556	1.26	1.60	2.01	1.90	0.435	0.750	0.793 a	0.832 a	0.892 a
Zoysiagrass		0.440	0.487 b	0.603	0.698	0.780	1.05	1.62	1.84	2.11	2.23	0.573	0.698	0.823 a	0.827 a	0.836 a

[†] Soil penetration resistance (MPa) was measured and averaged from two locations per plot at 5 depth levels (repeated measure); 0 cm, 2.54 cm, 5.08 cm, 7.6 cm, 10.16 cm. Drought period consisted of 41-days of no precipitation or irrigation with a cumulative total of 0 or 96 golf cart traffic passes applied and recovery period consisted of 40-days with no traffic applied and turfgrasses kept well-watered to promote recovery.

[‡] Model specification and statistical analysis was conducted separately for pre-drought, post-drought, and post-recovery periods.

[§] Test of slice effects indicate significant p-value according to the Bonferroni adjustment test ($P \leq 0.0025$) for each depth, bolded if significant.

[¶] At each depth within each mowing height x traffic interaction, turf species means with the same letter or no letters are not significantly different according to the Bonferroni adjustment test for slice differences ($P \leq 0.00417$).

Table C.7. Pearson correlation coefficients among root biomass (RB), root length density (RLD), average root diameter (RD), root surface area (RSA), soil bulk density (ρ_b), soil penetration resistance (SPR), gravimetric soil water content (w), visual turf quality (VQ), percent green cover (PGC), volumetric soil water content (θ_v), and turf firmness (FIRM). Analyses were performed for the combined post-drought periods in 2015 and 2016.

Variables	N	RB	RLD	RD	RSA	ρ_b	SPR
RB	64	-					
RLD	64	**0.698*****	-				
RD	64	-0.120	**-0.655*****	-			
RSA	64	**0.842*****	**0.929*****	**-0.396****	-		
ρ_b	128	-0.105	-0.210	**-0.0127**	-0.223	-	
SPR	128	-0.061	-0.042	-0.018	-0.036	0.100	-
w	128	**-0.482*****	**-0.563*****	**0.261***	**-0.548*****	**0.226***	-0.012
VQ	128	**-0.536*****	**-0.781*****	**0.501*****	**-0.747*****	0.128	0.104
PGC	128	**-0.531*****	**-0.731*****	**0.464*****	**-0.719*****	0.036	-0.041
θ_v	128	**-0.261***	**-0.354****	0.236	**-0.319***	0.167	0.041
FIRM	128	**-0.260***	**-0.411*****	**0.256***	**-0.414*****	**-0.186***	0.021

*, **, and *** are significant at the 0.05, 0.01, and 0.001 probability level, respectively.