CARBON, NITROGEN, AND WATER FLUXES FROM TURFGRASS ECOSYSTEMS

by

JASON DOUGLAS LEWIS

B.S., University of Nebraska, Lincoln, 2001
M.S., University of Nebraska, Lincoln, 2005

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture, Forestry, and Recreation Resources

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Abstract

Turfgrass covers 1.9% of the nation's surface area and is the largest irrigated crop in the USA. Developed urbanized land is projected to double by 2025, which will increase turf's environmental impact. Studies were conducted to evaluate environmental impacts by characterizing nitrogen, carbon, and water fluxes in turfgrass ecosystems.

Emissions of nitrous oxide (N_2O), a major greenhouse gas and ozone depleter were measured from bermudagrass (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Davy) (bermuda), perennial ryegrass, (*Lolium perenne* L.) (rye), and zoysiagrass, (*Zoysia japonica* Steud.) (zoysia) under regional N management. In a separate study, N_2O fluxes were measured from bermuda fertilized with controlled-release N fertilizers including polymer-coated and organic-N, and quick release urea. Emissions of N_2O were measured using static surface chambers and gas chromatography. Zoysia, with less N requirements, had lower emissions than bermuda. Cumulative N_2O emissions were similar among N types.

To measure water and carbon fluxes, a portable non-steady state chamber was designed and tested. The chamber had minimal affects to the canopy during field measurements: leak values averaged <1.5 μmol CO_2 m^{-2} s^{-1}; average chamber pressure was 0.09 Pa ±0.01 Pa; temperature rise inside the chamber averaged 0.74^{o}C; and the chamber had 90% photosynthetically active radiation transmittance. Using the chamber, differences were detected in net photosynthesis (Pnet), gross photosynthesis (Pg), evapotranspiration (ET), canopy stomatal conductance (g_c), and water use efficiency (WUE) in well-watered tall fescue (*Festuca arundinacea* Schreb.), Kentucky bluegrass (*Poa pratensis* L.) (KBG), zoysia, and bermuda.

Irrigation requirements, visual quality ratings, and genetic rooting potential of 28 KBG cultivars and 2 Texas bluegrass hybrids (*P. pratensis* x *P. arachnifera* Torr.) were quantified in greenhouse and rainout facility studies. Average water applied ranged from 23.4 to 40.0 cm among cultivars. Bedazzled, Preakness, and Bartitia required less water and had higher average quality than other cultivars. Compact America and Mid-Atlantic phenotypes exhibited greatest potential for success in integrating reduced water inputs with maintenance of acceptable visual quality. Results indicated that turfgrass management could mitigate N_2O emissions and conserve water while maintaining healthy turfgrass, and the new chamber will enhance turfgrass studies by providing rapid measurements of photosynthesis.

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CHAPTER 1 - Nitrous Oxide Fluxes from One Cool-Season and Two Warm-Season Turfgrasses in a Temperate, Continental Climate

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Abstract

Nitrous oxide (N_2O) emissions from turfgrass may be increasing with urban expansion, but emissions may vary among species and turfgrass selection may be a means to mitigate N_2O emissions. Objectives were to quantify N_2O fluxes in one cool-season and two warm-season turfgrasses under typical N-management recommendations for maintaining acceptable quality. Turfgrasses investigated were bermudagrass (*Cynodon dactylon* L. Pers. x *C. transvaalensis* Burtt-Davy) and perennial ryegrass, (*Lolium perenne* L.) with N applications of 200 kg N ha^{-1} yr^{-1}, and zoysiagrass, (*Zoysia japonica* Steud.) with N applications of 100 kg N ha^{-1} yr^{-1}. Emissions of N_2O were measured weekly for 600 days using static surface chambers and gas chromatography. Fluxes of N_2O ranged from 1633 µg N_2O-N m^{-2} hr^{-1} after summer fertilization to -17.63 µg N_2O-N m^{-2} hr^{-1} in late fall. Fluxes of N_2O generally increased 4.2 to 9.8 times above pre-fertilization levels after N application and with increases in soil water content and soil temperature. Flux responses after N applications were greater in summer than fall, especially when accompanied by rainfall. Summer fluxes from perennial ryegrass were 63% lower than bermudagrass and zoysiagrass, but fluxes in fall were highest in perennial ryegrass among species, following patterns of N fertilization timing. Cumulative annual emissions of N_2O-N were 3.37, 3.09, 2.79 kg N ha^{-1} yr^{-1} for bermudagrass, perennial ryegrass, and zoysiagrass, respectively; emissions from bermudagrass were higher than from zoysiagrass. Data suggests that zoysiagrass, because of lower N requirement, may be a better choice than bermudagrass for mitigation of N_2O emissions from turfgrass.

Introduction

Nitrous oxide is a greenhouse gas implicated in climate change (IPCC, 2001), and has been identified as the single-most important ozone depleting substance emitted into the atmosphere from anthropogenic activities (Ravishankara et al., 2009). Furthermore, N_2O is expected to remain the dominant ozone-depleting substance emitted throughout the 21st century (Ravishankara et al., 2009). Greater than 80% of the increase in atmospheric N_2O is believed to originate from agricultural soils, which are irrigated and fertilized with nitrogen (N) (Goodroad and Keeney, 1984; Sexstone et al., 1985; Isermann, 1994; Mosier et al., 1996; Bouwman, 1996). However, rapid urbanization is resulting in agricultural lands and native areas being replaced with turfgrass (Dillman et al., 1993; Kaye et al., 2004); turfgrass is already estimated to cover 1.9% of the surface area of the U.S (Milesi et al., 2005). Turfgrass is also often irrigated and fertilized with N and therefore, may increasingly become a source for atmospheric N_2O as areas of turfgrass increase (Alig et al., 2004; Milesi et al., 2005).

Emissions of N_2O from turfgrass differ from emissions from agriculture crops and native systems. Kaye et al. (2004) found that turfgrass emitted 10 times more N_2O into the atmosphere than native grassland and wheat-fallow soils, and urban lawns also contributed 30% of regional N_2O emissions in northeastern CO, USA. Hall et al. (2008) reported that urbanization in Phoenix, Arizona, USA increased N_2O emissions compared to native landscapes, primarily because of the increase in irrigated and fertilized lawns.

Few studies have quantified cumulative N_2O emissions from turfgrass. Annual estimates for N_2O emissions ranged from 1.01 kg N_2O-N ha^{-1} yr^{-1} in perennial ryegrass to 2.4 kg N_2O-N ha^{-1} yr^{-1} in Kentucky bluegrass (*Poa pratensis* L.) (Kaye et al., 2004; Bremer, 2006). Different amounts and timing of N application may affect cumulative N_2O emissions in turfgrasses. For example, Bremer (2006) demonstrated that N applied at 250 kg N ha^{-1} yr^{-1} to perennial ryegrass resulted in a 63% increase in annual N_2O-N emissions when compared to N applied at 50 kg N ha^{-1} yr^{-1}. Fertilizer applications during summer when temperatures are higher may also result in greater N_2O emissions. Bijoor et al. (2008) reported that higher temperatures from artificial heating at the time of N fertilization resulted in greater fluxes of N_2O than when N applications were made at ambient temperatures in a lawn comprised of tall fescue (*Festuca arundinacea* Schreb.) and crabgrass (*Digitaria* sp. Haller). Consequently, N_2O emissions may also vary among turfgrass species because of different N-fertilization regimes, both in amounts and in timing.

Total N application for cool-season (C3) grasses range from 150 to 250 kg ha^{-1} annually (Christians, 2007). The standard recommendation for warm-season (C4) grasses is 100 to 200 kg N ha^{-1} (Keeley and Fagerness, 2001). Nitrogen management of warm-season turfgrasses varies among species. For example, while bermudagrass and zoysiagrass are both warm-season grasses, zoysiagrass inherently requires less N input than bermudagrass. Zoysiagrass maintains acceptable density at lower amounts of N than bermudagrass and when excess N is applied to zoysiagrass excessive thatch results (Christians, 2007).

A variety of turfgrass species are grown in the transition zone of the USA. The U.S. transition zone measures 480 to 1120 km north to south between the northern regions where cool-season grasses are adapted and the southern regions where warm-season grasses are adapted (Dunn and Diesburg, 2004). Perennial ryegrass is a cool-season grass that has fair drought tolerance and has been used in several N_2O emission studies in the past (Denmead et al., 1979; Ryden, 1981; Maggiotto et al., 2000; Bremer, 2006). Perennial ryegrass is often used in lawns, sports fields and golf courses in the U.S. Midwest and transition zone, though it is distributed throughout the U.S. Bermudagrass is considered the primary warm-season grass in the Southern U.S. for a variety of uses including lawns, roadsides, parks, golf courses and sports fields. It has excellent drought tolerance. Zoysiagrass is a warm-season grass used in the transition zone of the U.S. for lawns, and golf courses. It has very good drought tolerance (Christians, 2007; USDA-NRCS, 2009).

Few studies have quantified cumulative emissions of N_2O from turfgrasses, or the impact of cultural practices, such as species selection, on N_2O emissions. The identification of turfgrass species that emit less N_2O could potentially be used to mitigate N_2O emissions from large urban areas. Under this scenario, recommendations of turfgrass species for a given region may be based partially on the relative contributions among species to regional atmospheric N_2O budgets. Therefore, our objectives were to quantify N_2O fluxes in one cool-season and two warm-season turfgrasses under typical N-management recommendations for maintaining acceptable quality lawn. (Christians, 2007; Keeley and Fagerness, 2001). Ancillary measurements of air temperature and soil moisture, temperature, NO_3^- and NH_4^+ were also measured to examine their effects on N_2O emissions among species.

Materials and Methods

The field study was conducted from day of year (DOY) 157, 2006 to DOY 40, 2008 at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas (Rocky Ford; lat. 39^{o}13'53" N, long. 96^{o}34'51" W). The soil at the site was a Chase silt loam (fine, smectitic, mesic, Aquertic, Argiudolls) (Soil Survey Staff, 2010). Mean annual air temperature was 13.6°C in 2006 and 12.8°C in 2007, which was 0.1°C and 0.9°C lower, respectively, than the 30-yr mean. The summer of 2006 (Jun-Aug) was cooler than normal; average air temperature was 25.4°C, or 2.2°C lower than the 30-yr mean. The summer of 2007 was also cooler than the 30-yr mean; average air temperature was 25.1°C, or 2.5°C lower than normal.

Treatments

Plots of bermudagrass, perennial ryegrass, and zoysiagrass were replicated six times each in a repeated Latin square design, for a total of 18 plots. Plots were 2 by 2 m each and separated by 1 m borders. Bermudagrass and zoysiagrass plots were established in May 2005, and perennial ryegrass plots were established in Sept. 2005. In this study, the N-management regimes used for each species were typical for the transition zone where maintenance of acceptable quality is desired (Keeley and Fagerness, 2001; Christians, 2007).

Granular urea N fertilizer was applied at 200 kg N ha^{-1} yr^{-1} to bermudagrass and perennial ryegrass and at 100 kg N ha^{-1} yr^{-1} to zoysiagrass according to the schedule shown in Table 1. After N applications, all plots were irrigated with 15 mm of water to incorporate fertilizer into the soil and reduce ammonia volatilization (Bowman et al., 1987). Plots were irrigated one to three times weekly or as needed to prevent drought stress. During the summer perennial ryegrass plots were irrigated more frequently than the bermudagrass and zoysiagrass plots, which is standard protocol to maintain acceptable quality. All plots were mowed twice weekly or as needed at a height of 7.5 cm.

Measurements of Nitrous Oxide Fluxes

Soil-surface N_2O fluxes were measured with static, vented poly-vinyl chloride chambers (7.5 cm high by 20-cm dia.) using the method described by Hutchinson and Mosier (1981). Using this method, heating inside the chambers was assumed to be negligible. Heating inside the chambers during measurements is minimized by constructing the chambers with white poly-vinyl chloride and by placing highly reflective aluminum foil tape on the topsides to reflect radiation away from the chamber.

Permanent poly-vinyl chloride collars were placed randomly at one location in each plot and were driven approximately 8 cm into the soil. Measurements were generally made mid-morning, ~10:00 local standard time. Measurements of N_2O-N were taken approximately once weekly although more frequent measurements were made after fertilizations on DOY 191, 2006 and DOY 251, 2006 and fewer were made during periods of snow cover in winter. After fertilization applications, measurements were usually taken 1 to 3 days after application. On measurement days, chambers were installed on the collars and gas samples from inside the chambers were removed with 12-mL polypropylene syringes fitted with nylon stopcocks at 0, 30 and 60 min. An airtight seal was maintained with 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. Gas samples were then transported to the lab and analyzed by a gas chromatography (Shimadzu GC14B, Shimadzu Scientific Instruments, Columbia, MD) equipped with a Porapak Q column (3.175×10^{-3} m diam. X 1 m, 80/100 mesh) and an electron capture detector. Gas samples were always analyzed on the same day as collected, and generally within 4 h. Fluxes were calculated as described by Hutchinson and Mosier (1981) and Mosier et al. (1991).

Ancillary Measurements

Soil temperature, soil water filled porosity (WFP), and periodically, NH_4^+, and NO_3^- were measured to evaluate their relationship with N_2O emissions. Ammonium and nitrate concentration in the 0 to 10 cm soil profile were measured on flux sampling dates shown in Table 2. Grass and thatch were removed from the sample. A single soil sample was collected from each plot and then combined by treatment and tested for NH_4^+, and NO_3^- concentration (Table 2.). Overall, soil N was sampled on 60% of the N_2O-N flux sampling dates for the entire study. Climatological variables were measured at a weather station located at Rocky Ford Turfgrass Research Center.

Volumetric soil water content and temperature at 5 cm were measured automatically using dual-probe heat-pulse technique (Campbell et al., 1991; Tarara and Ham, 1997; Song et al., 1998). Sensors were fabricated in the laboratory as described by Basinger et al. (2003) and

Bremer (2003). Water filled porosity was calculated by dividing volumetric soil water content by the total porosity (0.489 m^3 m^{-3}). Measurements of WFP were logged once daily and soil temperature was logged every 60 min. The sensors were not operated when the soil was frozen, so during those periods soil temperature data at 5 cm was obtained from the on-site weather station. All data acquisition and control were accomplished with a micrologger and accessories (CR10x and one AM16/32 Campbell Scientific, Logan, UT). Bulk density of the soil at 5 cm was 1.35 g cm^{-3} (determined from volumetric samples 5.4 cm diam. by 3 cm) and organic matter was 4% (Soil Testing Laboratory, Kansas State University).

Data Analysis

Nitrous oxide flux data from each plot on each measurement day were evaluated for chamber leakage and to ensure that fluxes were greater than the minimum detectable limit (MDL) of the gas chromatograph (10.4 μg m^{-2} hr^{-1}); if fluxes were below the MDL then fluxes were set to 0 for analysis. Flux rates were then calculated. Cumulative emissions of N_2O were estimated as the sum of the products of weekly flux rates and the number of days between samples. Cumulative values were first calculated for each plot, and treatment values were then obtained by averaging the cumulative values over all the plots within each respective treatment. If a flux measurement preceded or followed N fertilization, which had a large effect on N_2O emissions, the interpolation was truncated to the date of fertilizer application. Estimates of annual N_2O-N emissions for the 600-d study were calculated by averaging fluxes when dates were sampled in 2007 and 2008, then using the Feb. to June 2007 data to complete the 2008 estimate since data was not collected during that time in 2008. Cumulative estimates from the summer (Jun-Aug.) and fall (Sep-Nov) were also calculated for both 2006 and 2007 to illustrate seasonal dynamics and inter-annual variations in N_2O fluxes among species.

To evaluate the impact of N fertilization on N_2O-N fluxes, fluxes among species were averaged over the entire study except for all two-week periods after N fertilization. These fluxes were referred to as background fluxes, and were compared to average fluxes during the first week (0 to 7 days) and second week (8 to 14 days), respectively, after N applications.

Tests of differences in N_2O fluxes, WFP, and cumulative estimates among treatment means were conducted using the mixed linear model in SAS ($P<0.05$ for N_2O fluxes, season cumulative fluxes, and WFP; $P<0.10$ for annual cumulative fluxes, (SAS Institute Inc., 2002) using the LSD test; turfgrass species was the main effect, and row and column were random effects. Correlations between N_2O fluxes and soil NH_4^+ and NO_3^-, WPF, air and soil temperature were conducted with the correlation procedure (Spearman) of SAS.

Results and Discussion

General Trends

Daily fluxes of N_2O-N ranged from 1633 μg m^{-2} hr^{-1} in the summer of 2006 to -17.63 μg m^{-2} hr^{-1} in the late fall of 2007, which was comparable to N_2O fluxes from turfgrass reported in other studies (Figs. 1 and 2) (Bergstrom et al., 2001; Kaye et al., 2004; Bremer, 2006; Bijoor et al., 2008; Hall et al., 2008). With few exceptions, fluxes increased among species after N fertilization but returned to pre-fertilization values within two weeks. This is similar to results from other studies that revealed greater N_2O fluxes for up to 12 days after N-fertilizer application (Christensen et al., 1983; Bremer, 2006). In our study, as in Bremer (2006), the increase in N_2O-N fluxes after N fertilization was greater when accompanied by significant precipitation, which increased WFP (e.g., DOY 192, Fig. 1).

Background fluxes averaged over the entire study were 31.7, 37.5, and 31.9 μg N_2O-N m^{-2} hr^{-1} in bermudagrass, perennial ryegrass, and zoysiagrass, respectively, and were similar among species. When fluxes were averaged over all one-week periods after N fertilization, fluxes increased to 311.5, 161.2, and 300.5 μg N_2O-N m^{-2} hr^{-1} in bermudagrass, perennial ryegrass, and zoysiagrass, respectively. In perennial ryegrass, in which post-fertilization N_2O-N fluxes averaged significantly lower than bermudagrass and zoysiagrass, half of all N fertilizations occurred during the fall when soil temperatures were cooler. Cooler soil temperatures concurrent with N fertilization likely contributed to lower average, post-fertilization N_2O-N fluxes in perennial ryegrass among species. When fluxes were averaged over all of the second-week periods after N applications, N_2O-N fluxes remained numerically albeit not statistically higher than background values in bermudagrass and zoysiagrass; fluxes in the second-week after N fertilization averaged 50.6, and 54.5 μg m^{-2} hr^{-1} in bermudagrass, and zoysiagrass, respectively. Emissions from perennial ryegrass declined to slightly less than background in the second-week to 27.3 μg m^{-2} hr^{-1}.

Correlations between daily N_2O-N fluxes and WFP (r=0.19***, n=716) and soil temperature (r=0.10***, n=780) were both weak, but significant when computed from pooled data over the entire study. Fluxes of N_2O-N generally increased with higher soil temperature and soil water content. Other studies have reported similar relationships between N_2O fluxes, soil temperature and soil water content (Christensen, 1983; Bremer, 2006; Bijoor et al., 2008). Soil concentrations of NO_3^- and NH_4^+ were higher ($p<0.05$) after fertilizer applications compared to pre-fertilization values. When pooled for the entire study, however, N_2O fluxes were not correlated with soil NO_3^- or NH_4^+. In our study, soil samples for testing NO_3^- and NH_4^+ were collected and combined by treatment on each measurement day rather than testing each plot individually, which may have reduced our ability to detect significant correlations.

Seasonal N_2O fluxes: Dynamics, cumulative, and inter-annual variability

June to August (Summer)

Cumulative emissions of N_2O-N were 47% greater in bermudagrass than in perennial ryegrass during both summers (Table 3). Also, N_2O-N fluxes were greater in bermudagrass than in zoysiagrass in 2007. Greater emissions from bermudagrass during summer were likely caused by greater inputs of N into bermudagrass than in perennial ryegrass and zoysiagrass (Table 1).

In summer 2006, however, fluxes of N_2O-N were similar between bermudagrass and zoysiagrass despite greater corresponding inputs of N in bermudagrass (Tables 1 and 3). In 2007, fluxes in bermudagrass peaked immediately after N fertilizations on DOY 156 and 214 but declined again to similar levels as zoysiagrass within 6 to 14 days of fertilization (Fig. 2). Therefore, after N applications on DOY 179, 2006, fluxes may have already peaked and receded in bermudagrass by the time the first post-fertilization measurements were taken on DOY 186 (Fig. 1), which would have reduced cumulative estimates of N_2O fluxes from bermudagrass in 2006. In addition, the highest fluxes of the study occurred on DOY 192, 2006, which may have muted other differences between bermudagrass and zoysiagrass during the summer; fluxes on DOY 192 were 1,451, 1,100, and 1,633 μg N_2O-N m^{-2} hr^{-1} in bermudagrass, perennial ryegrass, and zoysiagrass, respectively.

The high fluxes on DOY 192, 2006, occurred one day after all species had been fertilized with N, which increased soil-N availability (Table 2). Additionally, WFP was greater than 0.75 v v^{-1} and soil temperature was greater than 24°C among species, which was higher than at any other sampling date that year (Fig. 1); high WFP was caused by a combination of the standard post-N-fertilization irrigation and by 36 mm of rainfall that night. On the next day (DOY 193), fluxes remained higher than before fertilization but had decreased by about 96% from the previous day. Fluxes of N_2O-N continued to decline on the third day after N fertilization (DOY 194) and returned to pre-fertilization values after two weeks (DOY 206). Denitrification rates may increase immediately and then decrease within a few hours to days after rainfall and irrigation (Sexstone et al., 1985), which probably caused the transitory high fluxes in our study on DOY 192.

Other studies have also reported increases in N_2O fluxes with N input and WFP, presumably because of enhanced conditions for denitrification (Denmead et al., 1979; Ryden, 1981; Christensen, 1983; Clayton et al., 1994; Bremer, 2006; Bijoor et al., 2008). Fluxes as great as 7,528 μg m^{-2} hr^{-1} were reported in perennial ryegrass after N fertilization ((Ryden, 1981), and 6,329 μg m^{-2} hr^{-1} in fertilized grasslands after a heavy rainfall (Clayton et al., 1994).

On DOY 191, 2007, which was one day after N fertilizer in all treatments (Table 1), fluxes were 66, 34, and 29 μg N_2O-N m^{-2} hr^{-1} in bermudagrass, perennial ryegrass, and zoysiagrass, respectively, and were similar to fluxes before fertilization (Fig. 2). These negligible responses of N_2O fluxes to fertilization were in stark contrast to the large responses observed one day after the same fertilization one year earlier (DOY 191, 2006). Lower WFP at sampling in 2007 probably contributed to negligible responses to N fertilization. In 2007 the WFP on DOY 191 was 0.61, 0.54, and 0.48 in bermudagrass, perennial ryegrass and zoysiagrass, respectively. In contrast, in 2006 the WFP on DOY 192 was 0.75, 0.77, and 0.79 in bermudagrass, perennial ryegrass, and zoysiagrass, respectively.

Despite substantially lower responses of N_2O fluxes to fertilizer applications on DOY 190, 2007 than on DOY 191, 2006, cumulative summer fluxes for bermudagrass were similar between 2006 and 2007 (Table 3). In 2007, cumulative N_2O fluxes in bermudagrass were elevated by the large responses to N applications on DOY 156 and 214; zoysiagrass and perennial ryegrass were not fertilized on those dates (Fig 2.). The largest N_2O-N flux in 2007 was on DOY 157 in bermudagrass (703 μg N_2O-N m^{-2} hr^{-1}) and was likely caused by a combination of N application and high soil temperatures and WFP. Furthermore, for perennial ryegrass and zoysiagrass, summer emissions of N_2O were lower in 2007 than in 2006 because there was no response to fertilization for perennial ryegrass or zoysiagrass on DOY 190, 2007.

September to November (Fall)

During the fall, fluxes of N_2O-N ranged from 130 to 1 μg N_2O-N m^{-2} hr^{-1} and became negligible by the end of November in both years after soil temperature had declined substantially (Figs. 1 and 2). The late fall N applications to perennial ryegrass (DOY 304, 2006, and DOY 319, 2007) did not result in increased fluxes of the magnitude that were observed in bermudagrass after N applications during summer (DOY 190 2006 and DOY 157 2007), probably because of lower fall temperatures (Bremer, 2006; Bijoor et al., 2008). Perennial ryegrass had greater cumulative emissions than bermudagrass and zoysiagrass in the fall of both years, however, undoubtedly because of N fertilization to perennial ryegrass in the fall concurrent with no N applications to bermudagrass or zoysiagrass (Table 1).

The N applications to perennial ryegrass elevated fluxes above bermudagrass and zoysiagrass for three of the four fall applications during the two-year study. Fluxes were greater in perennial ryegrass than in bermudagrass and zoysiagrass after the two fall N-fertilizations of perennial ryegrass in 2006 (DOY 250 and 304) (Fig. 1). Interestingly, fluxes increased in all species on DOY 254, 2006 after 21 mm of rainfall that caused WFP to increase to over 0.75 v v^{-1} among species. The greatest increase in fluxes among species was in perennial ryegrass, however, probably because of its N fertilization on DOY 250. Application of N to perennial ryegrass on DOY 304, 2006 also resulted in higher fluxes than in bermudagrass and zoysiagrass on DOY 305 and 312. Fluxes on DOY 305 and 312, 2006 were smaller than fluxes after N fertilization on DOY 250, 2006, probably because less N was applied on DOY 304 than on DOY 250 (Table 1) and because soils had cooled; soil temperature at 5 cm was 21°C on DOY 250 but had decreased to about 9°C on DOY 305 and 312. On DOY 254, 2007, which was one day after N fertilization, N_2O-N fluxes increased in perennial ryegrass and were higher than in bermudagrass and zoysiagrass despite perennial ryegrass having lower WPF than bermudagrass and zoysiagrass (Fig. 2).

On DOY 268, 2007 we observed negative fluxes among all treatments. This was the only day during the entire study that we observed negative fluxes; others have reported negative fluxes during the winter months (Ryden, 1981; Bremer, 2006). For a system to act as a sink for atmospheric N_2O, soil conditions must be conducive to microbial reduction of N_2O, when the NO_3^- available for reduction during denitrification is exhausted and when reductive stress is placed on the system (Ryden, 1981).

Fluxes from December to February (Winter)

In December of both years, fluxes were barely detectable, probably because of soil temperatures below 5°C on all measurement dates (Figs. 1 and 2). Other studies have reported negligible N_2O fluxes during the winter months in various ecosystems ((Mosier et al., 1996; Webb et al., 2004) and in turfgrass ((Ryden, 1981; Bremer, 2006).

We sampled N_2O-N fluxes during two separate snowmelt events: 1) DOY 51, 2007; and 2) DOY 40, 2008 (Fig. 2). Interestingly, the greatest fluxes observed in perennial ryegrass in 2007 were on DOY 51 (306 μg N_2O-N m^{-2} hr^{-1}). Fluxes in perennial ryegrass were also the greatest among species on DOY 51 although fluxes in bermudagrass and zoysiagrass also increased. Other studies have reported on brief and vigorous N_2O emissions during freeze/thaw cycles (Christensen and Tiedje, 1990; Flessa et al., 1998; Kaiser et al., 1998). Greater N_2O-N fluxes in perennial ryegrass among species on DOY 51 may have been related to N fertilization in the late fall, which was applied to perennial ryegrass but not to bermudagrass and zoysiagrass (Table 1).

Snowmelt increases soil moisture and the availability of easily degradable carbon and nitrate in the soil, resulting in enhanced microbial activity and denitrification in the soil's top layer (Nyborg et al., 1997; Muller et al., 2002; Wagner-Riddle et al., 2008); hence, greater N_2O emissions during snowmelt. In our study, however, greater N_2O emissions were not observed during the snowmelt in 2008. Air temperature at sampling was similar between snowmelt events, 6.8 and 8.7°C in 2007 and 2008, respectively. In 2007, soils were frozen at 5 cm among treatments during snowmelt, while in 2008 the soil temperature was slightly above freezing (1.2°C). Because of the transient nature of high N_2O fluxes following increases in soil moisture, it is possible that our measurements may have missed peak N_2O emissions during the snowmelt in 2008.

Others have reported large fluxes during winter in grasslands and fertilized crops, especially when snowmelts increased the soil water content. Mosier et al. (1996) reported N_2O-N fluxes greater than 5 μg N_2O-N m^{-2} h^{-1} from a shortgrass steppe, mostly during snow melts, which represented 20-40% of the annual N_2O emissions. Kaiser et al. (1998) reported N_2O-N fluxes collected from croplands were greater than 100 g N_2O-N ha^{-1} d^{-1} during the winter when soil moisture increased. Winter fluxes in those systems accounted for 20 to 50% of annual N_2O emissions (Mosier et al., 1996; Kaiser et al., 1998).

Fluxes from March to May (Spring)

Fluxes on DOY 123, 2007, after N fertilization to all plots on DOY 120, were similar to pre-fertilization levels despite high WFP at sampling (Fig. 2). Nitrous oxide fluxes increased among all treatments, however, by the next sampling date (DOY 131). Greater N_2O-N fluxes among treatments on DOY 131 than DOY 123 was likely caused by a combination of an average 4.1°C increase in soil temperatures, high soil N from fertilization, and higher soil moisture in perennial ryegrass and zoysiagrass after 113 mm of rainfall on DOY 127, 2007. The highest N_2O-N fluxes for zoysiagrass in 2007 were observed on DOY 131 (224 μg N_2O-N m^{-2} hr^{-1}).

Annual Cumulative Fluxes

Cumulative emissions of N_2O-N were 5.01, 4.67, and 4.13 kg N ha^{-1} for bermudagrass, perennial ryegrass, and zoysiagrass, respectively, for the entire 600 day study (Fig. 3). Weighted estimates of annual emissions during the study were 3.37, 3.09, 2.79 kg N ha^{-1} yr^{-1} from bermudagrass, perennial ryegrass, and zoysiagrass, respectively (Table 3). Emissions of N_2O-N from bermudagrass were higher than zoysiagrass but similar to perennial ryegrass ($p=0.10$). The similarity in emissions between bermudagrass and perennial ryegrass may be because they had both received identical amounts of N (400 kg N ha^{-1}) during the study, while zoysiagrass received only half as much as either bermudagrass or perennial ryegrass. Additionally, WFP consistently averaged higher in bermudagrass ($p=0.05$) than in perennial ryegrass and zoysiagrass (data not shown), which also may partially explain why cumulative fluxes in bermudagrass were numerically (albeit not statistically) greater than in perennial ryegrass. Higher WFP in bermudagrass may be related to its lower water use compared to perennial ryegrass (Fry and Huang, 2004). Cumulative emissions of N_2O increased rapidly after several N applications, especially during summer, reflecting peaks in fluxes after fertilizations. At the end of the first year, cumulative N_2O-N emissions were similar among treatments (Fig. 3).

Estimates of annual N_2O-N from this study are generally smaller or comparable to annual emissions reported from other urban and grassland ecosystems. Emissions from a Kentucky bluegrass lawn were 2.4 kg N_2O-N ha^{-1} yr^{-1} during a 1 year study Kaye et al. (2004) Bremer (2006) reported fluxes ranging from 1.65 to 1.01 kg N_2O-N ha^{-1} yr^{-1} from perennial ryegrass fertilized with different N sources and amounts. Nitrous oxide emissions from cut perennial ryegrass were reported at 1.9 to 7.8 kg N_2O-N ha^{-1} yr^{-1} in Scotland (Dobbie et al., 1999).

Emissions from native grassland and wheat ecosystems were 0.24 to 2.26 kg N_2O-N ha^{-1} yr^{-1} (Mosier et al., 1991; Mosier et al., 1996). In a grassland in Germany fertilized with 75 kg N ha^{-1} yr^{-1}, emissions were substantially greater (11.2 kg N_2O-N ha^{-1} yr^{-1}) than from an unfertilized control (3.4 kg N_2O-N ha^{-1} yr^{-1}) (Tilsner et al., 2003). In grass, barley, and fallow ecosystems in the boreal region of Finland nitrous oxide emissions ranged from 1.5 to 7.5 kg N_2O-N ha^{-1} yr^{-1}(Syvasalo et al., 2004). Rye croplands with a peat soil had emissions ranging from 4.2 to 56 kg N_2O-N ha^{-1} yr^{-1} (Flessa et al., 1998). Annual emissions of grass, barley, and bare soils were 2.75, 8.48, and 23.5 kg N_2O-N ha^{-1} yr^{-1} respectively (Maljanen et al., 2004). The bare soil emissions were very large compared to our study because the bare soil was wet and received N-fertilization, which increased NO_3^- concentrations.

Over our entire study the percentages of total N fertilizer emitted as N_2O were 1.4% in bermudagrass, 1.3% in perennial ryegrass, and 2.8% in zoysiagrass. Similar losses in turfgrass have been reported by Bremer (2006), Kaye et al. (2004), and Horgan et al. (2002). Losses as N_2O ranged from 0.4 to 3.9% from labeled N fertilizer applied to turfgrass at 49 kg ha^{-1} in a 42 day field study (Horgan et al., 2002). Bremer (2006) reported an approximate loss of 0.65% from urea N fertilizer applied at a rate of 250 kg N ha^{-1} yr^{-1}, and Kaye et al. (2004) found a 2.2% loss of N applied.

Conclusions

Daily fluxes of N_2O-N ranged from 1633 μg m^{-2} hr^{-1} in the summer of 2006 to -17.63 μg m^{-2} hr^{-1} in the late fall of 2007. Weighted estimates of cumulative N_2O emissions were 3.05, 2.83, 2.51 kg N ha^{-1} yr^{-1} for bermudagrass, perennial ryegrass, and zoysiagrass, respectively; N_2O emissions were significantly higher from bermudagrass than from zoysiagrass (p=0.10). Fertilizing when soil temperatures and WFP were higher generally resulted in larger fluxes of N_2O-N.

Data suggests that zoysiagrass may be a better choice than bermudagrass for mitigation of N_2O emissions from turfgrass, presumably because of lower N fertilization requirements for zoysiagrass. However, further research may be required to determine whether additional factors may contribute to differences in N_2O emissions among turfgrass species (e.g., root activity that may affect soil NO_3 and NH_4 amounts for denitrification and nitrification, irrigation regimes). Further research is also needed to investigate N_2O emissions among turfgrasses in other geographical areas with different climatic conditions to determine suitable, regionally appropriate species for reducing N_2O emissions from turfgrasses.

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Figures

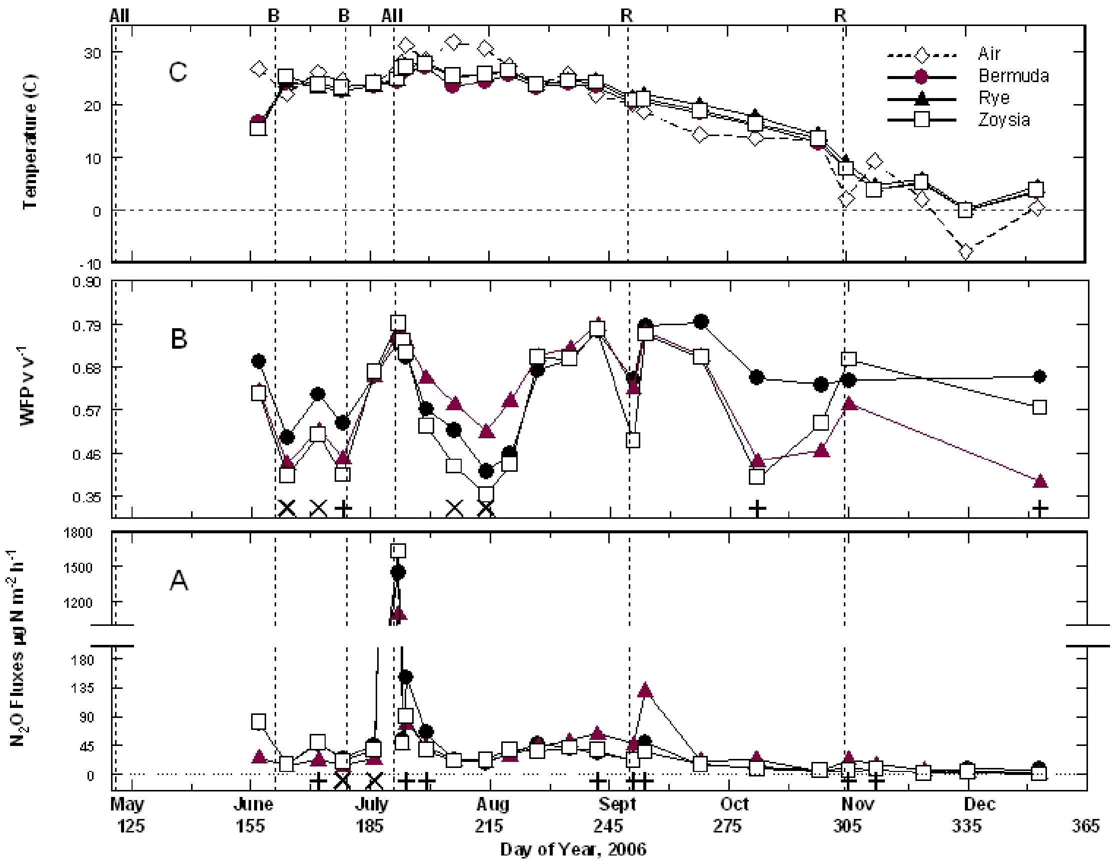

Figure 1.1 (A) Fluxes of N_2O-N from bermudagrass, perennial ryegrass, and zoysiagrass; (B) average soil water filled porosity (WFP) at 5 cm among treatments at sampling; (C) average soil temperature at 5 cm among treatments at sampling, and air temperature at 2 m. Vertical dashed lines represent N application dates. Dashed lines topped with an "All" indicate N applied to all treatments, "B" represent N applied only to bermudagrass, and "R" represent N applied only to perennial ryegrass. Symbols (×) along the abscissa in (A) indicate significant differences between at least 2 treatments ($P< 0.05$) and plus (+) indicate significant differences between one and the other two treatments.

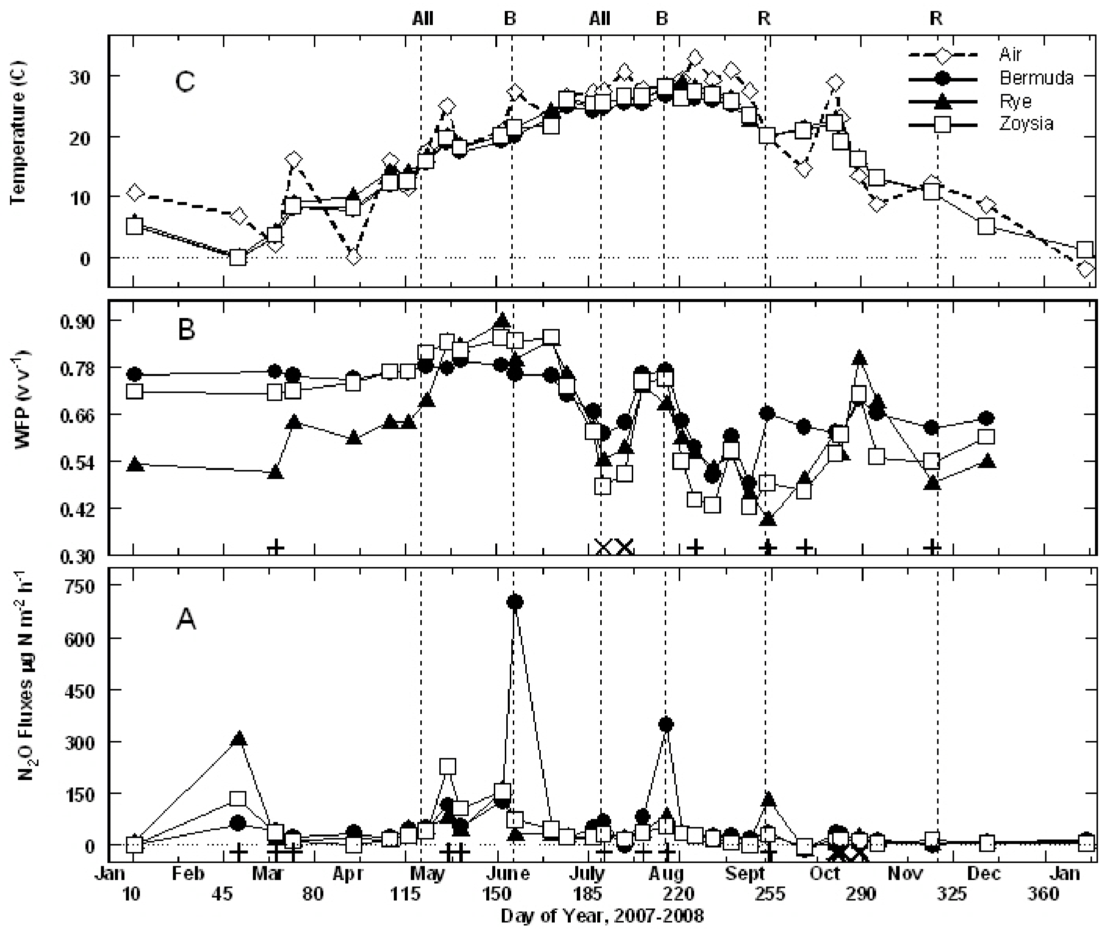

Figure 1.2 (A) Fluxes of N_2O-N from bermudagrass, perennial ryegrass, and zoysiagrass; (B) average soil water filled porosity (WFP) at 5 cm among treatments at sampling to DOY 338, 2007; (C) average soil temperature at 5 cm among treatments at sampling, and air temperature at 2 m. Vertical dashed lines represent N application dates. Dashed lines topped with an "All" indicate N applied to all treatments, "B" represent N applied only to bermudagrass, and "R" represent N applied only to perennial ryegrass. Symbols (×) along the abscissa in (A) indicate significant differences between at least 2 treatments ($P < 0.05$) and plus (+) indicate significant differences between one and the other two treatments.

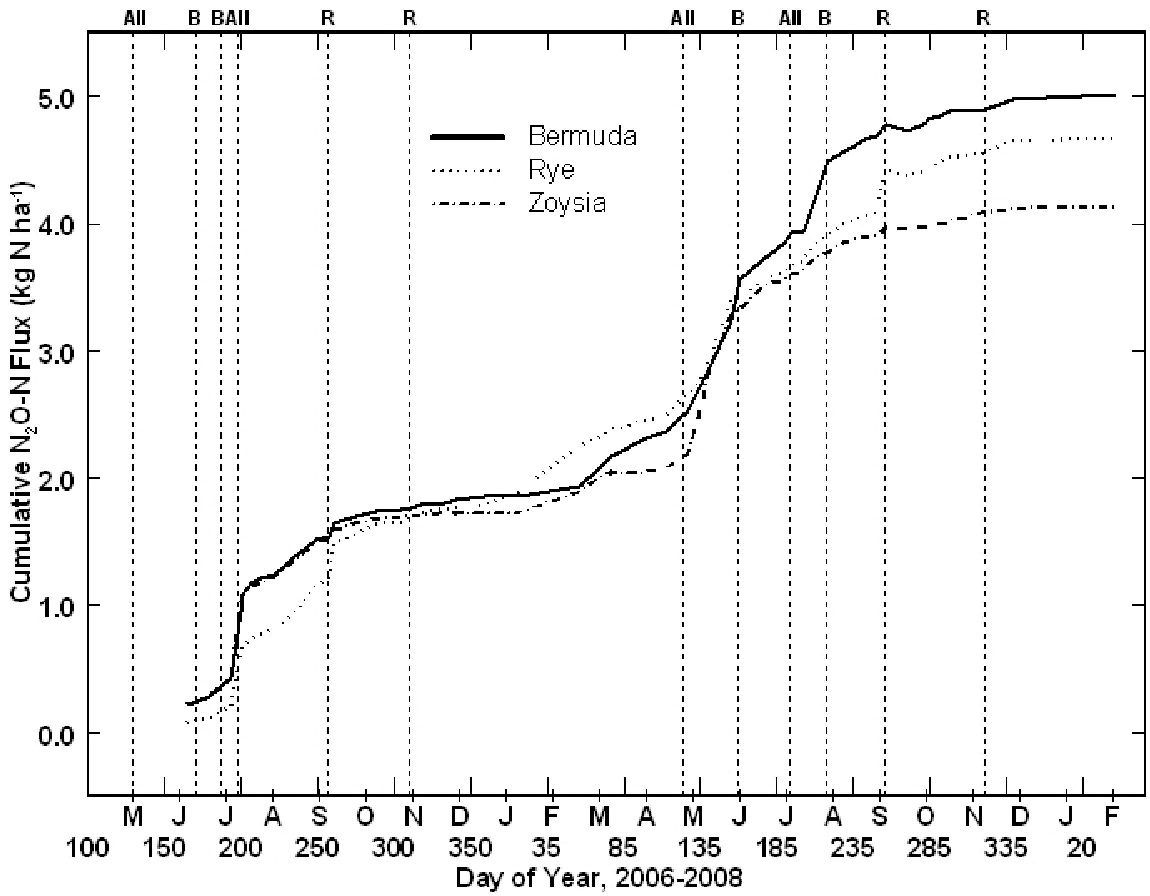

Figure 1.3 Cumulative fluxes of N_2O-N from bermudagrass, zoysiagrass, and perennial ryegrass plots. Vertical dashed lines represent N application dates. Dashed lines topped with an "All" indicate N applied to all treatments, "B" represent N applied only to bermudagrass, and "R" represent N applied only to perennial ryegrass. Data points are connected with lines to aid in interpreting the graphs and are not meant to represent fluxes between observations.

Tables

Table 1.1 Dates of granular urea nitrogen (N) fertilizer applications.

DOY†	bermudagrass	perennial ryegrass	zoysiagrass
2006		kg N ha^{-1}	
121	50	50	50
161	50		
179	50		
191	50	25	50
250		75	
304		50	
2007			
121	50	50	50
156	50		
190	50	25	50
214	50		
253		75	
319		50	

† Day of year.

Table 1.2 Soil nitrate and ammonium concentrations at 0 to 10 cm on measurement dates. Soil samples were combined by treatment.

DOY†	NO_3^- bermuda‡	NO_3^- rye§	NO_3^- zoysia¶	NH_4^+ bermuda	NH_4^+ rye	NH_4^+ zoysia	DOY	NO_3^- bermuda	NO_3^- rye	NO_3^- zoysia	NH_4^+ bermuda	NH_4^+ rye	NH_4^+ zoysia
2006	μg soil N g^{-1}						2007	μg soil N g^{-1}					
157	5.7	4.4	12.5	5.0	6.7	4.2	11	6.1	6.7	8.3	7.0	6.3	7.8
164	2.0	2.4	12.5	4.6	4.8	4.2	116	5.1	4.2	5.6	4.0	4.7	6.6
172	14.4	10.9	17.7	4.4	5.1	4.9	131	5.4	2.6	7.3	4.5	4.9	5.5
178	12.6	7.0	25.8	4.6	3.7	4.5	136	8.3	3.8	18.3	5.4	6.7	7.8
186	3.0	6.7	23.1	4.0	3.6	3.9	152	9.1	7.0	14.6	4.1	6.2	6.5
192	7.4	10.0	16.0	5.6	4.9	3.7	191	29.2	17.5	27.7	32.7	19.1	57.0
199	5.1	8.6	12.1	4.6	4.0	3.5	199	14.3	26.9	12.5	11.7	17.1	11.2
206	1.5	10.4	23.4	3.6	4.0	4.0	206	13.7	14.5	18.2	8.9	18.6	15.9
214	1.4	19.3	7.0	3.9	3.5	4.2	214	4.5	10.7	2.7	8.1	5.6	4.4
220	1.5	21.4	14.4	3.4	3.2	4.3	221	6.0	16.3	5.2	7.3	6.9	4.9
227	2.6	13.4	8.2	3.7	3.5	3.7	226	5.9	25.7	4.0	9.2	7.7	5.9
235	4.2	5.2	2.9	3.7	3.2	3.5	254	4.4	28.3	4.0	5.6	26.1	5.3
242	4.3	6.1	5.6	3.8	3.2	6.6	282	5.0	24.6	3.0	5.2	5.8	5.6
251	4.5	17.6	3.7	4.6	10.9	4.9							
254	3.2	13.3	8.7	5.8	6.2	6.3							
268	6.4	9.5	6.0	4.5	4.9	5.1							
282	2.3	3.4	1.8	3.7	3.6	3.0							
298	3.1	2.7	5.3	4.9	4.7	5.6							
312	3.1	2.8	5.7	4.8	4.6	5.3							
324	3.7	2.1	7.8	5.1	5.6	7.9							
353	5.1	2.2	9.7	6.4	8.1	7.0							

† Day of year.
‡ Bermudagrass
§ Perennial ryegrass
¶ Zoysiagrass

Table 1.3 Annual cumulative N_2O-N emissions and seasonal cumulative emissions during summer and fall of 2006 and 2007.

	Annual Emissions	Summer†		Fall‡	
	Yearly Ave. §	2006	2007	2006	2007
	kg N ha^{-1}				
bermudagrass	3.37 a	1.33 a	1.43 a	0.28 b	0.22 b
perennial ryegrass	3.09 ab	0.99 b ***	0.76 b ***	0.58 a	0.45 a
zoysiagrass	2.79 b	1.29 a ***	0.68 b ***	0.23 b	0.18 b

***, Means were significantly different (p=0.001) within a season compared across years.
† Summer consisted of data collected from June to Aug.
‡ Fall consisted of data collected from Sept. to Nov.
§ Within the column, means followed by the same letter are not significantly different (p=0.10).

CHAPTER 2 - Nitrous oxide emissions from bermudagrass fertilized with urea and slow-release organic and polymer-coated nitrogen

Abstract

Turfgrass ecosystems may be a source for atmospheric nitrous oxide (N_2O). One possible best management practice to reduce N_2O emissions from turf is through the use of controlled-release nitrogen (N) fertilizers. Our objectives were to compare N_2O emissions among turfgrasses fertilized with two controlled-release N fertilizers, including polymer-coated (poly) and organic N, and quick-release urea N in bermudagrass (*Cynodon dactylon* L. Pers. X *C. transvaalensis* Burtt-Davy). Fertilizer was applied at 200 kg N ha^{-1} yr^{-1} to field plots in Manhattan, KS, USA. Emissions were measured from day of year (DOY) 159 to 305, 2007 and DOY 148 to 285, 2008 using static surface chambers and gas chromatography. Fluxes of N_2O-N ranged from 7.5 to 833 μg N_2O-N m^{-2} hr^{-1}. Cumulative N_2O-N emissions during the two summers were 8.38, 7.97, and 6.91 kg N_2O-N ha^{-1} in the poly, organic, and urea treatments, respectively, and were not statistically different. Fluxes of N_2O-N averaged higher from urea than in poly in the week after fertilization, but background fluxes (fluxes among treatments averaged over the entire study except for all two-week periods after N application) were lowest in urea. The poly treatment had the highest background fluxes, but N application had no immediate transient effect on N_2O-N emissions. Increased water filled porosity (WFP) seemed to increase N_2O-N fluxes from all treatments, especially from poly. Controlled release polymer-coated urea or organic N do not seem to be effective measures in mitigating N_2O-N emissions from turfgrass systems compared to traditional urea applications.

Introduction

Nitrous oxide (N_2O) is a major greenhouse gas implicated in climate change (IPCC, 2001). Additionally, recent research has shown that N_2O is expected to remain the most important ozone-depleting substance emitted during the 21st century (Ravishankara et al., 2009). Agriculture may contribute more than 80% of N_2O emissions into the atmosphere (Goodroad and Keeney, 1984; Sextone et al., 1985; Isermann, 1994; Mosier et al., 1996; Bouwman, 1996; USEPA, 2008). However, rapid urbanization is resulting in agricultural lands and native areas being replaced with turfgrass (Dillman et al., 1993; Kaye et al., 2004). Turfgrass is also often irrigated and fertilized with N and therefore, may increasingly become a source for atmospheric N_2O.

In the United States, 16-20 million ha of urbanized land, or up to 18% of the land area in some regions, are covered with turfgrasses (NASS, 2004). This represents an area three times larger than any irrigated crop (Milesi et al., 2005). Because turfgrass is often fertilized with N, urban areas are probably increasingly contributing to atmospheric N_2O (Kaye et al., 2004). This indicates a need for research to identify best management practices that mitigate N_2O emissions from turfgrass.

One possible best management practice is use of controlled-release N fertilizers, which may reduce N_2O emissions by releasing N more synchronously with plant growth (Snyder et al., 2009). In consequence, controlled-release N fertilizers may slow the processes of nitrification and denitrification in the soil, which are the main sources for N_2O emissions in fertilized turfgrass (Firestone and Davidson, 1998; Bremer, 2006, Fig. 1).

In turfgrass, nitrification and denitrification and hence, emissions of N_2O, are controlled by several factors including: 1) soil moisture and temperature, which affect microbial processes; 2) the amount of mineralizable organic carbon, which is used as an energy source for denitrifiers; 3) soil oxygen, which controls denitrification; 4) concentrations of NO_3^- and NH_4^+, which are affected by N fertilization and plant uptake and release of N; and 5) soil pH (Bouwman, 1990).

Delgado and Moiser (1996) reported an initial lowering (21 days after N application) of N_2O emissions from the use of slow release fertilizers, but thereafter emissions were higher from the polyolefin-coated urea than from urea-fertilized plots. Polymer coated urea reduced cumulative mean N_2O emissions 30% and 17% over 3 growing seasons in potato (*Solanum* *tubersum* L.) (Hyatt et al., 2010). Minami (1994) found in a 83 d lysimeter study that slow-release fertilizer may be useful in reducing N_2O emissions compared to ammonium sulfate N. Jumadi et al. (2008) and Hadi et al. (2008) found that controlled release N (CRF-CP30) did not affect N_2O emissions in corn (*Zea mays* L.) compared to urea. In a comprehensive review of greenhouse gas emissions from crop production systems and fertilizer management effects, Snyder et al. (2009) called for research to evaluate the impact of newer fertilizer forms, including controlled-release sources.

Relatively little work has been done to investigate effects of slow-release fertilizers on N_2O emissions in turfgrass systems. To our knowledge, Maggiotto et al. (2000) were the only researchers to report about the effects of slow release fertilizers on N_2O fluxes in a turfgrass system. They found that to minimize N_2O emissions, ammonium-based fertilizers should be used when denitrification is anticipated, and nitrate-based fertilizers should be used when nitrification conditions are expected. Slow release urea did not result in reduced emissions than urea after year 2 in the study.

Our objectives were to compare N_2O emissions from turfgrass fertilized with two controlled-release N fertilizers, including polymer-coated and organic N, and quick release urea N. Specifically, we investigated the magnitudes, dynamics, and cumulative emissions of N_2O-N fluxes among the three N-fertilization types during the growing season of two consecutive years. Ancillary measurements of soil moisture, soil temperature, and soil nitrate and ammonium were collected to interpret basic environmental controlling factors in N_2O-N fluxes among treatments.

Materials and Methods

The field study was conducted during the summers of 2007 and 2008, from day of year (DOY) 159 to 305, 2007 and DOY 148 to 285, 2008 at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas (Rocky Ford; lat. 39°13'53" N, long. 96°34'51" W). The soil at the site was a Chase silt loam (fine, smectitic, mesic, Aquertic, Argiudolls). The summer months of June, July and Aug. in 2007 were also slightly cooler than the 30-yr mean; average air temperature was 25.1°C, or 0.3°C lower than normal. The summer months in 2008 were cooler than the 30-yr average; average air temperature was 24.2°C, or 1.2°C lower than normal.

Treatments

Three fertilizer treatments, replicated 6 times each, were applied to 2 by 2 m plots of established bermudagrass in a repeated Latin square design. All treatments received 200 kg N ha^{-1} annually applied on the dates listed in Table 2.1. The three N fertilizers included a polymer-coated urea (41-0-0) (Agrium, Calgary, Alberta, CA) (poly), an organic (8-2-4) (Sustane, Cannon Falls, MN), and urea (46-0-0). After N application, all plots were irrigated with 15 mm of water to incorporate fertilizer into the soil and reduce ammonia volatilization (Bowman et al., 1987); the poly treatment was also concurrently watered even though it did not receive N on the last three fertilization dates of each summer. Plots were irrigated additionally as needed to prevent drought stress, and all treatments were irrigated the same. All plots were mowed twice weekly or as needed at a height of 7.5 cm.

Measurements of Nitrous Oxide Fluxes

Soil-surface N_2O fluxes were measured with static, vented poly-vinyl chloride chambers (7.5 cm high by 20-cm dia.) using the method described by Hutchinson and Mosier (1981). Permanent poly-vinyl chloride collars were placed randomly at one location in each plot and were driven approximately 8 cm into the soil. Measurements of N_2O-N were taken approximately once weekly, although more frequent measurements were made after fertilizations on DOY 191 and 251, 2006 and fewer were made during periods of snow cover in winter. After N fertilization, N2O fluxes were usually measured within 1 to 3 days.

On measurement days, chambers were installed on the collars and gas samples from inside the chambers were removed with 12-mL polypropylene syringes fitted with nylon stopcocks at 0, 30 and 60 min. An airtight seal was maintained with 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. Gas samples were then transported to the lab and analyzed by gas chromatography (Shimadzu GC14B, Shimadzu Scientific Instruments, Columbia, MD) equipped with a Porapak Q column (3.175×10^{-3} m diam. X 1 m, 80/100 mesh) and an electron capture detector. Gas samples were always analyzed on the same day as collected, and generally within 4 h. Fluxes were calculated as described by Hutchinson and Mosier (1981) and Mosier et al. (1991).

Ancillary Measurements

Volumetric soil water content (θ_v) in the 0 to 15 cm profile was measured on sampling dates using time domain reflectometry (TDR) (model 6050XI, Soilmoisture Equipment, Santa Barbara, CA) then converted to WFP as described in Maggiotto et al., 2000. Soil temperature probes were constructed by longitudinally centering copper-constantan thermocouple junctions (Type T, 24 AWG, TT-T-24, Omega, Stamford, CT) in segments of copper tubing (7.5 cm in length x 6.4 mm diam.) and filling the tubes with thermally conductive epoxy (Omegabond 101, Omega Engineering, Stamfort, CT). Probes were placed longitudinally at a 5 cm depth. Soil temperature values collected during N_2O sampling were used for analysis. Data acquisition and control were accomplished with a micrologger (CR10x Campbell Scientific, Logan, UT).

Ammonium and nitrate concentration in the 0 to 10 cm profile were measured at least weekly on sampling dates until DOY 234, 2008. Soil samples were collected from each plot and then combined by treatment and tested for NH_4^+, and NO_3^- concentration. Overall, soil N was sampled on 60% of the N_2O-N flux sampling dates for the entire study. Climatological variables were measured at a weather station located at Rocky Ford Turfgrass Research Center.

Data Analysis

Nitrous oxide flux data from each plot on each measurement day were evaluated to ensure fitness, and flux rates were then calculated. Cumulative emissions of N_2O were estimated as the sum of the products of weekly flux rates and the number of days between samples. Cumulative values were first calculated for each plot, and treatment values were then obtained by averaging the cumulative values over all the plots within each respective treatment. If a measurement preceded or followed N fertilization, which had large effects on N_2O emissions, the interpolation was truncated based on the timing of the fertilization.

Fluxes of N_2O were not measured during winter months in this study. Measurements of N_2O fluxes were available, however, from bermudagrass fertilized with urea in a nearby study during the winter that immediately preceded and overlapped this study (Lewis and Bremer, 2010). In the nearby study, which was within 50 m of the current study, measurements of N_2O fluxes were collected from the same bermudagrass cultivar that was fertilized at the same rate of urea and irrigated in the same manner as in this study. This provided an opportunity to estimate annual emissions, which are important when evaluating potential contributions of turfgrass to global N_2O budgets, during the first year of this study from the urea treatment. Because of the close proximity of the two treatments, the identical cultivar, N-fertilization and irrigation regimes, and similar soils, it is likely that winter N_2O emissions were similar between studies. Therefore, an annual estimate was calculated by summing measurements of N_2O fluxes from the first growing season of the current study (DOY 159 to 305, 2007) with those from the preceding winter in the nearby study (DOY 312, 2006 to DOY 136, 2007) in the urea treatment.

To evaluate transient effects of N fertilization on N_2O-N fluxes, fluxes among treatments were averaged over the entire study except for all two-week periods after N application. These fluxes were referred to background fluxes, and were compared to average fluxes among treatments collected during the first week (0 to 7 days) and second week (8 to 14 days), respectively, after N applications. Additionally, orthogonal contrasts were made to compare pre and post N fertilization flux values for each treatment using SAS ($P<0.05$; SAS Institute, 2002). Contrasts were also made to compare N_2O fluxes before and after incidents of significant precipitation to evaluate effects of changes in soil moisture on N_2O emissions.

Tests of differences in N_2O fluxes and cumulative estimates among treatments were conducted using the mixed linear model in SAS ($P<0.05$; SAS Institute, 2003); fixed effects included row and column. Correlations between N_2O fluxes and soil NH_4^+ and NO_3^-, WFP, air and soil temperature were conducted with the correlation procedure (Spearman) of SAS.

Results and Discussion

Responses of nitrous oxide fluxes to nitrogen fertilization

Fluxes of N_2O-N ranged from 7.5 to 833 μg N_2O-N m^{-2} hr^{-1} (Figs. 2.1 and 2.2), which were comparable to N_2O fluxes from turfgrass reported in other studies (Bergstrom et al., 2001); (Kaye et al., 2004); (Bremer, 2006); (Bijoor et al., 2008); (Hall et al., 2008). Fluxes of N_2O-N generally increased after N fertilization (Table 2.2). Fluxes increased 4 times after 8 N applications to the urea treatment and 5 times after 8 N applications to the organic treatment.

When averaged over the entire study, N_2O-N fluxes in the urea treatment increased by more than three times above background levels during the first week after N fertilization (Table 2.3). Although not as pronounced as in the urea treatment, fluxes in the organic treatment increased by 93% above background levels during the first week after N fertilization. In the poly treatment, N_2O-N fluxes were similar before and after the single annual fertilization (Table 2.3), revealing no direct response to N fertilization in N_2O-N fluxes in either the first or second week after fertilization.

Nitrous oxide fluxes in the urea treatment decreased between the first and second week after N fertilization, but remained about 93% greater than background levels (Table 2.3). Fluxes in the organic treatment also decreased from the first to the second week after fertilization and became statistically intermediate to the fluxes from the first week and background fluxes. These data clearly indicate that N_2O-N fluxes increased in the urea and organic treatments during the first week after N fertilization. Effects of N fertilization on N_2O-N fluxes carried strongly over into the second week in the urea treatment but were subtle in the organic treatment during the second week.

Interestingly, background fluxes of N_2O-N from the poly treatment were 44% higher than those from the urea treatment during the 2-year study (Table 2.3). The reason for this is uncertain but maybe have been related to levels of soil NH_4^+, which averaged ~40% higher in the poly treatment than in the urea or organic treatments (Table 2.5). Polymer-coated urea is formulated to release N slowly during the growing season, which may have caused the greater, average soil NH_4^+ during the study. Soil NO_3^-, however, was similar between the poly and urea treatments in both years. A similar response was described in spring barley (*Hordeum vulgare* L.). Polyolefin coated urea initially (21 d) reduced emissions 71% compared to a urea treatment. However, the polyolefin continued to release N after 21 days and maintained higher N_2O emissions than the urea treatment through the remainder of the growing season (Delgado and Moiser, 1996). Dobbie and Smith (2003) also reported periods of higher N_2O fluxes in grassland fertilized with polymer-coated urea than with urea, despite similar (and low) soil NO_3^- in both treatments.

Responses of nitrous oxide fluxes to changes in soil moisture

Although the poly treatment was fertilized with N only once annually (Table 2.1), N_2O-N fluxes repeatedly increased in the poly treatment after N fertilization in only the urea and organic treatmenst, despite no concurrent N applications to the poly treatment (Figs. 2.1 and 2.2; Table 2.2. For example, orthogonal contrasts revealed significant increases in N_2O-N fluxes in the poly treatment after N applications to only the urea and organic treatments on DOY 186, 214, and 256, 2007, and on DOY 190, 2008. These increases in N_2O-N fluxes in the poly treatment, despite no concurrent N fertilization, may be partially explained by 15 mm of water applied to all plots after N fertilization to only the urea and organic treatmenst. It is likely that the corresponding increase in WFP among treatments (Figs. 2.1 and 2.2), combined with high average soil NH_4^+ and background N_2O-N fluxes in poly (Tables 2.2 and 2.3), contributed to the increase in N_2O-N fluxes in the poly treatment after N fertilization in only the urea and organic treatments. Fluxes of N_2O-N in the poly treatment also increased with WFP on DOY 291, 2007 and on DOY 179, 200, and 257, 2008 (Table 2.5). The sampling date in 2007 (DOY 291) was 126 d after N fertilization to the poly treatment, and followed 83 mm of precipitation. The WFP increased on DOY 179, 2008 from 21 mm of precipitation, on DOY 200 from 48 mm of precipitation and the flux increase on DOY 257, 2008 was from 11 mm of precipitation.

Increases in WFP from precipitation or irrigation also caused N_2O-N fluxes to increase in the other two treatments on occasions, even when no N fertilizer was applied. For example, between DOY 284 and 291, 2007, WFP increased by 18 to 28 v v^{-1}, which resulted in corresponding increases in N_2O-N emissions in the organic and urea treatments (Fig. 2.1, Table 2.5); fluxes increased by 439% in the organic treatment and 302% in the urea treatment. This sampling date was 36 d after fertilization in organic and urea. Nitrous oxide fluxes also increased with WFP from precipitation in the urea and organic treatments on DOY 200 and 257, 2008 (Fig. 2.2, Table 2.5), which was 11 and 14 d, respectively, after N fertilization. Overall, fluxes of N_2O-N were positively correlated with WFP ($r=0.42$, $p<0.0001$). Other studies have also reported positive correlations between N_2O fluxes and soil water content (Denmead et al., 1979);(Clayton et al., 1997);(Bijoor et al., 2008). Groffman et al. (2009) reported that soil water content is the key driver in N_2O emissions from urban landscapes fertilized with N.

Temperature and soil nitrogen effects on nitrous oxide fluxes

Fluxes of N_2O-N were not correlated with air or soil temperature. This is in contrast with other studies that have reported positive correlations between N_2O fluxes and soil temperature. For example, Christensen (1983) reported correlations between N_2O-N fluxes and soil temperature ($r= 0.55$) from a grass sward from April to Aug. Bremer (2006) also observed a positive correlation between temperature and N_2O-N fluxes in perennial ryegrass. Artificially heated plots had significantly ($p = 0.05$) higher N_2O-N fluxes than ambient temperature plots in a field study in California, USA (Bijoor et al., 2008). In our study measurements were made mostly during summer months, when variations in temperature were less than variations between seasons. Therefore, in our study, correlations between soil temperature and N_2O-N fluxes were likely confounded by the large responses in N_2O-N fluxes to N-fertilizations and changes in soil moisture (Figs. 2.1, 2.2).

Relationships between soil N and N_2O-N fluxes were inconsistent throughout the study. On DOY 167 and 173, 2007 N_2O-N emissions from urea were significantly higher than the poly and organic treatments (Fig. 2.1). This was likely the result from the fertilizer application on DOY 165, 2007, which increased the NH_4^+ and NO_3^- in the urea treatment compared to the poly and organic treatments on DOY 167, 2007 (Fig. 2.3). However, on DOY 225, 2008 after N application to the urea and organic treatments there was no significant flux response (Table 2.5) despite corresponding increases in soil N, particularly in organic (Figs. 2.2, 2.4). Fluxes of N_2O were not correlated with soil NH_4^+ or NO_3^-, which is in contrast with a number of other studies (Denmead et al., 1979);(Dobbie and Smith, 2003). Bremer (2006) found a significant but weak correlation between N_2O-N fluxes and NO_3^-. In our study, soil samples for testing NO_3^- and NH_4^+ were collected and combined by treatment on each measurement day rather than testing each plot individually, which may have reduced our ability to detect significant correlations.

Cumulative Fluxes

Despite the varied, transient responses of N_2O-N fluxes to N fertilization (Figs. 2.1 and 2.2), cumulative N_2O emissions during the 2-year study were similar among N-source types. Cumulative N_2O-N emissions over the 295-day study were 8.38, 7.97, and 6.91 kg N_2O-N ha^{-1} in the poly, organic, and urea treatments, respectively (Fig. 2.5).

Cumulative N_2O emissions in 2008 averaged 4 to 34% greater among treatments than in 2007. In 2007, cumulative N_20-N emissions from DOY 154 to 284 were 3.01, 3.06, and 3.14 kg N_2O-N ha^{-1} in the poly, organic, and urea treatments, respectively. During the same period in 2008, cumulative N_20-N emissions were 3.83, 4.10, and 3.27 kg N_2O-N ha^{-1} in the poly, organic, and urea treatments, respectively. Cumulative fluxes were higher in the organic treatment for both summers, though for the entire study organic emissions were .41 kg N_2O-N ha^{-1} lower than the urea treatment. For calculating summer comparison emissions, 40 days of sampling were not included so we could compare the same time frame in the analysis. Greater N_2O emissions in

2008 than in 2007 may have been caused in part by higher WFP in 2008; WFP averaged 60 v v^{-1} in 2007 and 73 v v^{-1} in 2008.

The effects of different N sources (including slow-release N) on cumulative N_2O emissions in turfgrasses have been mixed. Maggiotto et al. (2000) reported that urea-based fertilizers minimized N_2O emissions compared to ammonium sulfate N. Slow-release urea suppressed emissions for two-years, but emissions in the third year of study were increased compared as soil NO_3^- accumulated during the first two years. Bremer (2006) found no differences in cumulative annual emissions between urea and ammonium sulfate fertilizer types. No significant differences were found in N_2O production among plots of Kentucky bluegrass (*Poa pratensis* L.) fertilized with ammonium sulfate, calcium nitrate and urea (Bergstrom et al., 2001).

In other agronomic systems, responses of N_2O emissions to slow-release N fertilizers have been mixed. Cumulative Emissions of N_2O were reduced in carrot (*Daucus carota* L. subsp. *sativus*) during an 83 d study with the use of a slow release N source (Long: trade name) compared to ammonium sulfate (Minami, 1994). Supporting our findings on cumulative emissions from controlled release and urea N sources, controlled release fertilizer (LP-30) did not reduce cumulative N_2O-N emissions compared to urea in corn (Hadi et al., 2008; Jumadi et al., 2008).

Over our entire study the percentages of total N fertilizer volatilized as N_2O were 2.1% in poly, 2.0% in organic, and 1.7% in urea. Similar losses in turfgrass were reported by Lewis and Bremer (2010), Bremer (2006), Kaye et al. (2004), and Horgan et al. (2002). Total urea N fertilizer volatilized as N_2O were 1.4% in bermuda, 1.3% in rye, and 2.8% in zoysia (Lewis and Bremer, 2010). Losses as N_2O ranged from 0.4 to 3.9% from labeled N fertilizer applied to turfgrass at 49 kg ha^{-1} in a 42 d field study (Horgan et al., 2002). Bremer (2006) reported an approximate loss of 0.65% from urea N fertilizer applied at a rate of 250 kg N ha^{-1} yr^{-1}, and Kaye et al. (2004) found a 2.2% loss of N applied.

The estimated annual flux for the urea treatment, using winter data from the nearby study (Lewis and Bremer, 2010), was 5.4 kg N_2O-N ha^{-1} yr^{-1}. This estimate of annual N_2O-N from is larger, but comparable to annual emissions reported from other urban and grassland ecosystems. Emissions from a Kentucky bluegrass lawn were 2.4 kg N_2O-N ha^{-1} yr^{-1} during a 1-year study ((Kaye et al., 2004)). Bremer (2006) reported fluxes ranging from 1.01 to 1.65 kg N_2O-N ha^{-1} yr^{-}

^{1} from ryegrass fertilized with different N sources and amounts. Lewis and Bremer (2010), in a study near the present study, reported cumulative annual emissions of N_2O-N of 3.37, 3.09, 2.79 kg N ha^{-1} yr^{-1} from bermuda, rye, and zoysia, respectively.

Conclusions

Transient responses of N_2O-N to N application differed substantially among N source treatments. Fluxes of N_2O-N averaged higher from urea than in poly in the week after fertilization, but background fluxes were lowest in urea. The poly treatment had the highest background fluxes, and N application had no effect on N_2O-N emissions from those plots. Increased WFP seemed to increase N_2O-N fluxes from all treatments, but especially increased emissions from the poly N source. Cumulative N_2O emissions, however, were similar among N sources during the two-summer study. Controlled release polymer coated urea or organic N do not seem to be effective measures in mitigating N_2O-N emissions from turfgrass systems compared to traditional urea applications.

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Figures

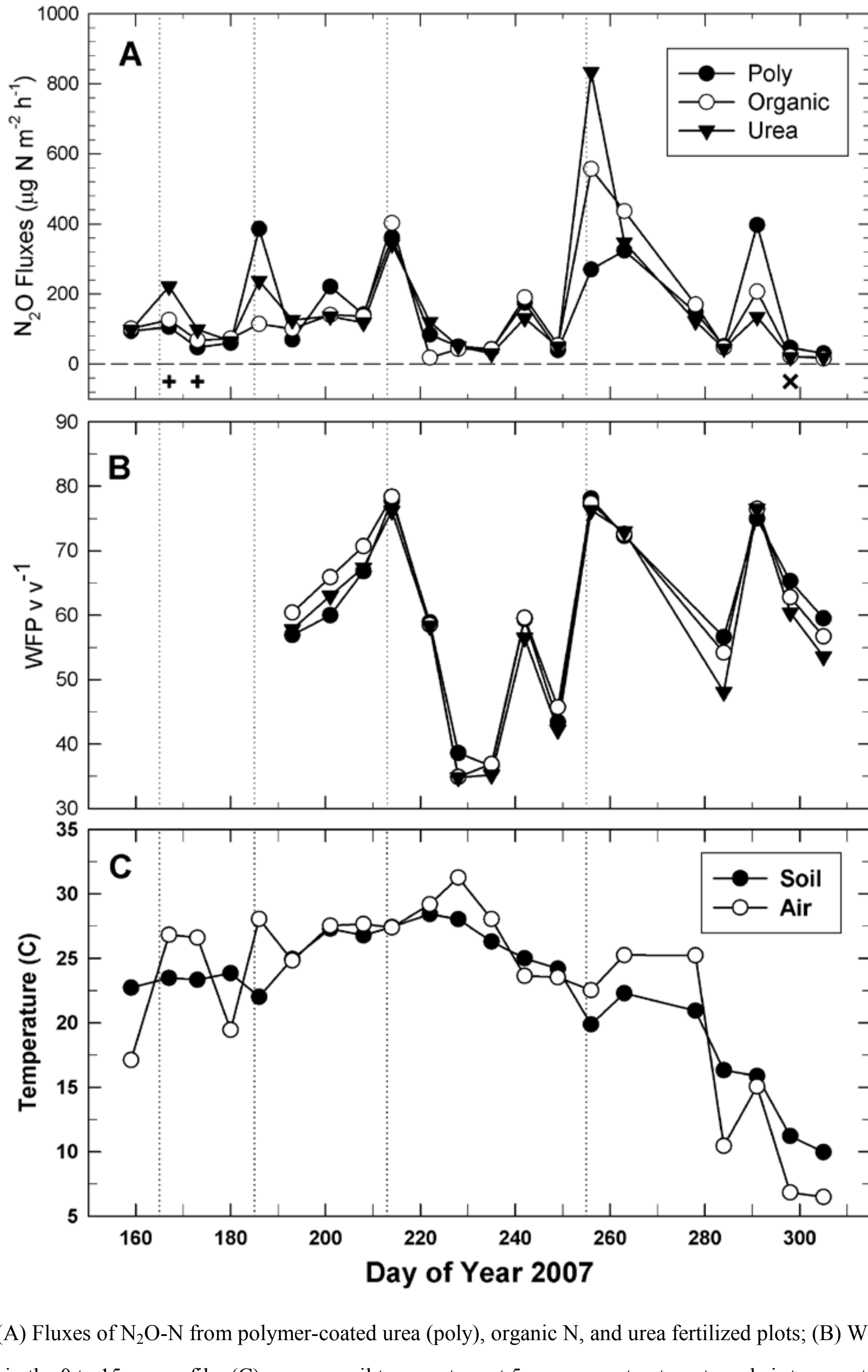


Figure 2.1 (A) Fluxes of N_2O-N from polymer-coated urea (poly), organic N, and urea fertilized plots; (B) Water filled porosity (WFP) in the 0 to 15 cm profile; (C) average soil temperature at 5 cm among treatments and air temperature at 2 m during sampling periods. Vertical dashed lines represent N application dates; Poly was applied at the first application date only (DOY 165). A plus (+) indicates significant differences between one and the other two treatments on a given date.

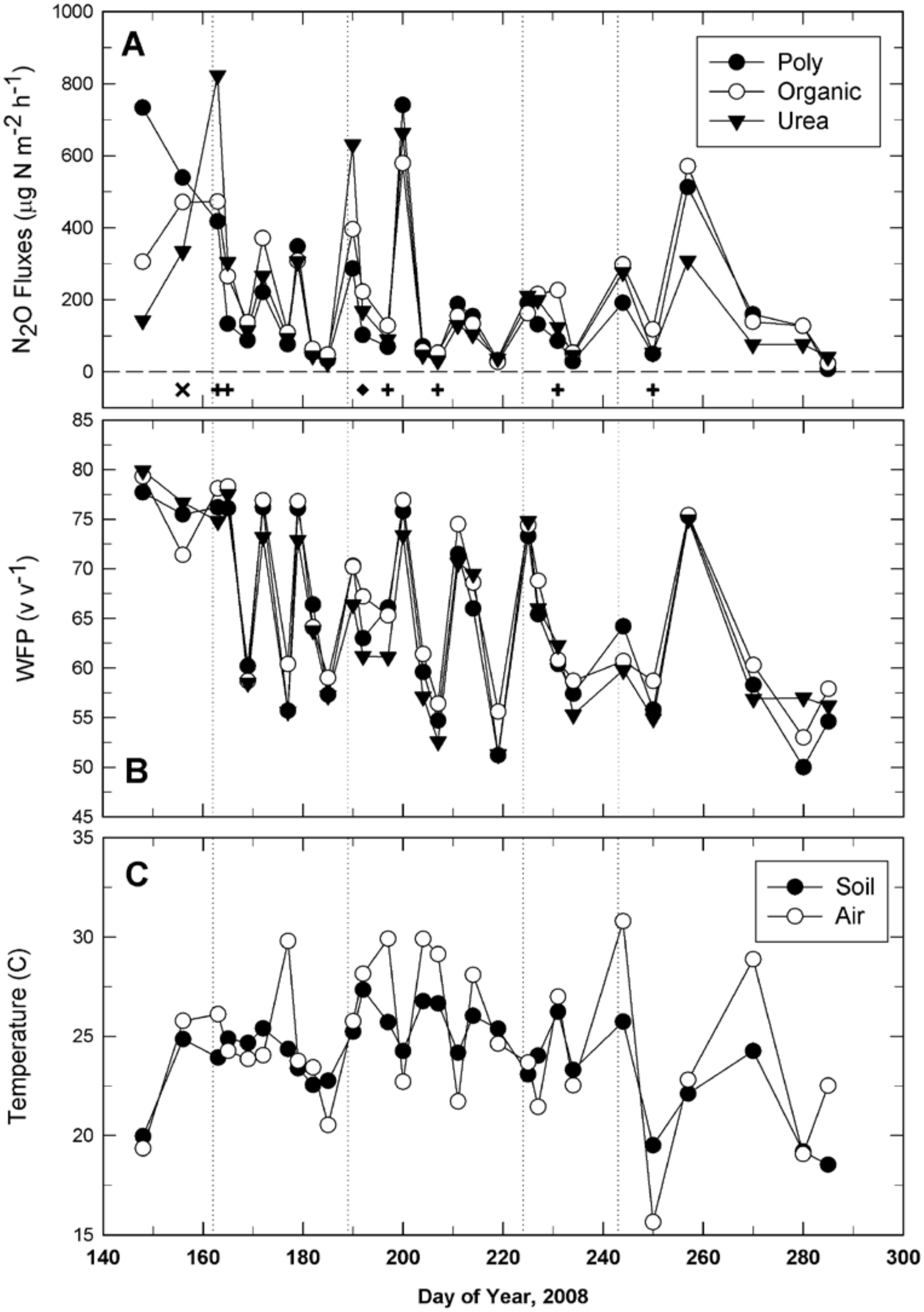


Figure 2.2 (A) Fluxes of N_2O-N from poly, organic, and urea fertilized plots; (B) Water filled porosity (WFP) in the 0 to 15 cm profile; (C) average soil temperature at 5 cm among treatments at sampling, and air temperature at 2 m. Vertical dashed lines represent N application dates; Poly was applied at the first application only (DOY 162). Symbols (×) along the abscissa in (A) indicate significant differences between at least 2 treatments ($P < 0.05$), 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.

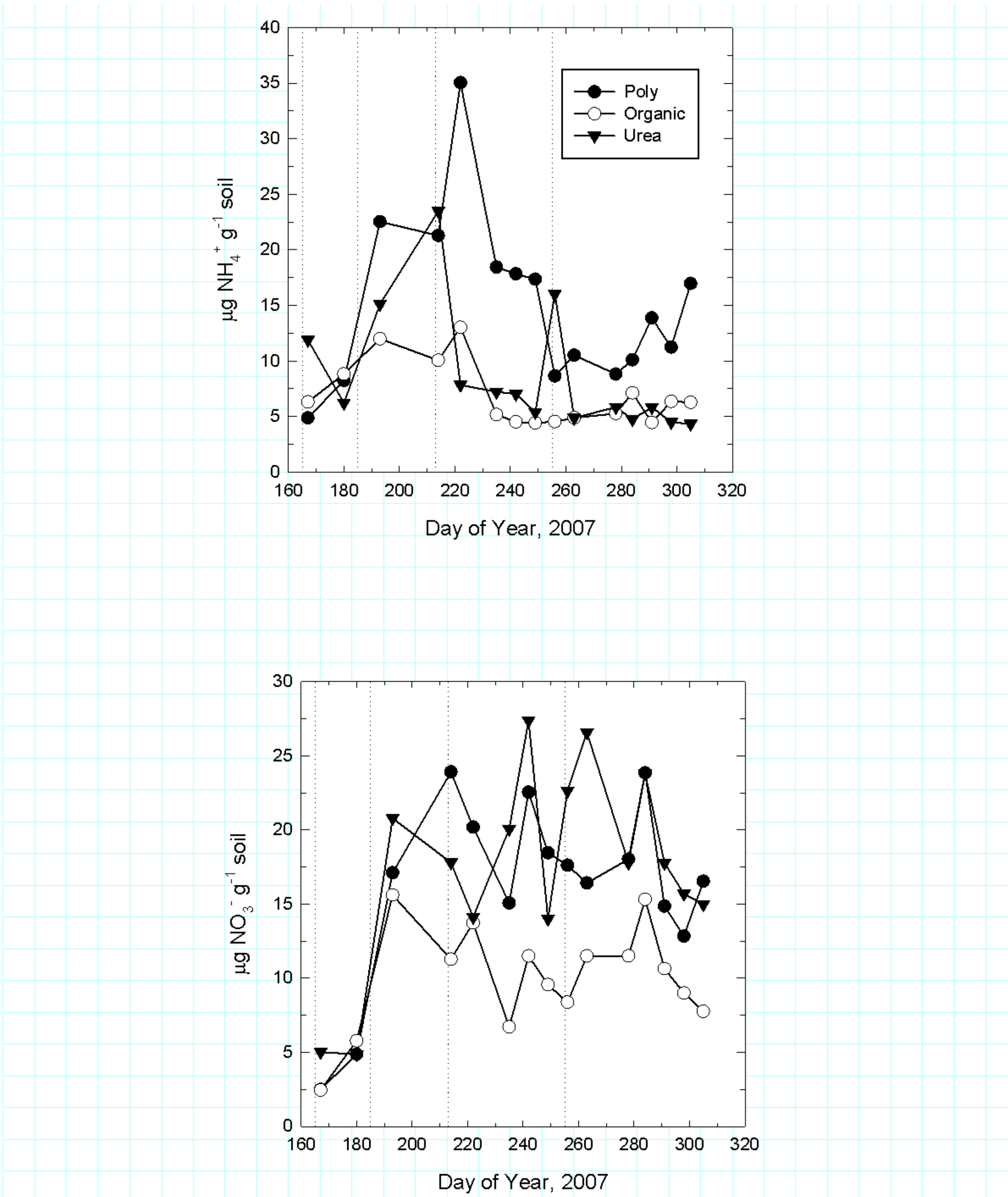
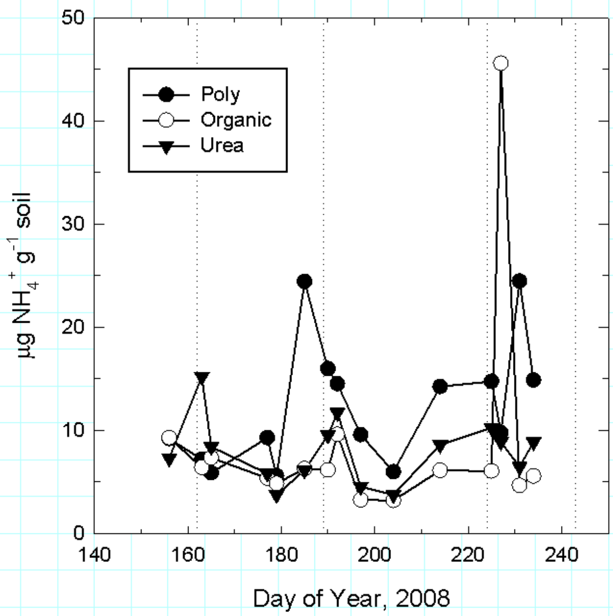


Figure 2.3 Soil ammonium (NH_4^+) and nitrate (NO_3^-) concentrations from 0 to 10 cm in 2007.



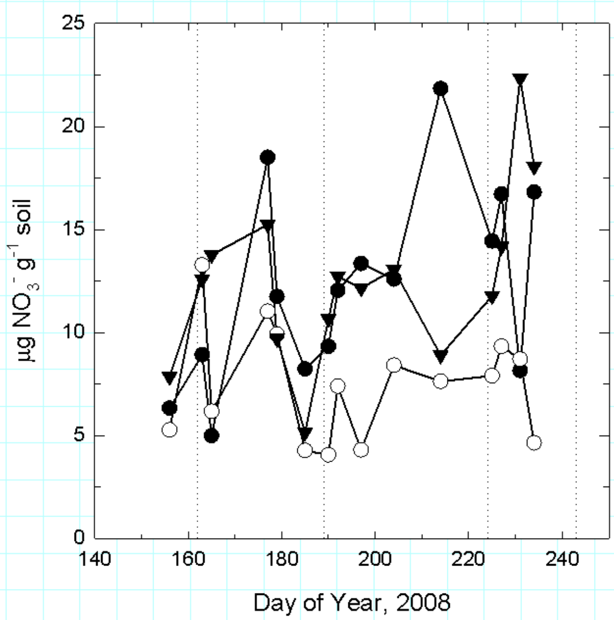


Figure 2.4 Soil ammonium (NH_4^+) and nitrate (NO_3^-) concentrations from 0 to 10 cm in 2008.

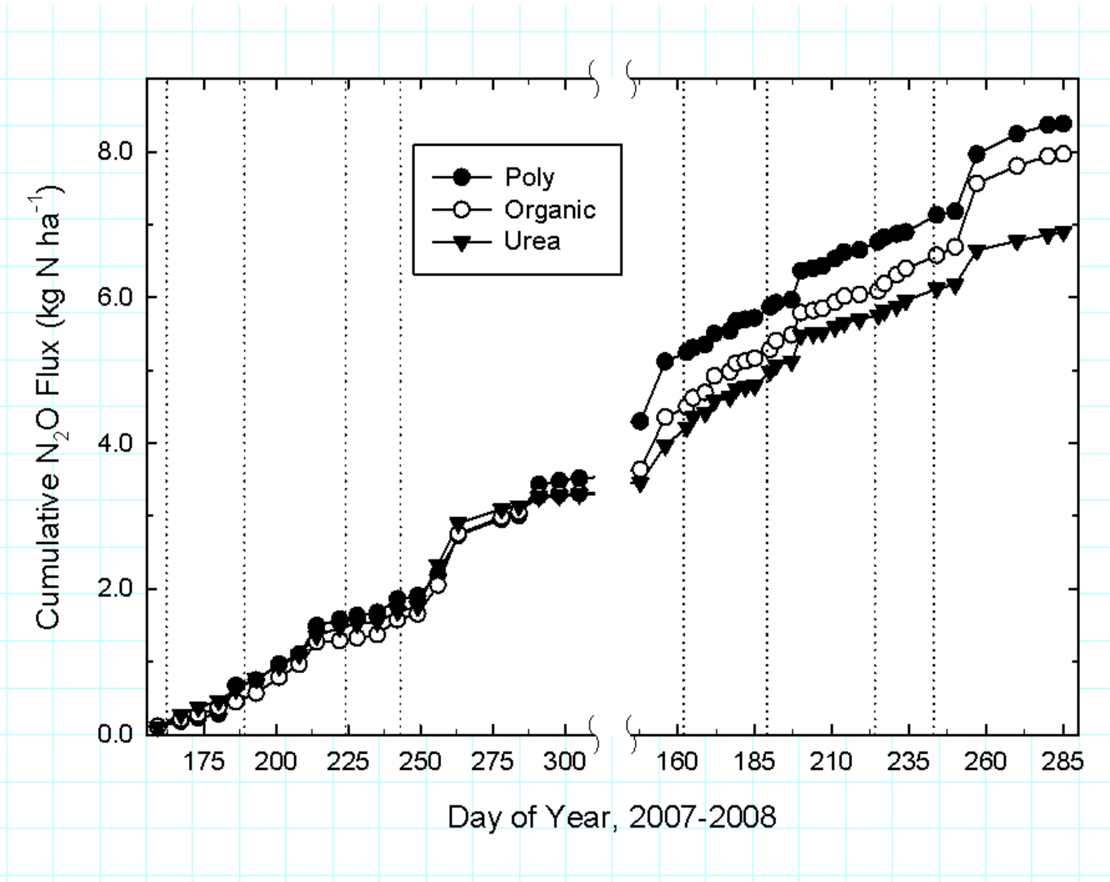


Figure 2.5 Cumulative fluxes of N_2O-N from polymer-coated urea (poly), organic N, and urea fertilized plots. Vertical dashed lines represent N application dates, poly was applied DOY 165, 2007 and 162, 2008, organic and urea were applied DOY 165, 185, 213, and 255, 2007 and DOY 162, 189, 224, and 243 2008.

Tables

Table 2.1 Dates of N fertilizer application to bermudagrass plots.

DOY†	Date	Poly	organic	urea
2007			kg N ha^{-1}	
165	June 14	200	50	50
185	July 4	-	50	50
213	Aug. 1	-	50	50
255	Sept. 12	-	50	50
2008				
162	June 10	200	50	50
189	July 7	-	50	50
224	Aug. 11	-	50	50
243	Sept. 30	-	50	50

† Day of year.

Table 2.2 Summary of contrast statements investigating effects of N application on sampling dates of N_2O-N fluxes in 2007 and 2008.

Contrast	N Source	Change in WFP†	N application	Change in flux
2007		v v^{-1}	kg ha^{-1}	μg N_2O-N m^{-2} hr^{-1}
159-167	Poly	. ‡	200	11.4
	organic	.	50	24.9
	urea	.	50	124.0
180-186	Poly	.	0	325.5**§
	organic	.	50	41.3
	urea	.	50	172.8
208-214	Poly	11.0	0	220.0**
	organic	7.7	50	266.3**
	urea	8.8	50	223.9**
249-256	Poly	34.7	0	230.7**
	organic	31.7	50	503.1***
	urea	34.1	50	784.3***
2008				
156-163	Poly	0.7	200	-121.7
	organic	6.7	50	0.3
	urea	-1.9	50	488.8***
185-190	Poly	13.0	0	253.6**
	organic	11.2	50	348.0**
	urea	9.2	50	606.0***
219-225	Poly	22.1	0	158.4
	organic	18.8	50	135.4
	urea	23.5	50	173.9
234-244	Poly	6.8	0	162.9
	organic	2.0	50	245.3**
	urea	4.5	50	229.8**

† Water filled porosity from 0 – 15 cm depth.

‡ Data not collected.

§ Indicates significant change in N_2O-N flux tested as a contrast statement, **, p=0.05, *** p=0.001.

Table 2.3 Average fluxes of N_2O-N one and two weeks after fertilization compared to fluxes collect at all other times (background).

Timing	Poly			organic			urea		
	——————————μg N_2O-N m^{-2} hr^{-1}——————————								
Background	187	a†	A‡	143	ab	B	105	b	C
1 week§	186	b	A	276	ab	A	333	a	A
2 weeks¶	136	a	A	211	a	AB	203	a	B

†Means followed by the same lowercase letter within a row are not statistically different according to LSD (0.05).

‡Means followed by the same uppercase letter within a column are not statistically different according to LSD (0.05).

§Average fluxes from 1 to 7 days after N application.

¶Average fluxes from 8 to 14 days after N application.

Table 2.4 Average soil NH_4^+ and NO_3^- for sampling periods in 2007 and 2008.

N Source	2007		2008	
	NH_4^+	NO_3^-	NH_4^+	NO_3^-
	$\mu g\ g^{-1}$			
Poly	15.1	16.3	12.4	12.3
organic	6.9	10.0	8.7	7.5
urea	8.7	17.6	8.0	12.5

Table 2.5 Summary of contrast statements investigating affects of soil moisture of N_2O-N fluxes in 2007 and 2008. Dates were selected when WFP† increased more than 10 v v^{-1} from the previous sampling period.

Contrast	N Source	Change in WFP	Days since N application	Change in flux
2007		v v^{-1}	d	µg N_2O-N m^{-2} hr^{-1}
235-242	Poly	22.8	77	126.1
	organic	21.3	29	115.2
	urea	22.9	29	164.2
284-291	Poly	18.4	126	345.7**‡
	organic	22.3	36	159.7**
	urea	28.4	36	90.1
2008				
169-172	Poly	16.0	10	133.9
	organic	18.2	10	233.7**
	urea	14.7	10	121.6
177-179	Poly	20.4	17	272**
	organic	16.4	17	199.7*
	urea	17.3	17	212.8*
197-200	Poly	9.7	38	671.4***
	organic	11.6	11	450.8***
	urea	12.3	11	573.7***
250-257	Poly	19.5	95	462.8***
	organic	16.7	14	452.7***
	urea	20.1	14	254.6**

† Water filled porosity from 0 – 15 cm depth.

‡ Indicates significant change in N_2O-N flux tested as a contrast statement, * p=0.1, ** p=0.05, *** p=001.

CHAPTER 3 - Fabrication of a Custom Gas Exchange Chamber to Measure Carbon and Water Fluxes in Turfgrass

Abstract

Photosynthesis is a fundamental indicator of plant stress and growth. In turfgrass, most measurements of photosynthesis are made with a single leaf clip attached to a steady-state photosynthesis system. It is unlikely that a single leaf or many replicate leaves represent the entire canopy. Our objectives were to fabricate and test a closed-system photosynthesis chamber, minimize altercations to the canopy microclimate, and estimate aerodynamic conductance to water vapor flux in turfgrass. The chamber was tested at the Rocky Ford Turfgrass Research Center near Manhattan, KS. Aerodynamic conductance to water vapor flux ($g_{a,v}$) was estimated from greens-height (0.4 cm) creeping bentgrass (*Agrostis stolonifera* L.) 'L-93', Kentucky bluegrass (*Poa pratensis* L.) 'Apollo' at fairway (1.6 cm) and lawn (9.3 cm) heights, and bermudagrass (*Cynodon dactylon* (L.) Pers.) 'Riviera' at lawn height (9.3 cm). The chamber sampled a surface area of 0.24 m^2 (0.49 m x 0.49 m). Chamber height was 0.29 m and the sides were constructed of 4.59 mm acrylic-FE (plexiglass). The top was heat stretched Propafilm-C. The chamber had minimal affects to the canopy during measurements: average leak values during field-testing ranged from 0.5 to 1.5 μmol CO_2 m^{-2} s^{-1}, average chamber pressure was 0.09 Pa ±0.01 Pa (positive indicates above atmospheric); average temperature rise inside the chamber during measurements at mid-day, with maximum ambient air temperatures of 39 ^oC was 0.74 ^oC; and the chamber had 90% PAR transmittance. Measurements of CO_2 flux on day of year (DOY) 168, 2010 were similar between the chamber and an onsite eddy covariance (EC) tower. Aerodynamic conductance increased with mowing height from 1.29 cm s^{-1} in creeping bentgrass at green height to 2.96 cm s^{-1} in Kentucky bluegrass at lawn height, and did not seem dependent on species.

Introduction

Photosynthesis is a fundamental indicator of plant stress and growth (Salisbury and Ross, 1978). In turfgrass studies, photosynthesis is sometimes measured using leaf clips attached to steady state, portable photosynthesis systems (Jiang and Huang 2000; Wang and Huang, 2003; DaCosta et al., 2004; Hu et al., 2009). While use of portable photosynthesis systems with leaf clips is popular in the literature, it is not likely that a single leaf, or even several replicate leaves are indicative of photosynthesis or transpiration rates within an entire crop canopy (Hunt, 2003).

As an alternative, small surface chambers have also been used in turfgrass studies to measure photosynthesis at the canopy level. These chambers, which cover a small area of the turfgrass canopy, are typically customized and attached to steady state, portable photosynthesis systems (Huang et al., 1998; Huang and Gao, 1999; Xu and Huang, 2000; Bremer and Ham, 2005; Su et al., 2007, 2008, 2009). In steady state systems, conditions in the chamber must come to equilibrium before a measurement can be taken, which can take several minutes. Because chambers alter the microclimate of the canopy, measurements should be taken as quickly as possible (Steduto et al. 2002; Hunt, 2003). Conditions in the chamber are also typically pressurized in a steady-state system, which may partially suppress soil respiration and thus, over estimate the net ecosystem carbon exchange (Bremer and Ham, 2005).

For this study, a chamber was fabricated using a design similar to Murphy (2007), who successfully designed, built, and tested a novel, closed-loop photosynthesis system to measure CO_2 and water vapor fluxes in tallgrass prairie ecosystems. Advantages to Murphy's chamber included measurement times that were faster than with steady-state systems, neutral pressure differential between the chamber interior and atmospheric, and a large measurement area (0.72 m^2).

The chamber fabricated for this study was slightly modified from that of Murphy (2007); namely, it was slightly smaller, and an infrared thermometer (IRT) was added to measure the temperature of the canopy enclosed by the chamber. Measurements of canopy temperature allowed for estimates of canopy stomatal (g_c) conductance to water vapor fluxes in turfgrass. Accurate measurements of g_c in turfgrass would be useful because, in addition to photosynthesis, g_c may be a good indicator of plant stress. Furthermore, accurate measurements of $g_{a,v}$ may be obtained from dead, wet turfgrass canopies, which allows for greater accuracy in measurements of g_c; details of these methods and calculations will be described below.

Therefore, our objectives were to: 1) fabricate and field test a closed system chamber after the design of Murphy (2007) to minimize alterations to the canopy microclimate during measurements; 2) estimate $g_{a,v}$ in turfgrass. Because $g_{a,v}$ typically varies by canopy height (Campbell and Norman, 1998), $g_{a,v}$ was measured in turfgrasses mown at 3 heights.

Theory of Operation

Flux Model and Calculations

The basic formulas for computing CO_2 (J_c) and water vapor (J_w) fluxes are:

$$J_c = \rho_m \frac{V}{A} \frac{\Delta CO_2}{\Delta t} \quad \text{[eq 3.1]}$$

$$J_w = \rho_m \frac{V}{A} \frac{\Delta W_c}{\Delta t} \quad \text{[eq 3.2]}$$

Where J_c and J_w are flux density of CO_2 and water vapor, respectively (mol m^{-2} s^{-2}), ρ_m is the molar density of air (mol_{air} $m^{-3}{}_{air}$) calculated from the ideal gas law, V is the chamber volume (m^3 air), A is the chamber area (m^2) and $\Delta CO_2/\Delta t$ and $\Delta w_c/\Delta t$ are the rate changes over time of CO_2 and water vapor concentrations within the chamber (mol_{CO2} or mol_{H2O} $mol^{-1}{}_{air}$ s^{-1}), respectively (Ham et al., 2005). The calculation of J_c is corrected for water vapor dilution as follows:

$$J_c = \rho_m \frac{V}{A}\left(\frac{\Delta CO_2}{\delta t} + \frac{\frac{CO_2}{(1-w_c)}}{\frac{\Delta w_c}{\delta t}} \right) \quad \text{[eq 3.3]}$$

Where w_c is the mole fraction of water vapor within the headspace (mol mol^{-1}) and $\Delta w_c/\Delta t$ is the rate change of w_c (mol mol^{-1} sec^{-1}). With a similarly designed, but larger chamber, correction for water vapor dilution was found to be significant (Murphy, 2007).

Determination of Flux

The preferred models for calculating $\Delta CO_2/\Delta t$ and $\Delta w_c/\Delta t$ have been discussed by Wagner and Reicosky, 1992, Wagner et al., 1997, Steduto et al., 2002, and Kutzbach et al., 2007. These studies mainly utilized either a linear or quadratic regression equation. The goal in selecting an appropriate model is to accurately predict fluxes when conditions in the closed system chamber match ambient conditions, or before the chamber significantly affects the canopy environment, which would be at the moment of deployment.

A weakness of linear model is that the rates of photosynthesis and transpiration are assumed to remain constant even as concentrations of CO_2 decrease and water vapor increase in the chamber during measurements. However, constant rates of CO_2 and H_2O fluxes under these circumstances are unlikely as shown by Fick's first law of diffusion.

$$F_j = -D_j \frac{\Delta c_j}{\Delta x} \qquad \text{[eq 3.4]}$$

Where F_j is the flux of j, D_j is the diffusion coefficient, and $\Delta c_j/\Delta x$ is the gradient of j between the chamber air and intercellular leaf air. The equation predicts the rate of diffusion of CO_2 into and water vapor out of the leaf will decrease as concentrations of CO_2 decreases and water vapor increase, respectively, within the chamber.

Wagner et al. (1997), Studeto et al. (2002) and Kutzbach et al. (2007) stated that the quadratic model is preferred for closed systems. A quadratic model expressing CO_2 and H_2O concentrations as a function of time after closing the system can be written as:

$$CO_2 = a + bt + ct^2 \qquad \text{[eq 3.5]}$$

$$H_2O = a + bt + ct^2 \qquad \text{[eq 3.6]}$$

$\Delta CO_2/\Delta t$ and $\Delta H_2O/\Delta t$ are obtained by differentiating these equations with respect to time (t):

$$\frac{\Delta CO_2}{\Delta t} = b + 2ct_0 \qquad \text{[eq 3.7]}$$

$$\frac{\Delta H_2O}{\Delta t} = b + 2ct_0 \qquad \text{[eq 3.8]}$$

Where t_0 is the initial time, when ambient conditions were predicted to occur within the chamber. The slope is computing by solving the first derivatives at time = t_0.

While a quadratic model is generally better than a linear model for calculating $\delta CO_2/\delta t$ and $\delta H_2O/\delta t$, situations exist where fluxes calculated with a quadratic model might be incorrect. In our study, a quantitative method developed by Murphy (2007) was used to discriminate between the appropriateness of a quadratic or regression model for each measurement. Using this method, a program was written (MATLAB, The Mathworks Inc., Natick, MA) to initially accept the quadratic model, since that model was preferred in the literature. Quadratic models were then tested using three criteria. First, the shape of the quadratic curve was tested. Specifically, the program determined whether the quadratic model predicted a local minimum or maximum value at the end of a measurement, or within the 40 sec sampling period. If the minimum CO_2 or maximum water vapor concentration was observed within the 40 sec time period, a linear model flux was used (Fig. 1.7; Murphy 2007). Also the derivatives at 30 sec and 60 sec were compared (Fig. 1.8; Murphy 2007). If the derivative at 30 sec was less than the derivative at 60 sec, a linear model flux was also used. Quadratic models that predicted a minimum or maximum value during sampling were discarded in favor of linear models because the minimum CO_2 and maximum water vapor concentration were expected to occur at the end of the reading. The final check was to test if the quadratic model predicted that conditions matching ambient conditions of CO_2 and H_2O were achieved inside the chamber within 15 s of placing the chamber on the soil frame. The time when conditions within the chamber matched ambient conditions was used for t_0 in predicting $\delta CO_2/\delta t$ and $\delta H_2O/\delta t$. If the predicted time that conditions within the chamber matched ambient conditions was outside 15 s, a linear model was used. Using this analytical method, the quadratic model was used for 52% of CO_2 flux calculations and 74% of water vapor flux calculations.

Estimating Aerodynamic Conductance

The canopy aerodynamic conductance to water vapor flux ($g_{a,v}$; m s^{-1}) was estimated from environmental data collected from the chamber.

Transpiration can be modeled as:

$$E = \left(\rho_v * (T_c) - \rho_{v,a}\right)\left[\frac{g_a g_c}{g_a + g_c}\right] \quad \text{[eq 3.9]}$$

Where E is the transpiration of the canopy (mmol m^{-2} s^{-1}); T_c is the canopy temperature (K); $\rho_v*(t_c)$ is the saturation vapor density at canopy temperature, (kg m^{-3}); $\rho_{v,a}$ is the vapor density of air (kg m^{-3});; and g_c is the canopy conductance to water vapor flux (m s^{-1}).

If the canopy is killed (i.e., $1/g_c = 0$), and therefore not transpiring, and the dead canopy is wet during measurements, the equation can be solved for $g_{a,v}$.

$$g_{a,v} = \frac{E}{\left(\rho_v * (t_c) - \rho_{v,a}\right)} \quad \text{[eq 3.10]}$$

Once $g_{a,v}$ is known it is possible to determine g_c for a normal live canopy if the grass is at a similar height.

$$g_c = \frac{\left(\frac{E}{\rho_v * - \rho_{v,a}}\right) g_{a,v}}{\left(g_{a,v} - \frac{E}{\rho_v * - \rho_{v,a}}\right)} \qquad \text{[eq 3.11]}$$

Aerodynamic conductance to water vapor transport can be modeled for an unchambered situation by:

$$g_{a,v} = uk^2 \left\{ \left[\ln\left(\frac{z-d}{z_m}\right) \right] \left[\ln\left(\frac{z-d}{z_v}\right) \right] \right\}^{-1} \qquad \text{[eq 3.12]}$$

Where $g_{a,v}$ is in m s^{-1}; u is wind speed (m s^{-1}); k is von Karmans constant (0.41); z is the height above the surface (m); d is the displacement height (m); z_m is the roughness length for momentum (m); and z_v is roughness length for vapor (m) (Campbell and Norman, 1998). By modeling $g_{a,v}$ with eq. 3.12 we can compare field measurements (eg. 3.10) to the modeled values to determine if aerodynamic conditions inside the chamber are similar to normal ambient conditions when no chamber is present.

Materials and Methods

Chamber Construction

The chamber sampled an area of 0.24 m^2 (0.49 m x 0.49 m). The chamber height was 0.29 m (Fig. 3.1)and the system volume was 0.7 m^3. Sides were constructed of 4.59 mm acrylic-FE (Acrylite, Cyro Industries, Clifton, NJ) (plexiglass). The top was heat stretched Propafilm-C (ICI Americas Inc., Wilmington, DE) and was used because of its high transmittances of thermal energy and photosynthetically active radiation (PAR). A closed cell foam gasket was attached along the bottom edge to seal the chamber to the anchoring collar. The anchoring collars were constructed of 2.54 cm x 2.54 cm x 0.32 cm thick angle iron that was set on the ground for measurements. Because the surfaces of the turfgrass plots were flat and uniform, the anchoring collars were heavy enough to provide a seal between the ground and collar.

One fan (700 L min^{-1}, BD 12A3, Comair Roton, San Diego, CA) circulated air through a perforated plenum that was attached around the inside base of the chamber. The plenum was 2.1 cm x 4.3 cm electric conduit (PN10L08V. Wiremold, Fallbrook, CA) with 2 rows of 1.8 mm holes drilled on the vertical surface facing the inside of the chamber; holes were 10 mm from the top and 10 mm from the bottom of the conduit and spaced 25 mm apart horizontally. Another row of holes were drilled along the top of the conduit 1 cm from the inner edge, and also spaced 25 mm apart. Four additional fans, were used to circulate air within the chamber. Two fans (422 L min^{-1}, V571M, Micronel, Fallbrook, CA) were positioned near the top of the chamber to increase air mixing and promote heat transfer across the propafilm from the chamber interior. The other two fans (595 L min^{-1}, KD1209PHB1, Sunon, Brea, CA) were placed below the other two fans, but above the plenum, to aid in air circulation above the sample canopy. One vent (0.25 m long by 14.3 mm inside diam.) was installed on the chamber to equilibrate chamber and atmosphere pressure. A pressure transducer (264, Setra, 0-0.1 H_2O range, Boxborough, MA) was used to measure pressure differences between atmospheric and the inside of the chamber during sampling. One end of the vent tube was suspended near the center of the chamber approximately 50 mm above the soil surface and the other tube was positioned outside the chamber at approximately the same height. Both tubes were capped with a porous stone to minimize pressure fluctuations caused by turbulence from wind or the fans.

A closed path infrared gas analyzer (IGRA, LI-840, Li-Cor Industries, Lincoln, NE) was used to measure CO_2 and water vapor concentrations every second during measurement. A continuous air sample from inside the chamber was supplied to the IRGA at 1.0 L min^{-1} by a rotary suction pump (G12/02 EB model 50095, Rietschie Thomas Pumps, Sheboygan, WI); rotary pumps minimized pressure fluctuations in the optical bench of an IRGA. Air was sampled from an intake port located above the canopy to obtain a well mixed sample, and it was returned from the IRGA back into the chamber through the plenum. Tubing used to transport air samples to and from the chamber to the IRGA was 6.35 mm outside diameter, 3.175 mm inside diameter Excelon Bev-a-line IV tubing (Thermoplastic Processes Inc., Stirling, NJ). A 0.4 mm diameter thermistor (10K3MCD1, Betatherm Corp., Shrewburg, MA) placed inside the plenum, 5 cm downstream from the air circulation fan, measured chamber air temperature. Temperature of the turfgrass canopy inside the chamber was measured using an infrared thermometer (IRTS P3, Apogee, Boxborough, MA). Photosynthetically active radiation flux was measured outside the chamber with a quantum sensor (LI-190, Li-Cor Inc.). A datalogger (CR10X, Campbell Scientific, Logan, UT) recorded data from all instruments at 1 Hz. The IRGA and pressure transducer was mounted to a vertical white plastic plate (5 mm thick) mounted on one side of the chamber. The L-shaped plastic plate extended over the top of the IRGA to shield it from direct solar radiation (Fig. 3.1A).

Measurements were initiated by holding the chamber ~ 0.6 m above the canopy and recording ambient air temperature and relative humidity for 20 sec. An audible chime then alerted the operator, and data acquisition was paused for 5 sec to allow time to place the chamber onto the anchoring collar in the plot. After the 5 sec pause, data acquisition resumed for 40 sec with the chamber over the canopy. Two measurements were usually conducted in each plot: first with the chamber uncovered (sunlit) (Fig. 3.2) and then with the chamber covered with an opaque cardboard box (Fig. 3.3), after the method of Bremer and Ham (2005); a brief explanation of this method is in Chapter 5. Following each measurement, the chamber was removed from the canopy and CO_2 and water vapor concentrations and air temperature within the chamber were allowed to return to ambient.

Environmental Tests

Leak Test

Precautions were taken during construction to prevent entry of ambient air into the chamber during measurements. The acrylic-FE that formed the chamber walls was fused with trichloroethylene and further sealed with silicone at each joint. The Propafilm top and the joints on the outside of the chamber were sealed with clear packing tape. Eliminating all air exchange from the chamber and ambient environment was difficult. Leak tests were conducted after every sampling period to quantify any errors caused from leaks. Leak tests were conducted in the field by placing the chamber on a smooth surface of sheet metal and increasing the CO_2 concentration inside the chamber by about 100 $\mu l\ l^{-1}$ above ambient. This gradient was considerably higher than those created during normal chamber measurements (usually the gradient was no greater than 35 $\mu l\ l^{-1}$ between the chamber interior and ambient). The decrease in CO_2 concentration during the 40-sec leak test measurement was recorded and used to calculate a leakage rate of CO_2 from the chamber (Fig. 3.4). Average leak values from in field testing ranged from 0.5 to 1.5 $\mu mol\ m^{-2}\ s^{-1}$. These rates were considered negligible as the average flux values collected were 14.05 $\mu mol\ m^{-2}\ s^{-1}$, representing a leak percent of 3.5 to 10%, and the final flux calculations were not corrected for leaks.

Pressure tests

Bremer and Ham (2005, Eq. 5) reported that pressures inside a surface chamber as small as 1 Pa greater than atmospheric suppressed efflux of CO_2 from the soil, which may artificially elevate measurements of net photosynthesis. Whether a system is open or closed-loop, pressure changes may arise from the air handling systems. In our chamber, air movement within the chamber from forced ventilation of the mixing fans may increase or decrease pressure at the soil surface, which would depress or elevate, respectively, soil CO_2 flux. The perforated air plenum was designed to evenly distribute air and reduce air speed throughout the chamber. If air is forced out of the air handling system through leaks, a vacuum inside the chamber may result, which inflate soil CO_2 flux and thus, reduce estimates of net photosynthesis. Venting the chamber with the atmosphere as described above helped attenuate pressure fluctuations and differences between the chamber interior and the atmosphere. The average chamber pressure in the laboratory was -0.17 Pa ±0.06 Pa (mean ±SE, n=26; negative indicates below atmospheric). In the field, the average chamber pressure was 0.09 Pa ±0.01 Pa (mean ±SE, n=299; positive indicates above atmospheric). These pressure differentials between the chamber interior and atmospheric, in both the laboratory and field, were considered negligible (Fig. 3.5).

Temperature

Temperature increases during measurements should be minimized within a chamber because increases in temperature above ambient affect photosynthesis (Hunt 2003). A benefit of our chamber design is the relatively short measurement time (40 s), which minimizes heating. Average temperature rise inside the chamber during flux measurements at mid-day, on August 3 and 4 (i.e., with maximum ambient air temperatures of 38 and 40 ^{o}C, respectively) was 0.74 ^{o}C. The temperature rise of the entire measurement run is shown in Fig. 3.6. In other surface chambers, temperature increases of 2 to 4 ^{o}C during measurements are commonly reported in the literature. Wagner and Reicosky (1992) reported a 2 to 4 ^{o}C increase in a 8.15 m^3 surface chamber designed to measure gas exchange in corn (*Zea mays* L.). Steduto et al. (2002) reported a temperature increase of 1 to 2 ^{o}C in a closed system chamber designed for use in field crops. A non-steady state chamber used in barley (*Hordeum vulgare* L.) had a temperature increase of 3 ^{o}C (Muller et al., 2009).

Photosynthetically Active Radiation Attenuation

Chamber materials were selected to minimize attenuation of photosynthetically active radiation (PAR); reductions in PAR may directly affect photosynthesis. Attenuation of PAR by our chamber was determined using a 0.5 m light bar with six quantum sensors (LQS506-SUN, Apogee, Logan, UT). The measurements were made on a level surface during a clear day at solar noon. Transmittance of PAR was 90%, which was similar to the larger chamber with the same design as in this study (Murphy, 2007). The 10% attenuation by the chamber was less than reported by Pickering et al. (1993) and Steduto et al. (2002), who reported attenuation at 20% and 12%, respectively. The higher transmittance values of our chamber design may be attributed to the use of Propafilm for the top of the chamber rather than plexiglass (Murphy, 2007).

Aerodynamic Conductance

Plots of greens-height creeping bentgrass (0.4 cm), Kentucky bluegrass at fairway (1.6 cm) and lawn (9.3 cm) heights, and bermuda at lawn height (9.3 cm) were sprayed with glyphosate on DOY 184, 2008. Measurements were taken on DOY 192, 2008 after it was determined that grass in the plots was completely dead. Plots were misted with a mixture of water and surfactant immediately prior to measurements.

CO_2 Flux

To test the viability of the chamber, measurements of CO_2 fluxes were compared between the chamber and EC, which is another common method of measuring CO_2 fluxes (Ham and Knapp, 1998; Owensby et al., 2006; Bremer and Ham, 2010). Field-testing was conducted at Rocky Ford Turfgrass Research Center near Manhattan, Kansas (Rocky Ford; lat. 39^{o}13’53” N, long. 96^{o}34’51” W). Measurements of CO_2 flux were taken with the sunlit chamber every 5 min from 1100 CST to 1400 CST on DOY 168, 2010, in an area of turfgrass in the source area of an on-site EC tower. Flux measurements from both the chamber and EC tower were averaged into corresponding half hour readings for direct comparisons; all flux values are presented as positive values in this chapter. The turf was primarily a mix of tall fescue (*Festuca arundinacea* Schreb.) and perennial ryegrass (*Lolium perenne* L.) mown at a 6.35 cm height.

Canopy Conductance

Measurements of canopy conductance were collected at the same time and location as the measurements of CO_2 were collected on DOY 168, 2010. Aerodynamic conductance was assumed to be 2.78 based on the $g_{a,v}$ data collected on DOY 192, 2008.

Data Analysis

Data were analyzed using the mixed models procedure in SAS as a completely random design (SAS Institute, 2002). Means of $g_{a,v}$, and CO_2 flux from the chamber and the EC tower were separated using Fisher's protected least significant difference (LSD) at $p = 0.05$.

Results and Discussion

Fluxes of carbon dioxide

Overall, measurements of CO_2 fluxes taken from 1100 to 1400 CST on DOY 168 were comparable between the chamber and the EC tower (Fig. 3.7). Differences between the two methods were probably caused by the different sizes of the respective sample areas and duration of measurements (i.e., chamber every 5 min, EC was continuous). Mean fluxes of CO_2 during the measurement period were 12.3 μmol m^{-2} s^{-1} from the chamber and 14.4 μmol m^{-2} s^{-1} from the EC tower, and were not significantly different. Murphy (2007) also found good agreement between his chamber, which was the same design as the current chamber, and EC measurements of seasonal CO_2 fluxes.

Aerodynamic Conductance

Aerodynamic conductance ($g_{a,v}$) increased with mowing height. The values for $g_{a,v}$ were 1.29 cm s^{-1} in a creeping bentgrass green mowed at 0.4 cm, 1.65 cm s^{-1} in a Kentucky bluegrass fairway mowed at 1.6 cm, and 2.6 cm s^{-1} and 2.96 cm s^{-1}, respectively, in Kentucky bluegrass and bermudagrass mowed at lawn height (9.3 cm) (Fig. 3.8). Statistically $g_{a,v}$ was similar between species at lawn height as it was in the grasses between green and fairway height ($p=0.05$). In bermudagrass, the stems are compressed, erect, or ascending from a prostrate base, while Kentucky bluegrass has stems that are only erect. Bermudagrass also develops a more upright, stemmy growth habit at cutting heights above 3.8 cm (Beard 1973). Despite the differences in canopy structures, however, Kentucky bluegrass and bermuda had similar $g_{a,v}$. Therefore, $g_{a,v}$ is apparently more related to mowing height than to turfgrass species.

By using equation 3.12 to model $g_{a,v}$ and comparing it to the values we collected we were able to confirm that there was good mixing of air inside the chamber. The chamber environment simulates aerodynamic transport equal to a wind speed between 6 and 8 m s^{-1} at 2 m above un-chambered turf. This maybe higher than would be normally seen in the field, in the future we may reduce the fan speed.

Canopy Conductance

Measurements of g_c taken on DOY 168 were consistent, except for the measurement taken at 13:15 CST (Fig. 3.9). More measurements need to be made with the chamber and compared to other established methods of measuring g_c. Measurements of g_c did not seem correlated to measurements of CO2 flux (Fig. 3.7).

Summary

The non-steady state chamber described in this chapter is a novel design for turfgrass research. Measurements could be made with minimal effects to the microclimate because of a quick sampling time. During measurements, air temperature increased 0.74 ^{o}C, pressure differential between the chamber interior and atmospheric was 0.09 Pa ±0.01 Pa, and PAR attenuation was 10%. Testing indicated that no correction for leaks was necessary on any sampling dates, and chamber measurements of CO_2 flux were comparable to established EC methods. Additionally, with the inclusion of an IRT to measure canopy temperature, we were able to get estimates of $g_{a,v}$. The latter ($g_{a,v}$) seemed to be independent of turfgrass species and dependent on mowing height.

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Figures

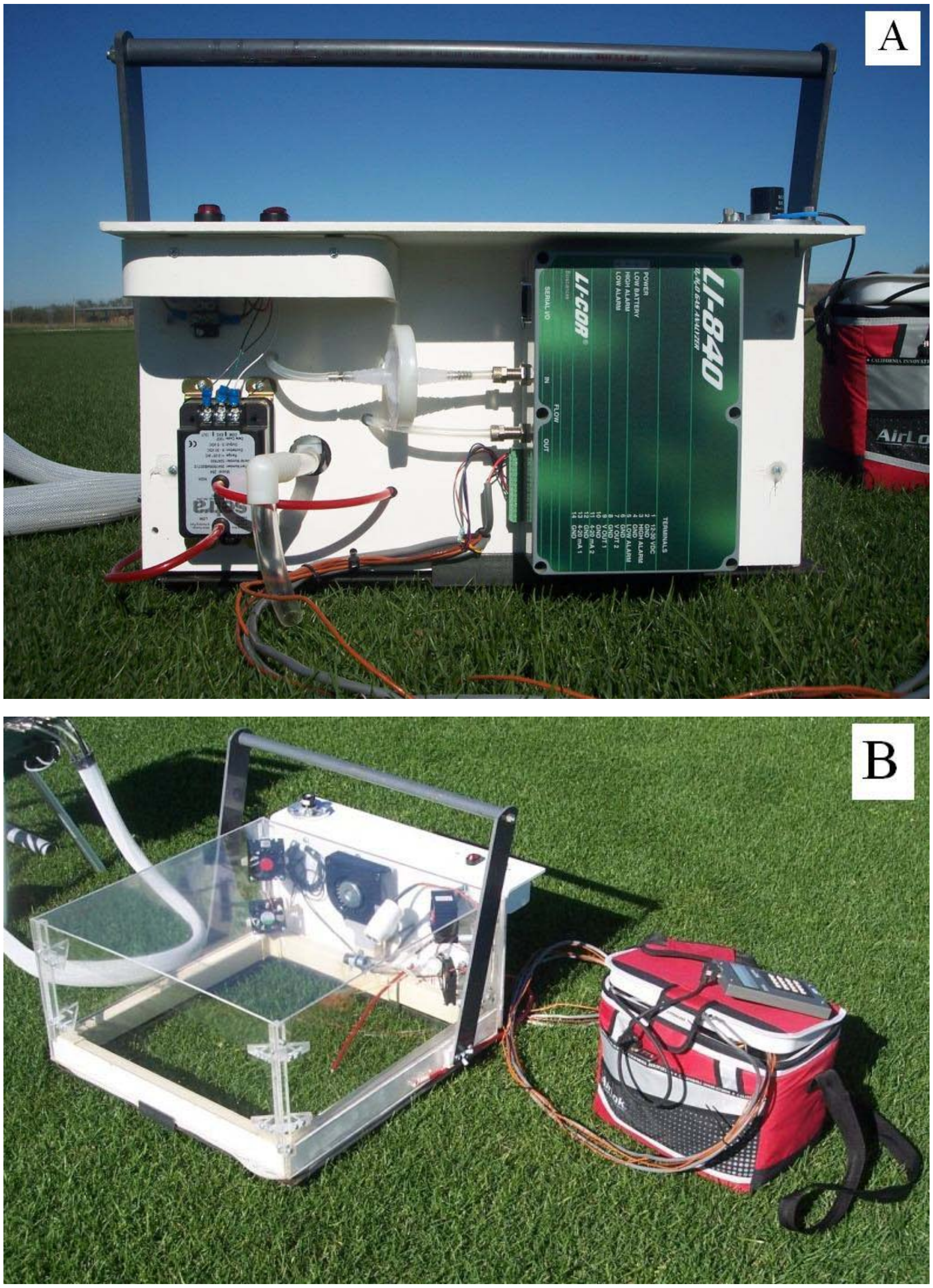

Figure 3.1 Picture taken of the chamber from the infrared gas analyzer (IRGA) showing the pressure transducer, and quantum sensor (A). Picture from the opposite of the IRGA. The CR10x was inside the cooler.

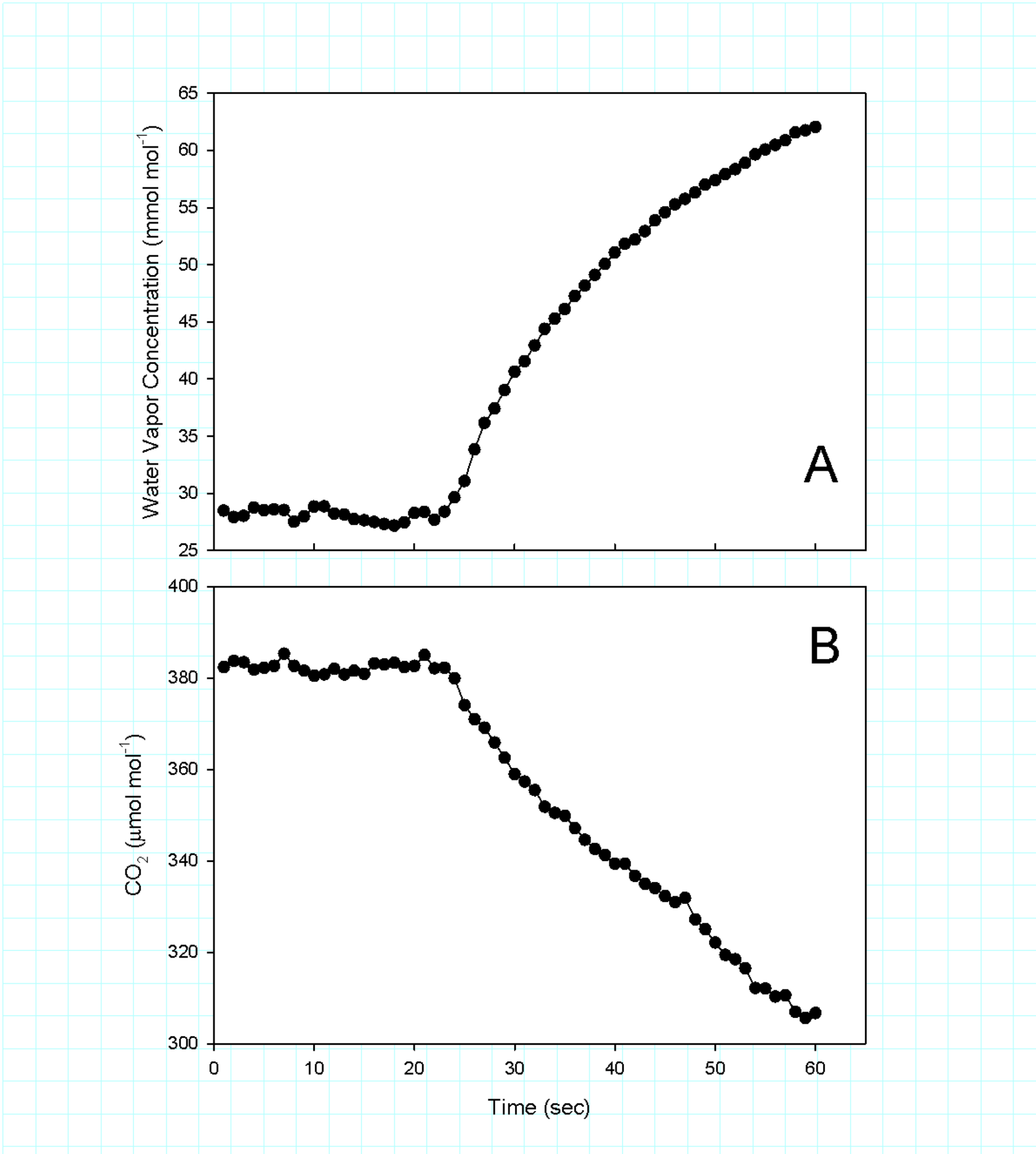

Figure 3.2 Typical rate of change of water vapor (A) and CO_2 (B) concentration measured with the sunlit chamber over well watered grass canopy.

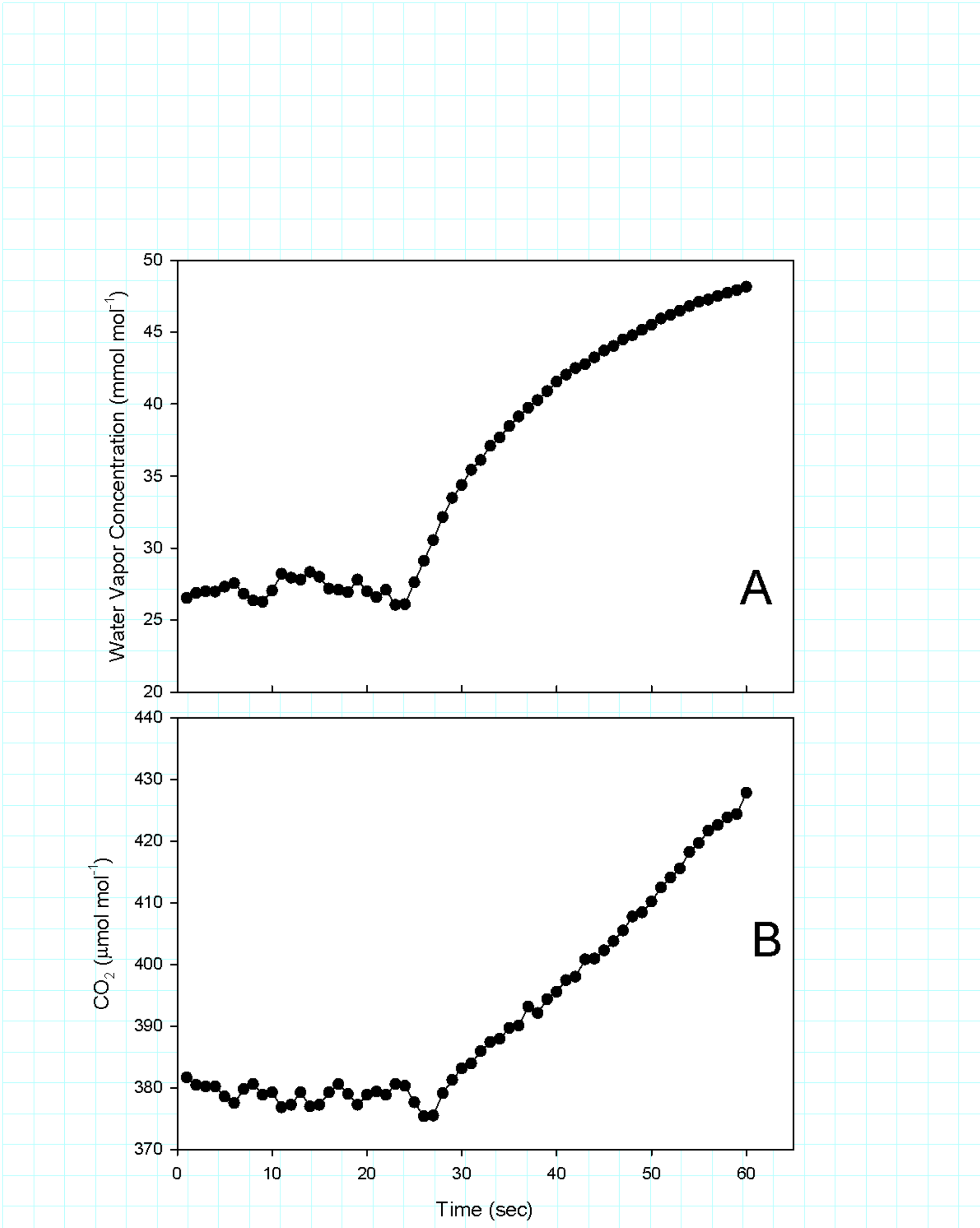

Figure 3.3 Typical rate of change of water vapor (A) and CO_2 (B) concentration measured with the covered chamber over well watered grass canopy.

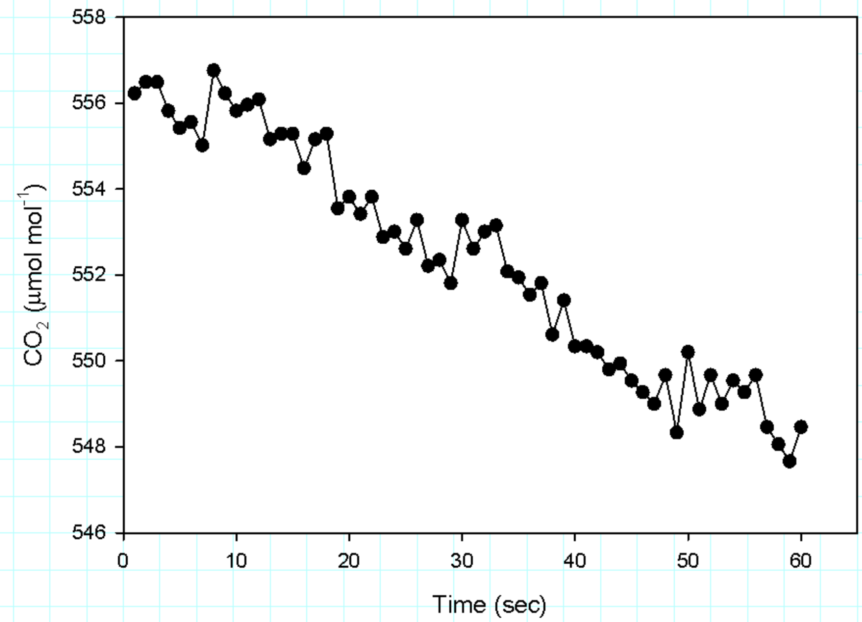

Figure 3.4 A typical example of the rate change of CO_2 during a leak test conducted in the field on a sheet of aluminum. At the start of the test CO_2 was injected to raise the concentration 100 µmol mol^{-1} above ambient (e.g. 470 vs 370 µmol mol^{-1}).

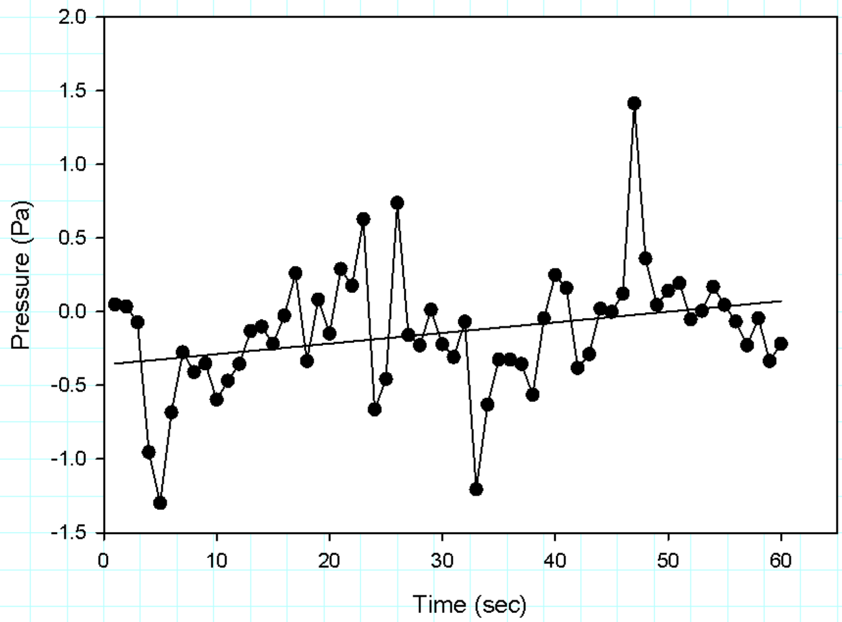

Figure 3.5 Typical example of chamber pressure observed during a measurement. The solid black line represents the linear regression equation ($y = 0.0072x - 0.3598$, $r^2=0.07$).

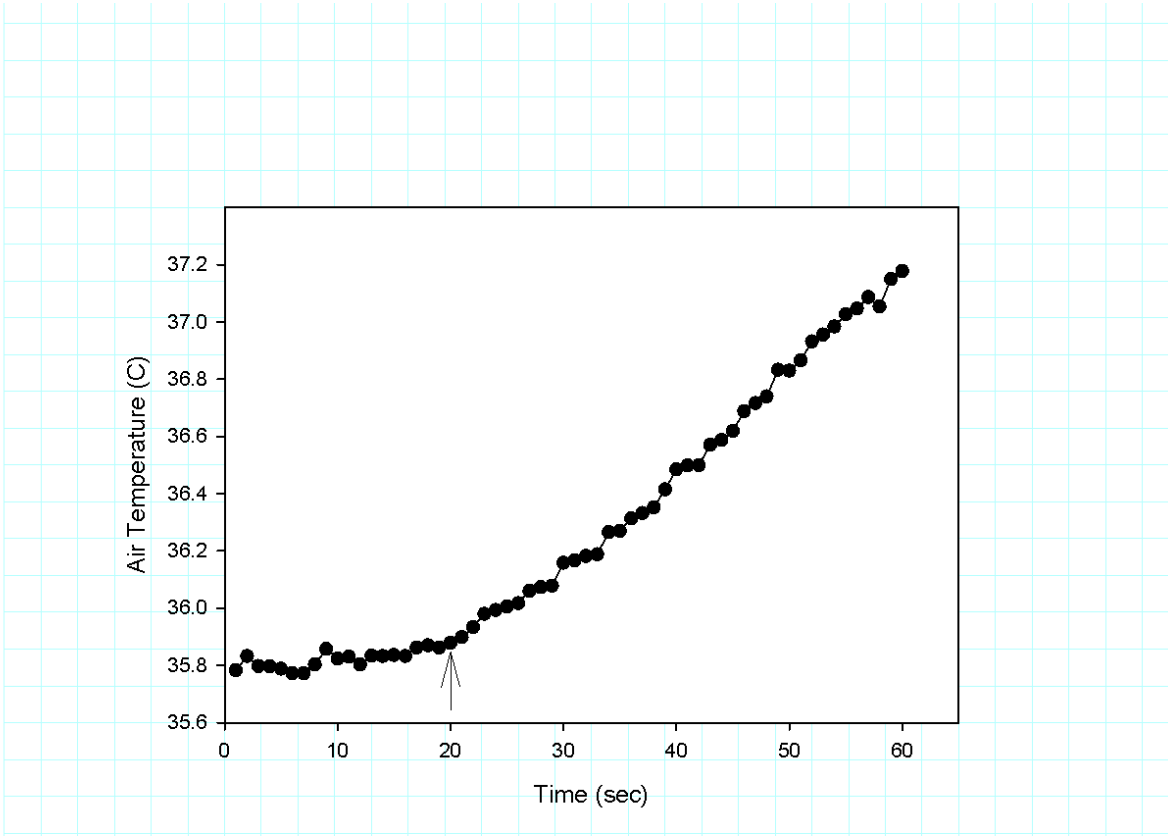

Figure 3.6 Typical air temperature inside the sunlit chamber observed during a measurement. The arrow indicates the lowering of the chamber at 20 sec.

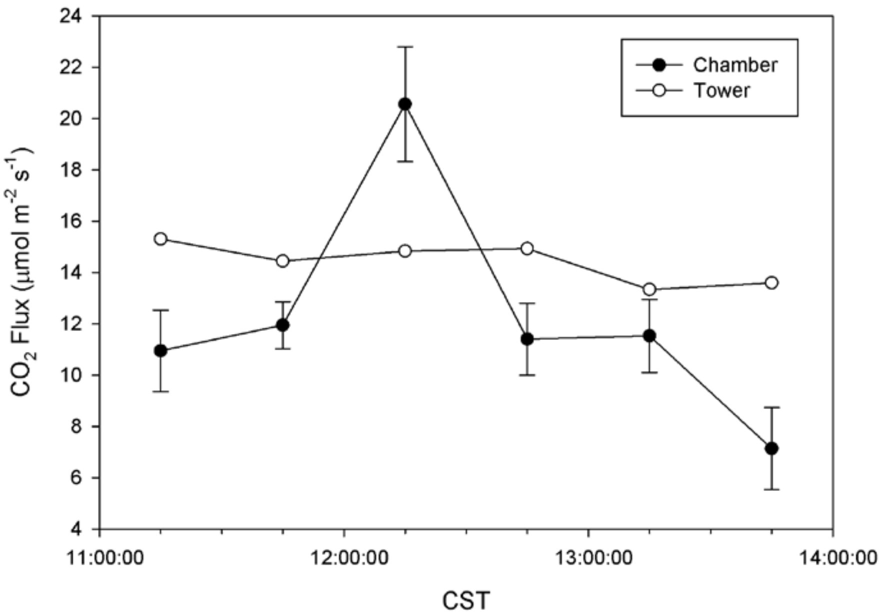

Figure 3.7 Measurements of CO_2 flux collected on DOY 168, 2010 from the chamber and an eddy covariance (EC) tower. Measurements were made every 5 min. with the chamber, while the EC tower measures continually. The bars around the chamber means represent +/- 1 standard error.

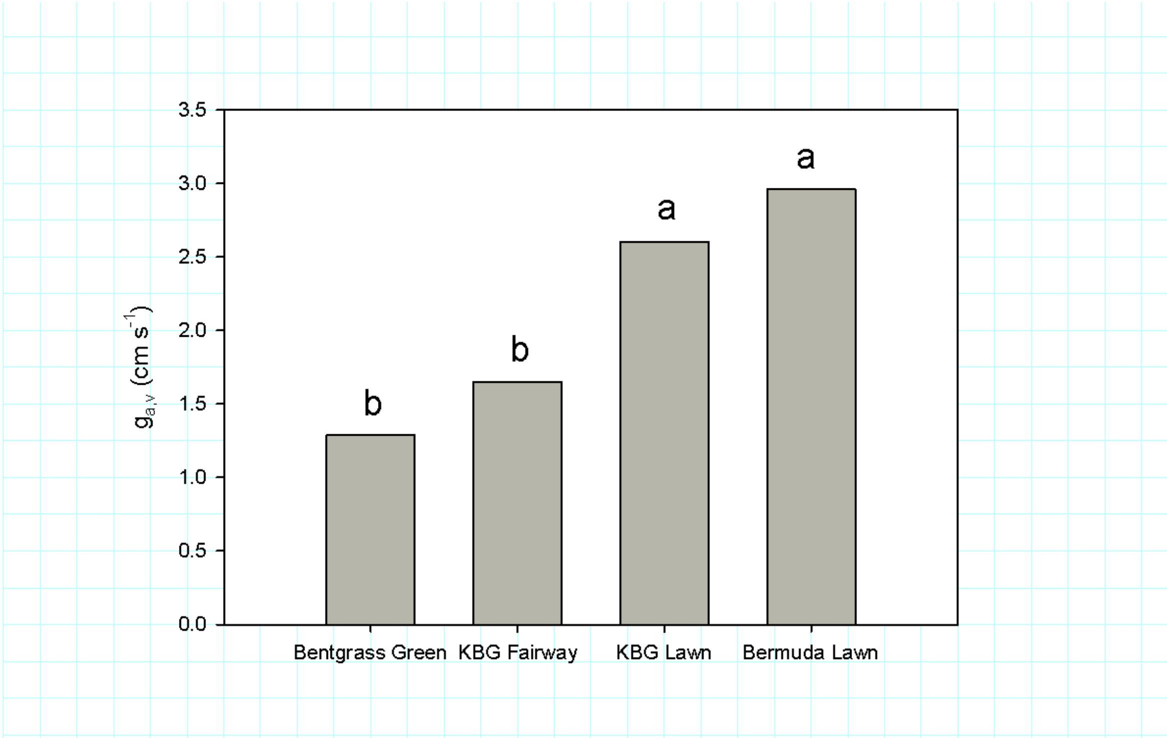

Figure 3.8 Measurements of aerodynamic conductance ($g_{a,v}$) from plots of bentgrass at 0.4 cm height, Kentucky bluegrass at 1.6 cm and 9.3 cm height, and bermuda at 9.3 cm height. Plots were sprayed with glyphosate 8 days prior to testing.

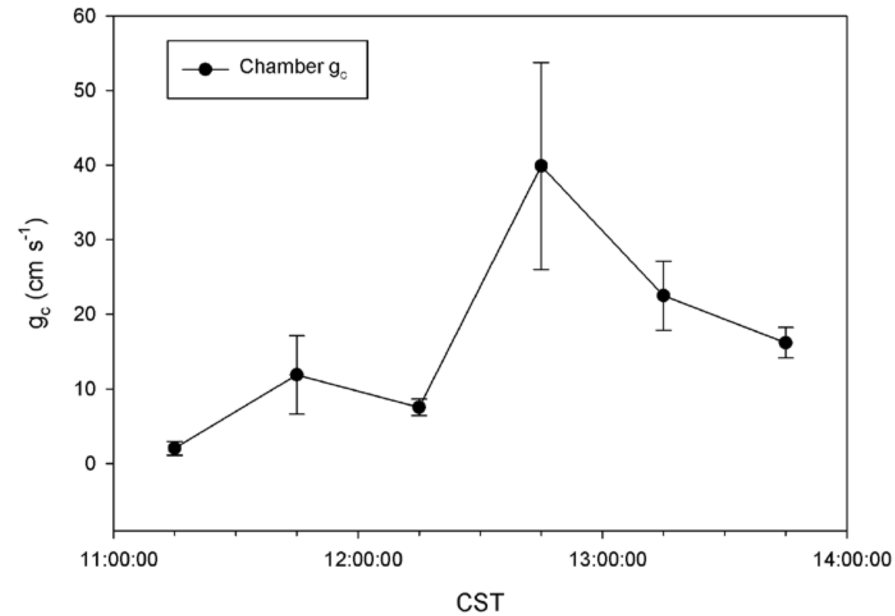

Figure 3.9 Measurements of canopy conductance (g_c) collected on DOY 168, 2010 from the chamber. An aerodynamic conductance (ga,v) of 2.78 was used based on the findings from Fig. 3.8.

CHAPTER 4 - Comparative Irrigation Requirements of 28 Cultivars of Kentucky Bluegrasses and 2 Texas Bluegrass Hybrids under a Rainout Facility in the Transition Zone

Abstract

One of the most important challenges facing the turfgrass industry is an increasingly limited supply of water for irrigation. One strategy to mitigate irrigation demands for turfgrass is identification of cultivars that use less water and resist drought better. The objectives of this study were to quantify irrigation requirements, visual quality ratings, and genetic rooting potential of 28 Kentucky bluegrass (*Poa pratensis* L.) (KBG) cultivars and 2 Texas bluegrass hybrids (*P. pratensis* x *P. arachnifera* Torr.). Visual quality was rated daily during two summers under a rainout shelter near Manhattan, KS. Irrigation was based on visual drought stress symptoms. When a plot had greater than 50% drought stress, indicated by wilting and darkening of the turf it was irrigated with 2.54 cm of water. Amount of water applied was recorded for the season. Rooting characteristics of maximum root extension (MRE), root length density (RLD) (root length/soil volume), root surface area, and average root diameter were measured in a separate greenhouse study. The average amount of water applied ranged widely among cultivars, from 23.4 to 40.0 cm during the 2-yr study. Several cultivars including Bedazzled, Preakness, and Bartitia required less water and had higher average quality than other cultivars. MRE ranged from 89.5 cm in Moonlight to 40.7 cm in Nu Destiny, but none of the rooting characteristics measured were correlated to water applied in the field. KBG cultivar had a significant impact on quality ratings, MRE and amount of water applied when drought stress was evident. Results suggest that Compact America and Mid-Atlantic phenotypes have the greatest potential for success in integrating reduced water inputs with maintenance of acceptable visual quality.

Introduction

One of the most important challenges facing the turfgrass industry is an increasingly limited supply of water for irrigation. Consequently, water conservation and improving turfgrass' resistance to drought stresses have become increasingly important. Turf managers commonly face drought, which can occur anywhere in the United States. In 2004, a task group from the Environmental Institute for Golf concluded that future water availability is a serious issue in the western United States, there is a lack of data on water use in many states, and state and local drought restrictions may be imposed on turf managers with no regard for damage to turfgrasses (Beard and Kenna, 2008). Nevertheless, clients and the public express displeasure when turfgrass is not of expected quality when irrigation is restricted.

A 2005 NASA study determined that turfgrass already covers an area three times greater than any irrigated crop in the United States, and urban expansion in the US is projected to increase nearly 80% by 2025 (Alig et al., 2004). Because turfgrass acreage is increasing with urban expansion, demand for water irrigation will also likely continue to increase. One strategy to mitigate irrigation demands for turfgrass may be the identification of cultivars that use less water and tolerate drought better.

Kentucky bluegrass (KBG) is one of the most widely used turfgrasses for home lawns, golf courses, parks, and athletic fields (Turgeon, 2002). Kentucky bluegrass often goes dormant under drought conditions, which severely decreases its visual quality. At present there is a lack of information on relative irrigation requirements for growing quality Kentucky bluegrasses under field conditions. Although information is available on turfgrass quality among cultivars of Kentucky bluegrass (i.e., annual trials of the National Turfgrass Evaluation Program), more information is needed on cultivars that conserve water while maintaining acceptable quality.

Significant variation in water use has been observed among cultivars of Kentucky bluegrasses in experiments conducted in growth chambers, greenhouses, and lysimeter-based field studies (Steinegger et al 1980; Shearman 1986; Ebdon et al. 1998a, 1998b, and 1998c; Abraham et al., 2004). Growth chambers and greenhouses have the advantage of more controlled environments but do not necessarily represent water use among cultivars in the field where conditions are more variable. Lysimeters which are used in growth chamber, greenhouse, and some field studies to may restrict soil volumes for root growth and result in higher root temperatures and alter certain physiological aspects of the turfgrasses (e.g., leaf area, above and below ground biomass density) that may impact water use (Bremer 2003). In a controlled-environment study in a greenhouse, Ebdon et al. (1998a) observed significant interactions in water use among cultivars of Kentucky bluegrass as evaporative environments changed. Those authors concluded that 87% of the variation in ET in Kentucky bluegrass was due to the evaporative environment and not the plant's pedigree, and argued that making recommendations for specific cultivars may be difficult because of highly variable evaporative conditions that are common in the field. Nevertheless, non-lysimeter based field studies that integrate water use over several weeks or months in turfgrasses may be useful because they represent conditions more typical of those in golf courses or lawns.

Field studies investigating drought tolerance in KBG has been conducted by withholding irrigation and measuring plant responses (Keeley and Koski, 2001; Richardson et al., 2008; Richardson and Karcher, 2009; Merewitz et al., 2010). Richardson and Karcher (2008) concluded that KBG had wide variability in drought tolerance, and that broad screening could result in water conservation. Similarly, Richardson et al. (2008) identified several cultivars including Mallard, Moonlight, Prosperity, SR2284, Brilliant, and Diva, as having better drought tolerance among 50 KBG cultivars screened; drought tolerance was defined as the number of days until a cultivar reached 50% green tissue, using digital image analysis.

Kentucky bluegrasses can be classified into specific groups, which may be useful in determining drought tolerance (Murphy et al., 1997; Bonos et al., 2000). Keeley and Koski (2001) investigated visual quality and leaf firing during field dry-downs of 22 to 33 days of 15 cultivars of KBG, representing various KBG phenotypic groups. Those authors reported that dehydration avoidance rankings were: Mid-Atlantic > Bellevue > BVMG > Common. In contrast, Richardson et al. (2008) did not find any clear trends in drought tolerance, as measured by days to 50% green cover, among phenotypic groups of KBG. Beyond the latter two studies, few have investigated relative drought resistance among phenotypic groups of KBG.

Texas bluegrass hybrids, which are genetic crosses between native Texas bluegrass and KBG (primarily *P. arachnifera* Torr. x *P. pratensis*), may have greater heat and drought resistance than other cool-season turfgrasses (Read et al., 1999; Merewitz et al., 2010). Abraham et al. (2004) found that 2 Texas bluegrass hybrids tested had high drought resistance compared to KBG and other Texas bluegrass hybrids. Richardson and Karcher (2009) specifically mention the hybrid Longhorn as having excellent drought tolerance, but found that a number of other hybrids were not superior to KBG for drought tolerance. Conversely, several other studies reported negligible differences in drought tolerance between Texas bluegrass hybrids and KBG (Bremer et al., 2006; Richardson et al., 2008; Su et al., 2007; 2008, 2009).

Measurements of rooting characteristics have successfully been used to screen turfgrasses for drought tolerance (Bonos et al., 2004). For example, selecting germplasm based on high root/shoot ratio in the greenhouse was found to be a viable method for selecting for drought tolerance in turf-type tall fescue (*Festuca arundinacea* Schreb.) grown in the field (Karcher et al., 2008). Ebdon and Kopp (2004) found that deeper rooting reduced leaf firing in KBG under drought stress, indicating that deeper rooting improved drought tolerance in a greenhouse experiment. Also, KBG cultivars that were characterized as tolerant of summer stress had 19% more roots in the 15-30 cm depth and 65% more roots in the 30 to 45 cm depth (Bonos and Murphy, 1999). In contrast, Richardson et al. (2008) reported that selection of KBG germplasm with deep rooting or high root/shoot ratios did not necessarily result in greater drought tolerance.

Identification of KBG cultivars that require less water use while maintaining acceptable quality in the field has not been done. Such an effort, however, could be useful in efforts to conserve water in lawns, golf courses, and sports fields. Additionally, relationships between rooting characteristics and water use in KBG cultivars have not been investigated. The objectives of our study were to quantify irrigation requirements, visual quality ratings, and genetic rooting potential for 28 KBG cultivars, and 2 Texas bluegrass hybrids, to identify cultivars that maintained higher quality with the least amount of water applied.

Materials and Methods

Field Study

Data were collected from 6 June, 2007 to 1 Oct., 2007, and 22 June, 2009 to 7 Oct., 2009. Data were not collected in the summer of 2008 because of billbug infestation (*Sjphenophorus parvulus* Gyllenhal). The plots were under an automated rainout shelter (12 by 12 m) at the Rocky Ford Turfgrass Research Center near Manhattan, KS (39º13’53” N, 96º34’51”W). Manhattan lies in the U.S. transition zone, which covers 480 to 1120 km north to south between the northern regions where cool-season grasses are adapted and the southern regions where warm-season grasses are adapted (Dunn and Diesburg, 2004). The rainout shelter rested north of the plot area but automatically covered the research plots as precipitation began and retracted 1 h after it ceased. The soil at the site was a Chase silt loam (fine, smectitic, mesic Aquertic Argiudoll).

Turfgrasses in the study included 28 KBG cultivars and 2 Texas bluegrass hybrids (Table 4.1). Cultivars were selected to include representatives from major KBG types (Murphy et al., 1997; Bonos et al., 2000). Most cultivars were best performers in the National Turfgrass Evaluation Program (NTEP) trials (National Turfgrass Evaluation Program, 2006). Four standard entries selected because of their widespread use prior to this study, included Midnight, Baron, Eagleton, and Kenblue.

Plots were arranged in a randomized complete block design with three replications. Ninety plots measuring 1.13 by 1.22 m were bordered by metal edging (10 cm depth) to prevent lateral soil water movement. Before seeding the plot area was treated with dazomet (tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thi-one) at 575 kg a.i. ha^{-1} to kill vegetation and insect, weed, and pathogen pests. On 19 Sept., 2006, plots were seeded at 10 g m^{-2} pure live seed. Starter fertilizer (18-46-0) was applied at the rate of 5 g N m^{-2} and plots were covered with a seed germination blanket (Futerra F4 Netless, Profile Products LLc, Buffalo Grove IL) to prevent movement of seed across plots from wind or water. Plots were irrigated several times daily to maintain a moist seedbed during establishment.

The plots were well watered until 19 June 2007. Thereafter, daily evaluations of turfgrass quality and drought stress were collected; generally, this was in mid-afternoon. Drought stress was defined as the turf displaying wilting, failure of the canopy to remain upright after traffic, and a general darkening color of the turf. When about 50% of the plot displayed drought stress, it was watered with 2.54 cm of water and the watering was recorded for the plot. Water was applied by hand through a fan spray nozzle attached to a hose; a meter (Model 03N31, GPI, Inc., Wichita, KS) was attached to ensure proper application amount. The dry-down cycles continued until 1 Oct., 2007, after which plots were well watered to allow for recovery. Turfgrass quality evaluations were made daily using a visual rating scale of 1 to 9, with 1 = poorest, 6 = acceptable, and 9 = best (Skogley and Sawyer, 1992). The experiment was repeated in 2009; the dry-down started on 22 June 2009, and was completed 7 Oct., 2009.

Plot Maintenance

Plots were mown weekly with a rotary mower at 7.6 cm. Aerification was done on 18 Mar. 2009, and 4 May 2009, with 13 mm diam. by 7.6 cm hollow tines; approximately 50 cores were taken per plot and cores were not harvested.

Imidacloprid was applied to control billbug grubs and white grubs (*Cyclocephala lurida* Bland) included (1-[(6-chloro-3-pyridinyl)methyl 3 (2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate) at 0.12 kg a.i. ha^{-1} on 1 May, 2007 and 4 May, 2009.

Azoxystrobin ((methyl(E)-2-{2-[6-(2-cyanpphenoxy) pyrimidin-40yloxy]phenyl}-3-methoxyacrylate)) was applied at 0.61 kg a.i. ha^{-1} on 4 June 2007 and 9 June 2009 for summer patch control (*Magnoporthe poae*).

Herbicide applications of carfentrazone-ethyl (Ethyl α,2-dichloro-5-[4(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-trizol-1-yl]-4-fluorobenzenepropanoate) at (0.03 kg a.i. ha^{-1}) + 2,4-D, 2-ethylhexyl ester (2,4-dichlorophenoxyacetic acid) (1.29 kg a.i. ha^{-1}) + Mecoprop-p acid ((+)-R-2-(2-methyl-4-chlorophenoxy)propionic acid) (0.27 kg a.i. ha^{-1}) + dicamba acid (3,6-dichloro-o-anisic acid (0.08 kg a.i. ha^{-1}) on 16 March 2007, 20 Oct. 2007, 15 March 2009, and 23 Oct. 2009 for broadleaf weed control. Applications of dithiopyr (S,S'-dimethyl 2-(difluoro-methyl-4-(2-methylpropyl)-(trifluoromethyl)-3,5-pyridin-edicarbothioate) were made at 0.58 kg a.i. ha^{-1} on 27 May 2007 and 15 May 2009 to control annual grassy weeds.

All plots were fertilized with urea at 50 kg N ha^{-1}on 15 April 2007; 25 kg N ha^{-1} on 1 June 2007; 50 kg N ha^{-1} on 5 Oct. 2007; 25 kg N ha^{-1} on 24 April 2009; 25 kg N ha^{-1} on 24 May 2009; 38 kg N ha^{-1} on 8 June 2009. A polymer-coated urea was applied on 24 April 2009 at 75 kg N ha^{-1}.

Rooting study

Measurements of rooting characteristics were conducted in a greenhouse study at Kansas State University. Seeds of the same 28 KBG cultivars and 2 Texas bluegrass hybrids used in the field study were planted in clear polyethylene tubes (3.5 cm in diam. by 120 cm long) that were filled with 100% calcined clay (Turface, Buffalo Grove, IL). The calcined clay inside was saturated with water before planting the grasses. Each tube was inserted into an opaque polyvinyl chloride (PVC) pipe. The method of Qian et al. (1997) was followed to prepare and position the tubes. Briefly, each PVC pipe was 120 cm long and 4 cm i.d. The bottom was capped by a PVC plug in which holes were drilled to allow for drainage. Ninety tubes were arranged on a tube rack at a 20° angle from vertical in a random complete block design with three replications.

Seeds were planted in the tubes on 23 May 2007 and allowed to grow until 15 July 2008. Irrigation was applied with a mist system that was automatically turned on six times per day for 10 sec. each. Fertilizer was applied once weekly with irrigation water at 250 mg L^{-1} N of Peters Peat-lite Special 20-10-20 water-soluble fertilizer (Scotts-Sierra Horticultural Product Co., Marysville, OH).

Maximum root extension (MRE) was determined by measuring the length of the deepest root visible at the calcined clay-clear polyethylene tube interface every 2 weeks. When MRE growth had ceased the study was halted. Tubes were then divided into four 30-cm long sections. Roots in every section were washed to remove any soil substrate. After washing, a methyl-based violet staining solution was applied to enhance image of the finer roots. Root length density (RLD) (root length/soil volume), root surface area, and root diameter were determined by digital image analyzer (WinRHIZO Model 2002a, Regent Instruments Inc., Quebec, Canada). After digital analysis, root samples were dried for 24 h at 60°C and weighed.

Data Analysis

Climatological variables were measured at a weather station located at the Rocky Ford Turfgrass Research Center. Evapotranspiration (ET) for the field study was calculated by using the FAO-56 Penman-Montieth equation (Allen et al., 1998).

Water application amounts, visual quality, MRE, RLD, root surface area, root diameter and root dry weight were analyzed by the general linear models (GLM) procedure, and means were separated using Fisher's protected least significant difference (LSD) at $p = 0.10$. Correlations between rooting data collected and water applied was done with the correlation (corr) procedure (Spearman) of SAS (SAS Institute Inc., 2002).

Results and Discussion

Water Applied to Cultivars

Water applications during the two-summer study ranged from 23.4 cm in Bedazzled to 45.0 cm in Kenblue, and significant differences ($p=0.05$) were observed among cultivars (Fig. 4.1). There was no interaction between summer and cultivar effects, indicating consistent results between 2007 and 2009. The cultivars that required the least amount of water were Bedazzled, Apollo, Cabernet, Unique, Preakness, Abbey, Julia, and Envicta, all of which had less than 30 cm of water applied. The first significant difference in water applied was between Bedazzled and Blue Velvet (Table 4.2).

Wide ranges in water applied as observed in this study are similar to results from Shearman (1986), who reported ET rates of 3.86 to 6.34 mm d^{-1} among 20 KBG cultivars in a greenhouse. While the current study did not evaluate drought tolerance, per se, the range of water use suggests different drought tolerances among cultivars. Indeed, field investigations into the drought tolerance of up to 50 KBG cultivars and hybrid bluegrasses revealed wide variations in responses to drought tolerance and in recovery (Richardson et al., 2008, 2009); drought tolerance was rated by measuring the number of days until the cultivars reached 75, 50 and 25% green cover. In those studies, it was concluded that cultivar selection in KBG can have significant impacts on turf responses to long-term drought stress.

In our study, Diva ranked 6th for greatest water requirements (38.1 cm) and Midnight was midway in the water-application rankings (31.8 cm) (Fig. 4.1; Table 4.2). This does not appear to correlate well with the drought tolerance rankings of Richardson et al. (2008), who reported Diva and Midnight as having good drought tolerances. Differences in objectives and hence, methodologies between studies probably explain this apparent disagreement and indicates that screening for lower water requirements may not result in cultivars with better drought tolerance.

The average cumulative grass reference crop ET for the two summers, as calculated with the Penman-Monteith equation, was 49.4 cm. The cultivars that required the least amount of water was only ~50% of that amount (Fig. 4.1; Table 4.2). This is seemingly less than water requirements for the KBG cultivar Brilliant, in which acceptable quality (i.e., 6) was maintained only at 100% of actual ET and quality ratings around 5 were achieved at 80% actual ET (Fu et al., 2004).

Water applications among KBG phenotypic groups

Among phenotypic groups (Murphy et al., 1997; Bonos et al., 2000), the least amount of water was applied to mid-Atlantic (27.4 cm) and compact America (28.2 cm) and there was a significant group effect (p=0.05) (Fig. 4.2; Table 4.3). Notably, the five cultivars that required the least amount of water were all Mid-Atlantic (Preakness and Cabernet) and compact America

(Bedazzled, Apollo, and Unique) types (Table 4.2). Conversely, the common types required the most water (39.9 cm), and the European and Compact also required more water than the other groups. The first statistical difference was between Mid-Atlantic and the Compact types (Table 4.3). The Common types Kenblue, and Wellington required the most, and third most water, or 44.9 and 41.9 cm of water, respectively, while the last Common entry, Park, required 33.5 cm of water which was in the middle of the rankings (Table 4.2). European types ranked as a high water requirement group, primarily because of Blue Knight, which received a high amount of water (42.4 cm). However, the other European entry, Bartitia, required substantially less water (30.1 cm).

Our results are supported by the findings of Keeley and Koski (2001), who reported dehydration avoidance rankings among KBG phenotypic groups as Mid-Atlantic > Bellevue > BVMG > Common. In another KBG study, however, no clear trends were found relating phenotypic groups with drought tolerance (Richardson et al., 2008). In the latter study, the authors did recommend the use of Compact types (Moonlight and Diva) and Compact America types (Mallard, SR 2284, and Brilliant) for future breeding efforts for drought tolerance, since those cultivars in their respective groups performed well.

Cultivar Quality

There was a cultivar effect and a year effect for the yearly average quality rankings. When comparing across years, average visual quality of all the cultivars was 4.62 in 2007, and 4.46 in 2009. There was not a year*cultivar interaction, however, so quality rankings of cultivars are presented as their respective averages between 2007 and 2009.

Quality rankings of the KBG cultivars ranged from 3.9 in Kenblue to 4.9 in Blue Velvet, with significant differences among cultivars ($p=0.10$) (Fig. 4.3 and Table 4.3). Generally the top 20 cultivars screened were similar in average quality rankings, ranging from 4.9 to 4.5, and the first statistical difference was between Blue Velvet and Midnight (Table 4.2).

Though the highest average quality was below our minimal acceptable level of 6, this could be expected for frequently stressed KBG. Keeley and Koski (2001) reported a range of mean visual turf quality under drought stress, from 2.3 to 5.1 on a 1 to 9 scale, which are comparable to quality ratings in our study. We use the same quality rating scale as the National Turfgrass Evaluation Program. Their reported quality ranged from 6.3 to 3.8 for high input cultivars under well-watered conditions at various locations across the United States (National Turfgrass Evaluation Program, 2006).

Cultivar Quality Ratings of KBG Phenotypic Groups

There was a significant group effect for quality ratings (p=0.05) when analyzed as KBG phenotypic groups. The highest visual quality, averaged between 2007 and 2009, was the European type at of 4.7 (Fig. 4.4; Table 4.3). The two European cultivars were Bartitia, which had the second highest quality rating at 4.8, and Blue Knight, which was rated in the middle (16^{th}) with a 4.6 quality rating (Fig. 4.3). Other types that had high quality during the study were the Aggressive, and Compact Midnight types. The two Aggressive entries, Limousine and Touchdown, were both in the top 10 quality ratings. The Compact Midnight types that had high quality were Blue Velvet, which had the highest average quality in the study at 4.9, then Nu Destiny ranked 4^{th}, Midnight II ranked 7^{th}, and Award ranked 9^{th}, all with a 4.7 quality rating (Fig. 4.3). The first significant difference in quality rating among groups was between Shamrock and the European type (Table 4.3). The lowest quality rating was the Common group, which averaged 4.1. The 3 common entries of Wellington, Park, and Kenblue had the lowest overall quality ratings, 4.3, 4.0, and 3.9, respectively (Table 4.2).

Water and Quality Analysis of KBG Cultivars

The objective of the field study was to identify cultivars and types of KBG that retained good visual quality with a minimum amount of water input. The differences in water applied and visual quality may not be significantly different among various cultivars (Table 4.2). But by plotting relationships between average quality ratings and water requirements, we can identify general trends between water applied and visual quality. The ideal cultivar would have a high quality and a low amount of water applied.

When examining cultivars that met these criteria, which appear in the lower right section of Figure 4.5, Bedazzled had the lowest water requirement while having over a 4.6 quality rating. The cultivars Unique, Cabernet, and Apollo were all fairly close to Bedazzled.

Evaluation of other cultivars that had both a low water requirement and a high quality rating reveals a tradeoff between additional water and higher quality for some of the cultivars. For example, the quality of Preakness was 0.14 greater than Bedazzled but required an additional 3.7 cm of water. Quality also improved with additional water in Bartitia and Blue Velvet.

Kenblue had neither the high visual quality nor low water requirement traits we were screening for in this study; it required the greatest amount of water and had the lowest visual quality of all the cultivars tested. Park had the second lowest quality, and a mid-ranking of water applied.

Water and Quality Analysis of KBG Types

When data are plotted by KBG phenotypes, Mid-Atlantic, and Compact America required the least amount of water while maintaining a relatively high visual quality rating of ~4.6 for both types (Fig. 4.6). The Julia, Aggressive and European types had higher quality than the Mid-Atlantic and Compact America, but they also required more water. Therefore, Compact America, and Mid-Atlantic types may result in greater success when the objective is to reduce water inputs while maintaining acceptable visual quality.

The Julia type, which consisted of only one cultivar in our study, could be investigated further because it had a higher quality than compact America and the Mid-Atlantic types and required only ~ 2 cm more water. The Texas bluegrass hybrids were midway among groups for water applied and visual quality ratings. This is similar to results from other studies that have indicated hybrid bluegrasses did not demonstrate improved drought tolerance (Richardson et al., 2008; Richardson and Karcher, 2009; Su et al., 2007, 2008, 2009). Though not meeting our criteria of low water input and high visual quality, the European types could be investigated to identify higher quality selections, because those cultivars had the highest quality ratings in our study at irrigation requirements comparable to the compact and shamrock types.

Rooting KBG Cultivars

It took almost 14 months for the roots of the Moonlight cultivar to reach a MRE of 90 cm, cease growth, and thus, end the study. In a similar greenhouse study, Apollo KBG reached a depth of over 80 cm at 70 days after transplanting plugs taken from the field (Su et al., 2008). It is likely that seeding into calcined clay in the rooting tubes resulted in slower root development in our study. Statistical analyses revealed significant cultivar effects for MRE ($p=0.05$), dry root weight ($p=0.10$), and RLD in the 0 to 30 cm depth ($p=0.10$) (Table 4.4).

The MRE in the KBG cultivars ranged from 40.7 cm to 89.5 cm, revealing a substantial spread of 48.8 cm from shortest to longest (Fig. 4.7; Table 4.4). The cultivar Moonlight had the greatest MRE of 89.5 cm, and Thermal Blue Blaze and Touchdown were the only other cultivars with MRE of greater than 80 cm. Nu Destiny had the lowest MRE of 40.7 cm, which was only 45% as deep as Moonlight. Kenblue, and Wellington also had low MRE (<50 cm).

Differences in dry root weight among cultivars were significant only in the 0 to 30 cm depth (Fig. 4.8; Table 4.4). The effect was not significant at the other individual depths or for the whole rooting tube (0-90 cm). The first statistical difference was between Skye and Cabernet.

Differences in RLD were also significant among cultivars in the 0 to 30 cm depth (Fig. 4.9; Table 4.4). Root length density was greatest for Midnight II at 41.07 cm root cm^{-3} of media. Apollo, Longhorn and Julia had the lowest RLD at 24.2, 23.3, and 21.3 cm root cm^{-3} of media, respectively. Our RLD was higher than reported by Su et al. (2008), which reported RLD in KBG and Texas bluegrass hybrids ranging from 7.28 to 14.10 cm root cm^{-3} of media. The longer growing period in our study could explain the difference in rooting. Su et al. (2008) ran their rooting study for 70 days, while in our study rooting was collected after more than 420 days.

There was a relatively wide range of values for surface area, root diameter, and root length density of the entire profile, but no significant differences among cultivars (data not shown). Surface area averaged from 404 cm^3 in Longhorn to 858 cm^3 in Abbey. Average root diameter ranged from 0.11 mm in Longhorn to 0.20 mm in Nu Destiny. Root length density ranged from 9.1 cm root cm^{-1} media in Longhorn to 17.4 cm root cm^{-1} in Abbey.

Rooting KBG Type

There was a significant KBG phenotypic group effect for RLD and root surface area in the 0 to 30 cm depth (p=0.10) (Figs. 4.10 and 4.11, Table 4.5). The Texas bluegrass hybrids and the Julia types had the lowest RLD and root surface area compared to all the other types. Interestingly, the Common phenotypes had high RLD and root surface area.

Rooting and Water Applied

Correlations were not significant between all rooting metrics measured in the greenhouse and cumulative water applied in the field to cultivars and groups in 2007, 2009, and averaged between 2007 and 2009. Supporting our findings, Richardson et al. (2008) did not find correlations between root characteristics and drought tolerance. However, our results differ from those of Bonos and Murphy (1999), who reported that KBG cultivars classified as summer stress tolerant in the field had greater root mass in the upper 30 cm and 30 to 45 cm profiles than less tolerant cultivars. The genetic rooting potential of the KBG cultivars we observed in the greenhouse may not be realized in the field, especially when growing during heat and drought stress. The large differences in MRE did not appear to affect water applied, which differs from the relationship of deeper rooting and lowered water use in tall fescue (Karcher et al., 2008). Further research into understanding how these rooting parameters affect such things as heat stress, pest resistance, soil water use and other physiological aspects is warranted.

Conclusions

Results indicated that KBG cultivar selection had significant impacts on quality ratings, MRE and the amount of water applied to avoid drought stress. Differences in water applications were as great as 27 cm among cultivars, while differences in MRE were as great as 49 cm. This information could assist turfgrass managers in the selection of KBG cultivars that result in significant water conservation during a growing season. Avoiding drought stress in KBG may not be dependent on rooting parameters. We would recommend Compact America and Mid-Atlantic types for use and for future breeding efforts directed at reduced water inputs while maintaining acceptable visual quality.

Acknowledgements

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Figures

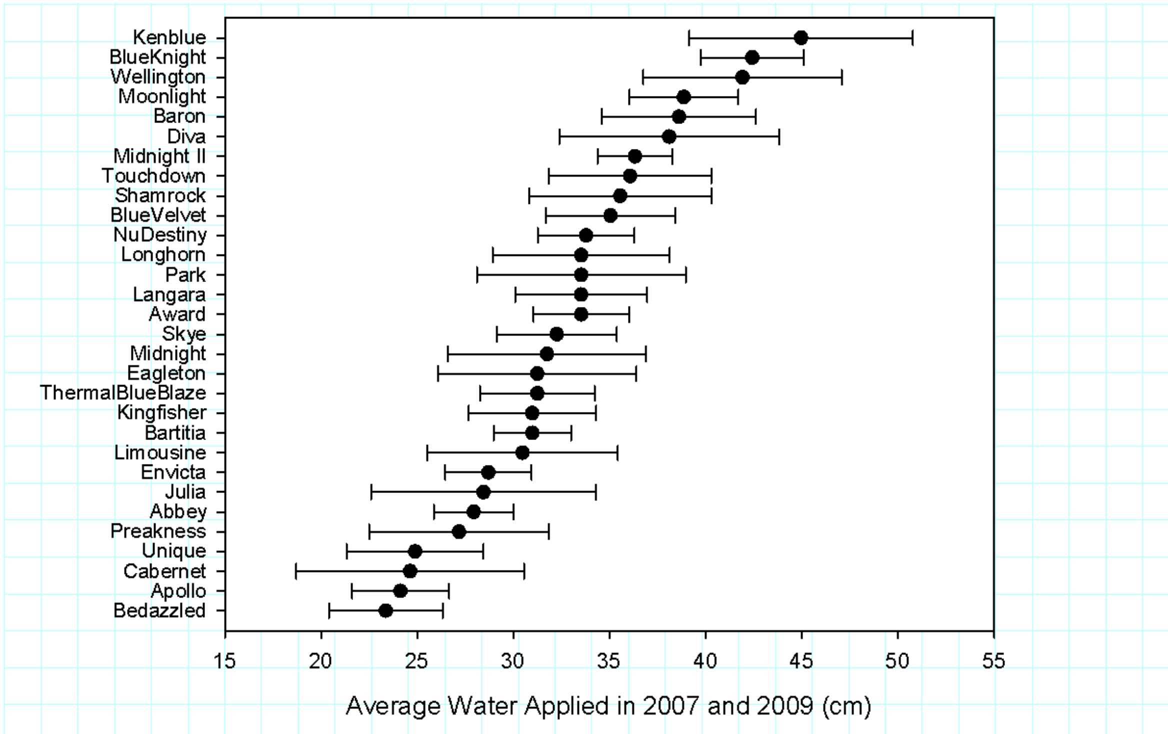

Figure 4.1 Average amount of water required to maintain visual quality by Kentucky bluegrass cultivars and Texas bluegrass hybrids in the summers of 2007 and 2009; 117 and 107 days, respectively. Horizontal bars represent ± one standard error.

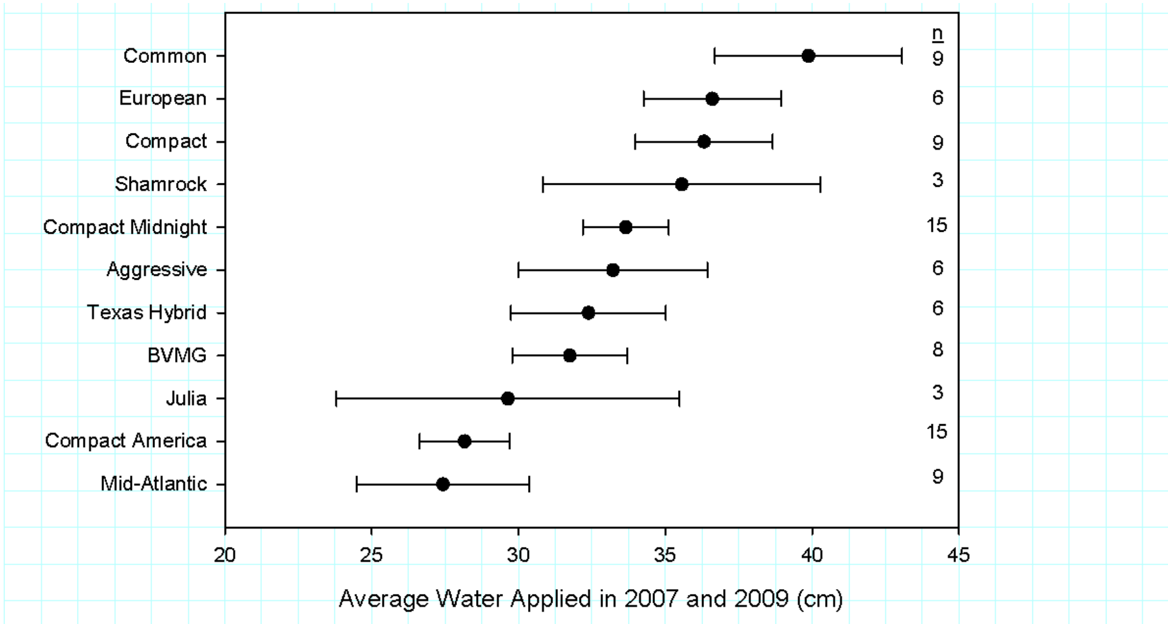

Figure 4.2 Average amount of water applied to Kentucky bluegrass phenotypes the summer of 2007 and 2009; 117 and 107 days, respectively. The bars represent the standard error. The column labeled n represents the number of replicates.

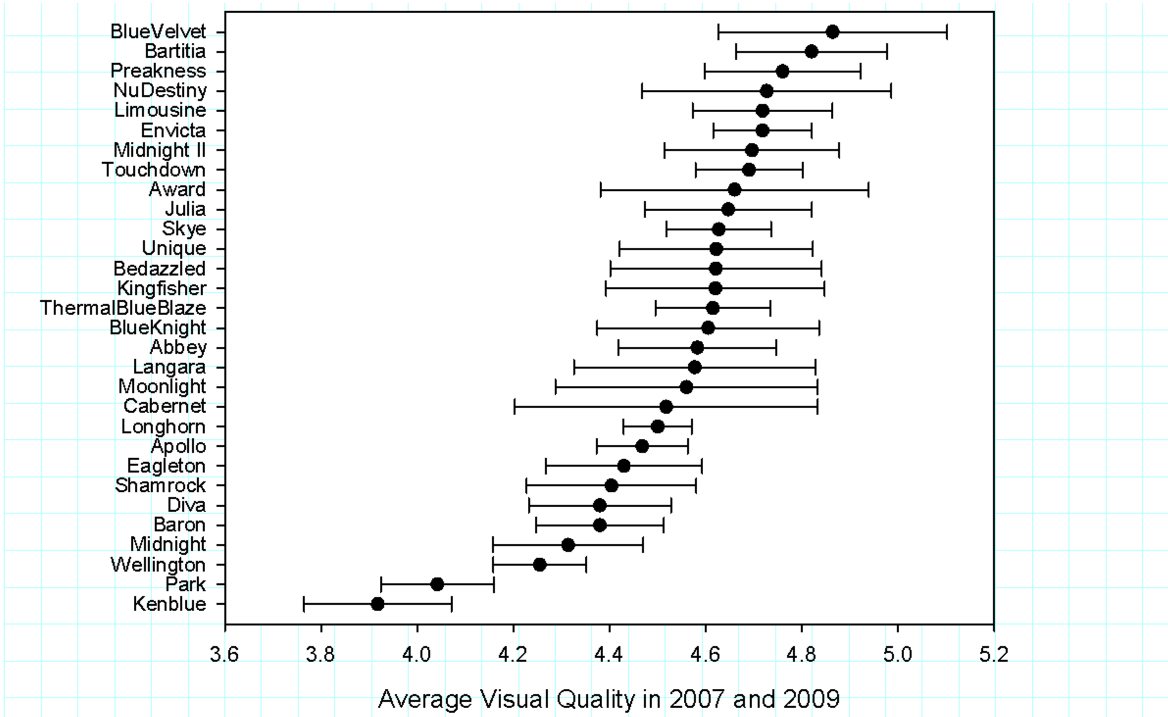

Figure 4.3 Average visual quality ratings on a 1-9 scale, with 6 being minimal acceptable, of Kentucky bluegrass cultivars and Texas bluegrass hybrids in the summer of 2007 and 2009; 117 and 107 days, respectively. The bars represent the standard error.

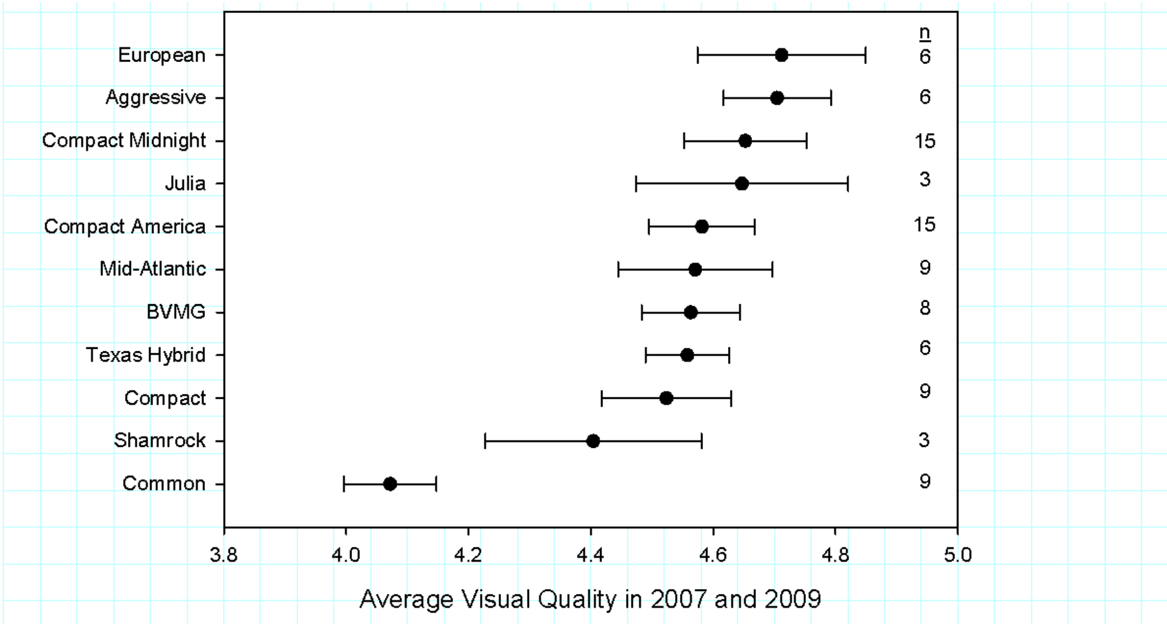

Figure 4.4 Average visual quality ratings on a 1-9 scale, with 6 being minimal acceptable, of Kentucky bluegrass phenotypes in the summer of 2007 and 2009; 117 and 107 days, respectively. The bars represent the standard error. The column labeled n represents the number of replicates.

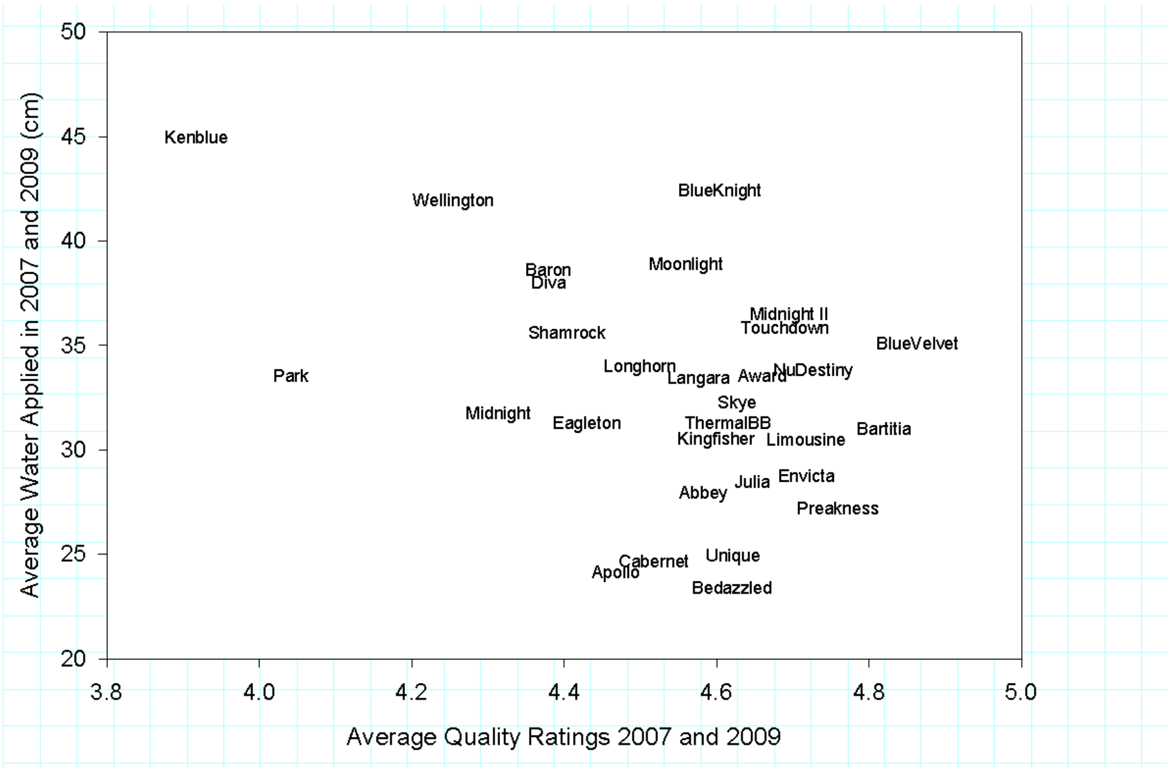

Figure 4.5 Average amount of water applied to Kentucky bluegrass cultivars and Texas bluegrass hybrids in the summer of 2007 and 2009; 117 and 107 days, respectively, versus average visual quality ratings on a 1-9 scale, with 6 being minimally acceptable.

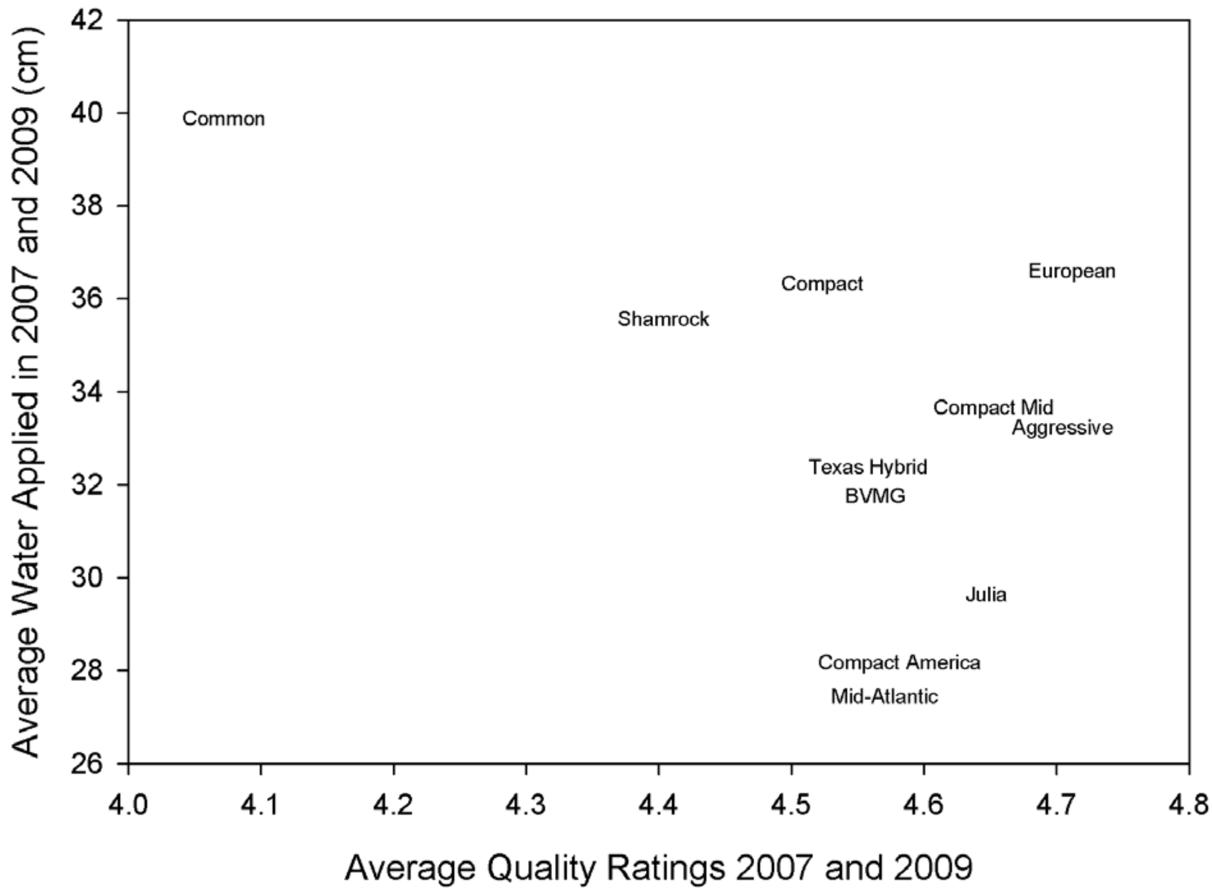

Figure 4.6 Average amount of water applied to Kentucky bluegrass phenotypes in the summer of 2007 and 2009; 117 and 107 days, respectively, versus average visual quality ratings on a 1-9 scale, with 6 being minimally acceptable.

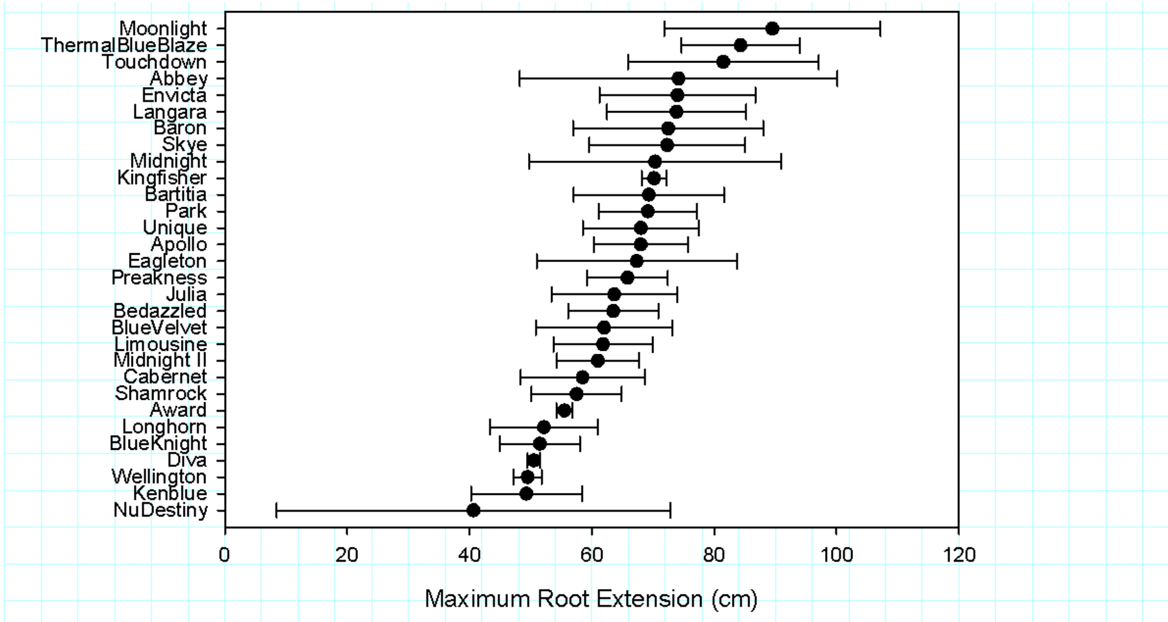

Figure 4.7 Maximum root extension (MRE) of Kentucky bluegrass cultivars and Texas bluegrass hybrids measured from greenhouse rooting tubes. The bars represent the standard error.

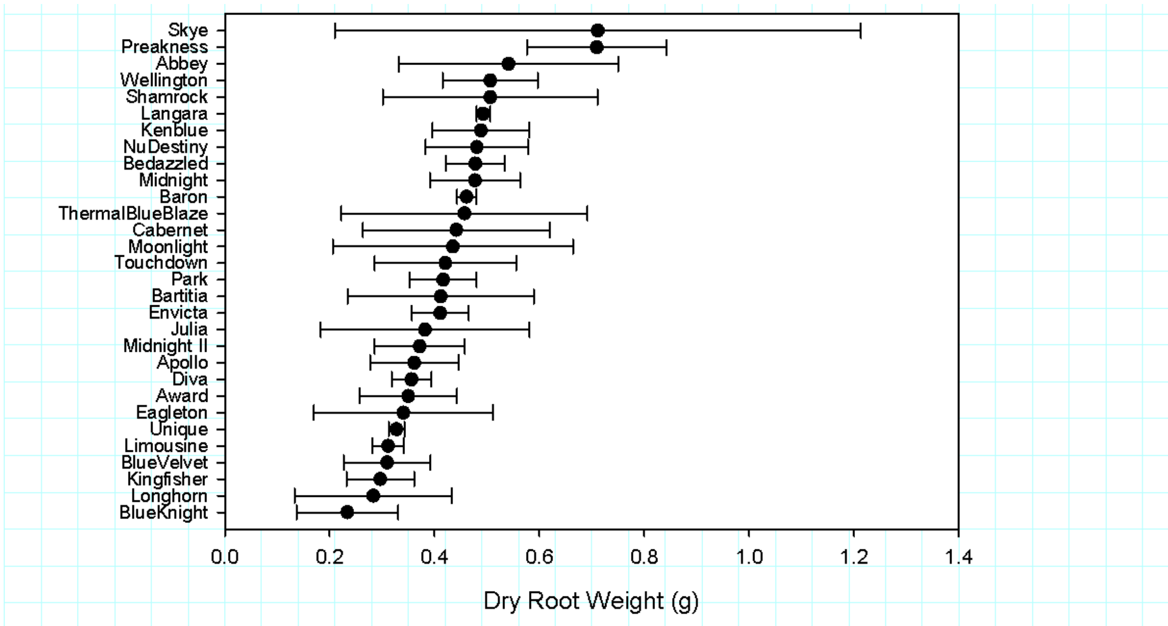

Figure 4.8 Dry root weight of Kentucky bluegrass cultivars and Texas bluegrass hybrids collected in the 0-30 cm depth from greenhouse rooting tubes. The bars represent the standard error.

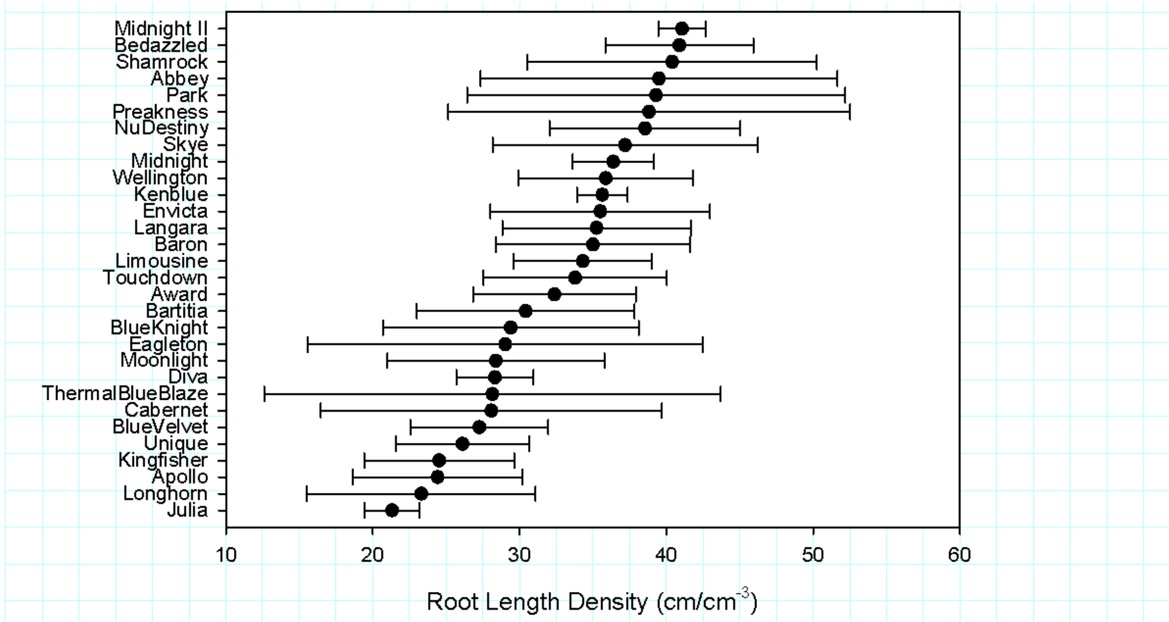

Figure 4.9 Root length density of Kentucky bluegrass cultivars and Texas bluegrass hybrids collected in the 0-30 cm depth from greenhouse rooting tubes. The bars represent the standard error.

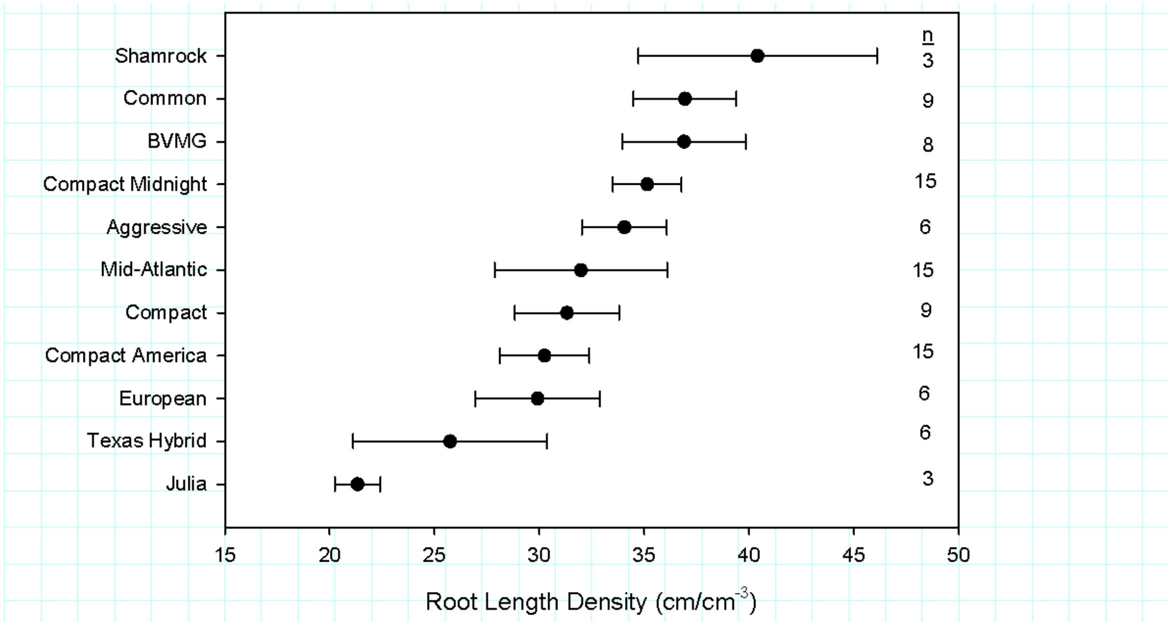

Figure 4.10 Root length density of Kentucky bluegrass phenotypes collected in the 0-30 cm depth from greenhouse rooting tubes. The bars represent the standard error. The column labeled n represents the number of replicates.

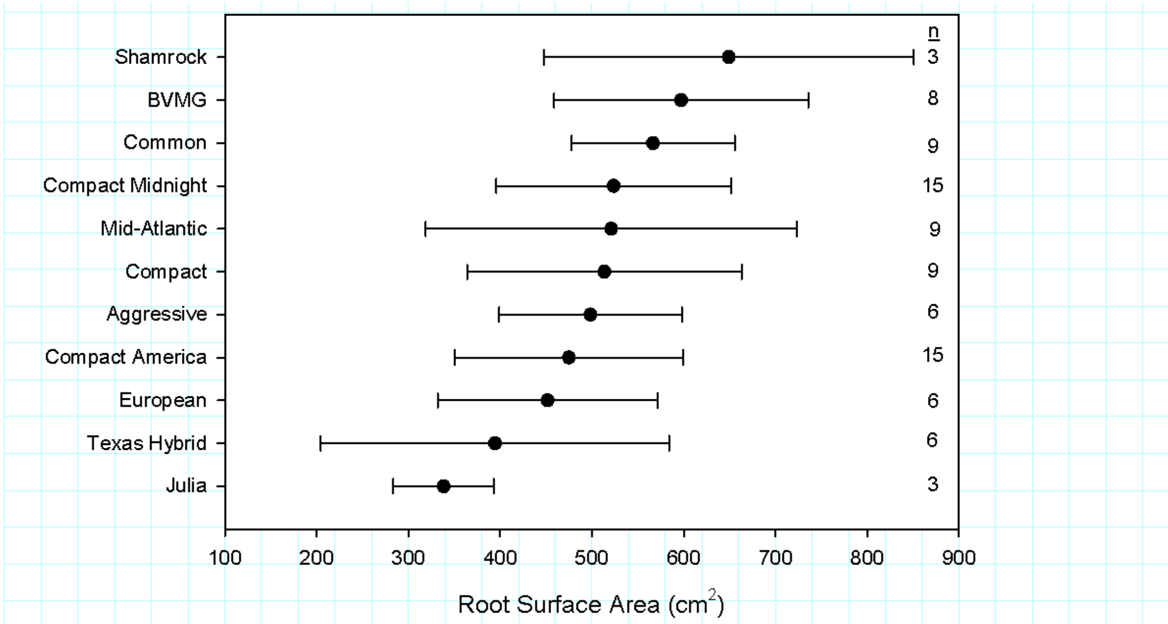

Figure 4.11 Root surface area of Kentucky bluegrass types collected in the 0-30 cm depth from greenhouse rooting tubes. The bars represent the standard error. The column labeled n represents the number of replicates.

Tables

Table 4.1 Types and cultivars of Kentucky bluegrasses and Texas bluegrass hybrids.

Type†	Cultivar	Type	Cultivar
Compact America	Langara	Common	Kenblue‡
	Bedazzled		Wellington
	Apollo		Park
	Unique	Compact	Diva
	Kingfisher		Skye
Mid-Atlantic	Eagleton‡		Moonlight
	Preakness	Julia	Julia
	Cabernet	BVMG	Baron‡
Compact Midnight	Midnight‡		Envicta
	Midnight II		Abbey
	Blue Velvet	Shamrock	Shamrock
	Nu Destiny	European	Blue Knight
	Award		Bartitia
Aggressive	Limousine	Texas Bluegrass Hybrids	Thermal Blue Blaze
	Touchdown		Longhorn

†Kentucky bluegrass classification types as described in Bonos et al., 2000.

‡Indicates that the cultivar was included as a standard entry.

Table 4.2 Average water applied and visual quality ratings of Kentucky bluegrass cultivars and Texas bluegrass hybrids averaged from the summers of 2007 and 2009.

Cultivar	Water Applied (cm)	Significance	Cultivar	Visual Quality	Significance
Kenblue	45.0	a†	Blue Velvet	4.86	a
Blue Knight	42.4	ab	Bartitia	4.82	a
Wellington	41.9	abc	Preakness	4.76	ab
Moonlight	38.9	abcd	Nu Destiny	4.73	abc
Baron	38.6	abcd	Envicta	4.72	abc
Diva	38.1	abcde	Limousine	4.72	abc
Midnight II	36.3	abcde	Midnight II	4.70	abc
Touchdown	36.1	abcdef	Touchdown	4.69	abc
Shamrock	35.6	abcdefg	Award	4.66	abc
Blue Velvet	35.1	abcdefgh	Julia	4.65	abc
Nu Destiny	33.8	abcdefghi	Skye	4.63	abc
Award	33.5	bcedfghi	Unique	4.62	abc
Langara	33.5	bcedfghi	Bedazzled	4.62	abc
Park	33.5	bcedfghi	Kingfisher	4.62	abc
Longhorn	33.5	bcedfghi	Thermal Blue Blaze	4.62	abc
Skye	32.3	bcedfghi	Blue Knight	4.61	abc
Midnight	31.8	bcedfghi	Abbey	4.58	abc
Thermal Blue Blaze	31.2	bcedfghi	Langara	4.58	abc
Eagleton	31.2	bcedfghi	Moonlight	4.56	abc
Bartitia	31.0	cedfghi	Cabernet	4.52	abcd
Kingfisher	31.0	cedfghi	Longhorn	4.50	abcd
Limousine	30.5	defghi	Apollo	4.47	abcd
Envicta	28.7	defghi	Eagleton	4.43	abcd
Julia	28.4	defghi	Shamrock	4.40	abcde
Abbey	27.9	defghi	Baron	4.38	abcde
Preakness	27.2	efghi	Diva	4.38	abcde
Unique	24.9	fghi	Midnight	4.31	bcde
Cabernet	24.6	ghi	Wellington	4.26	cde
Apollo	24.1	hi	Park	4.04	de
Bedazzled	23.4	i	Kenblue	3.92	e

† Means followed by differing letters are significantly different by the lsd at p=0.05.

Table 4.3 Average water applied and visual quality ratings of Kentucky bluegrass groups and Texas bluegrass hybrids averaged from the summers of 2007 and 2009.

Group	Water applied (cm)	Significance	Group	Visual Quality	Significance
Common	39.9	a†	European	4.71	a
European	36.6	ab	Aggressive	4.70	a
Compact	36.3	ab	Compact Midnight	4.65	a
Shamrock	35.6	abc	Julia	4.65	a
Compact Midnight	33.7	abc	Compact America	4.58	a
Aggressive	33.2	abc	Mid-Atlantic	4.57	a
Texas Hybrid	32.4	bc	BVMG	4.56	a
BVMG	31.8	bc	Texas Hybrid	4.56	a
Julia	29.6	bc	Compact	4.52	a
Compact America	28.2	c	Shamrock	4.40	ab
Mid-Atlantic	27.4	c	Common	4.07	b

† Means followed by differing letters are significantly different by the lsd at p=0.05.

Table 4.4 Kentucky bluegrass and Texas bluegrass hybrid maximum root length extension (MRE), and root length density (RLD) measured from the 0 to 90 cm depth, and dry root weight measured in the 0-30 depth in greenhouse rooting tubes.

Cultivar	MRE (cm)	Significance	Cultivar	Dry root weight (g)	Significance	Cultivar	RLD (cm cm^{-3})	Significance
Moonlight	89.5	a†	Skye	0.711	a	Midnight II	41.1	a
Thermal Blue Blaze	84.3	ab	Preakness	0.709	a	Bedazzled	40.9	a
Touchdown	81.5	abc	Abbey	0.541	ab	Shamrock	40.4	ab
Abbey	74.2	abcd	Shamrock	0.506	abc	Abbey	39.5	ab
Envicta	74.0	abcd	Wellington	0.506	abc	Park	39.3	abc
Langara	73.8	abcd	Langara	0.493	abc	Preakness	38.8	abc
Baron	72.5	abcde	Kenblue	0.488	abcd	Nu Destiny	38.6	abc
Skye	72.3	abcde	Nu Destiny	0.481	abcd	Skye	37.2	abcd
Midnight	70.3	abcde	Bedazzled	0.478	abcd	Midnight	36.4	abcde
Kingfisher	70.2	abcde	Midnight	0.477	abcd	Wellington	35.9	abcde
Bartitia	69.3	abcde	Baron	0.461	abcd	Kenblue	35.6	abcde
Park	69.2	abcde	Thermal Blue Blaze	0.457	abcd	Envicta	35.5	abcde
Apollo	68.0	bcde	Cabernet	0.442	bcd	Langara	35.3	abcde
Unique	68.0	bcde	Moonlight	0.435	bcd	Baron	35.0	abcdef
Eagleton	67.3	bcde	Touchdown	0.421	bcd	Limousine	34.3	abcdef
Preakness	65.8	bcde	Park	0.416	bcd	Touchdown	33.8	abcdef
Julia	63.7	bcde	Bartitia	0.412	bcd	Award	32.4	abcdef
Bedazzled	63.5	cde	Envicta	0.411	bcd	Bartitia	30.4	abcdef
Blue Velvet	62.0	cde	Julia	0.382	bcd	Blue Knight	29.4	abcdef
Limousine	61.8	cde	Midnight II	0.372	bcd	Eagleton	29.0	abcdef
Midnight II	61.0	cdef	Apollo	0.361	bcd	Moonlight	28.4	abcdef
Cabernet	58.5	def	Diva	0.356	bcd	Diva	28.3	abcdef
Shamrock	57.5	def	Award	0.350	bcd	Thermal Blue Blaze	28.2	abcdef
Award	55.5	def	Eagleton	0.341	bcd	Cabernet	28.1	abcdef
Longhorn	52.2	ef	Unique	0.327	bcd	Blue Velvet	27.3	bcdef
Blue Knight	51.5	ef	Limousine	0.312	bcd	Unique	26.1	cdef
Diva	50.5	ef	Blue Velvet	0.309	bcd	Kingfisher	24.5	def
Wellington	49.5	ef	Kingfisher	0.297	bcd	Apollo	24.4	def
Kenblue	49.3	ef	Longhorn	0.283	cd	Longhorn	23.3	ef
Nu Destiny	40.7	f	Blue Knight	0.234	d	Julia	21.3	f

† Means followed by differing letters are significantly different by the lsd at p=0.05.

Table 4.5 Kentucky bluegrass and Texas bluegrass hybrid group root length density (RLD), and root surface area from the 0 to 30 cm depth collected from greenhouse rooting tubes.

Group	RLD ($cm\ cm^{-3}$)	Significance	Group	Root Surface Area (cm^2)	Significance
Shamrock	40.4	a†	Shamrock	649.2	a
Common	36.9	a	BVMG	597.3	a
BVMG	36.9	a	Common	566.7	a
Compact Midnight	35.1	a	Compact Midnight	523.8	ab
Aggressive	34.1	ab	Mid-Atlantic	521.1	abc
Mid-Atlantic	32.0	abc	Compact	513.7	abc
Compact	31.3	abc	Aggressive	498.5	abc
Compact America	30.2	abc	Compact America	474.9	abc
European	29.9	abc	European	451.8	abc
Texas Hybrid	25.7	bc	Texas Hybrid	394.5	bc
Julia	21.3	c	Julia	338.4	c

† Means followed by differing letters are significantly different by the lsd at p=0.05.

CHAPTER 5 - Field measurements of carbon and water fluxes in turfgrass with a custom surface chamber

Abstract

Photosynthesis is a fundamental indicator of plant stress and growth, but basic information about photosynthesis in turfgrass is lacking. Using a custom chamber our objectives were to: 1) measure CO_2, water vapor fluxes and water use efficiency (WUE) in two warm- and two cool-season turfgrasses during hot midsummer and cool late summer days; and 2) estimate canopy stomatal conductance to water vapor flux (g_c) in the same grasses in a field study near Manhattan, Kansas. Diurnal measurements of net photosynthesis (Pnet), gross photosynthesis (Pg), evapotranspiration (ET), g_c, and WUE were taken on day of year (DOY) 216 and 262 (Aug. 5 and Sept. 19) on well-watered tall fescue (*Festuca arundinacea* Schreb.), Kentucky bluegrass (*Poa pratensis* L.), zoysia (*Zoysia japonica* Steud.), and bermuda (*Cynodon dactylon* (L.) Pers.). Volumetric soil water content (θ_v) in the 0 to 15 cm profile was measured using time domain reflectometry (TDR). Additional measurements were taken at solar noon on DOY 217. In warm-season grasses, Pg averaged 2.7 times greater than in cool season grasses on DOY 217. By DOY 262, Pg had decreased in all species; Pg was ~27 µmol m^{-2} s^{-1} in tall fescue and bermuda, 12 µmol m^{-2} in zoysia, and 20 µmol m^{-2} in Kentucky bluegrass. Diurnal measurements of Pnet and ET increased with PAR. Maximum Pnet was 20.7 µmol m^{-2} s^{-1} in tall fescue, 16.4 µmol m^{-2} s^{-1} in Kentucky bluegrass, 18.4 µmol m^{-2} s^{-1} in zoysia and 25.2 µmol m^{-2} s^{-1} in bermuda. Average daily gc was: 3.22, 4.47, 1.88, and 0.87 cm s^{-1} in Kentucky bluegrass, tall fescue, bermuda, and zoysia, respectively. Instantaneous WUE was almost 10 times greater in the warm- than the cool-season grasses on DOY 217. On DOY 262, with lower air temperature, WUE was statistically similar among the grasses and averaged 1.3 µmol CO_2 (mmol H_2O)$^{-1}$.

Introduction

Photosynthesis is a fundamental indicator of plant stress and growth (Salisbury and Ross, 1991). In studies where various stresses are imposed on turfgrass ecosystems (e.g., drought, heat, cold, mowing height, pests), measurements of photosynthesis may be used to evaluate suitability for a given environment or use (Mancino, 1993; Qian et al., 1997; Huang et al., 1997; Swarthout et al., 2009). Gaussoin et al. (2005) investigated fundamental mechanisms affecting photosynthesis (e.g., light, temperature, vapor pressure deficits, and ambient CO_2 concentrations) in three turfgrass species. Those authors noted a general lack of basic information in the literature about photosynthesis in turfgrass and recommended that further research was warranted.

Of the limited studies about basic photosynthesis processes in turfgrass, most have been conducted either in growth chambers or greenhouses (Jiang and Huang, 2000; Gaussion et al,. 2005; Su et al., 2007; Hu et al., 2009). While this may further our understanding about basic photosynthesis processes, it does not necessarily indicate how turfgrass will respond in the field, where conditions are usually more complex and stressful (Hunt, 2003). For example, variation and extremes in radiation, windspeed, temperature, and humidity are typically greater in the field, which may affect plants in ways that are unpredictable in chamber or greenhouse studies.

If photosynthesis and ET measurements are collected simultaneously, instantaneous WUE can then be estimated. In turfgrass, WUE has not been investigated extensively, presumably because greater visual quality and not biomass yield is a primary goal in turfgrass management, and WUE may not be related to turf quality (Mehall et al., 1984; Shearman, 1985). Under heat stress or limited soil moisture, however, WUE could potentially be used to screen for improved performance under stressful environmental conditions (Ebdon et al., 1998; Ebdon and Kopp, 2004). Most WUE estimates in turfgrass have been made using clipping dry weight and water use over a period of time. Although instantaneous measurements of WUE using gas exchange instrumentation have been reported in ecological or agronomic studies (Adam et al., 2000; Griffin et al., 2004; Kadir et al., 2006), we could find no such papers relating to turfgrasses.

Stomatal conductance (g_c) is closely related to photosynthesis, and also may be a fundamental indicator of plant stress and growth (Jiang and Huang, 2000; Blonquist et al., 2009;

Hu et al., 2009). Measurements of stomatal conductance have been used to determine the effects on heat and drought on turfgrass (Jiang and Huang, 2000; Hu et al., 2009). Ribeiro et al. (2006) measured diurnal trends in leaf level stomatal conductance in a bahiagrass (*Paspalum notatum* Fluegge) lawn and found that stomatal conductance was influenced by leaf-to-air vapor pressure deficit and photosynthetic photon flux density.

In turfgrasses, stomatal conductance measurements have been reported from leaf level measurements (Hu et al., 2009; Ribeiro et al., 2006). However, leaf-level measurements of stomatal conductance are not likely accurate representations of the entire canopy (Hunt, 2003). The new custom chamber, which was described in Chapter 3, presents an opportunity to conduct such investigations in turfgrass because it provides estimates of the integrated stomatal conductance at the canopy scale.

Development of the chamber described in Chapter 3 allowed for investigation into basic processes of photosynthesis, respiration, evapotranspiration, and stomatal conductance in field environments. The location of Manhattan, Kansas in the transition zone of the United States also offered an opportunity to compare the performance of C_3 (cool season) and C_4 (warm season) turfgrasses, which are both grown there. Heat stress is common among cool-season turfgrasses during summers in the transition zone, while warm-season grasses may suffer from cold temperatures during winter (Dunn and Diesburg, 2004).

In this study, the chamber described in Chapter 3 was used to: 1) measure instantaneous CO_2, water vapor fluxes, and WUE in two warm-season and two cool-season turfgrasses during hot midsummer and cooler late summer days; and 2) estimate stomatal conductance to water vapor flux at canopy scale in the same turfgrasses.

Materials and Methods

A field study was conducted at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas (Rocky Ford; lat. 39°13’53” N, long. 96°34’51” W). Diurnal measurements were taken with the chamber on DOY 216 (4 Aug. 2008) and DOY 262 (19 Sept. 2008) on well-watered tall fescue, Kentucky bluegrass, zoysia, and bermuda plots, all maintained at a height of 9.3 cm. Additional measurements were taken at solar noon on DOY 217 (5 Aug. 2008).

Gross photosynthesis in each plot was estimated from measurements of photosynthesis and respiration using the chamber described in Chapter 3 according to the method of Bremer and

Ham (2005). Briefly, this method involves consecutive measurements with a sunlit and shaded chamber, respectively, at each location; shaded measurements were obtained by covering the chamber with an opaque cardboard shell that blocked solar radiation from the chamber. Using Eq. [5] and [6] from Bremer and Ham (2005), sunlit measurements were used to determine Pg - (Rc+Rs) and the shaded chamber measurements to determine Rc + Rs, where Pg is gross photosynthesis, Rc is canopy respiration, and Rs is residual soil respiration; all values are positive and units are μmol m^{-2} s^{-1}. Gross photosynthesis was calculated using their Eq. [8]: Pg=sunlit chamber + shaded chamber.

Water vapor flux, or ET and g_c were also measured with the chamber as described in Chapter 3. Instantaneous water use efficiency (WUE) was calculated from chamber measurements by dividing photosynthetic rates, determined from the (sunlit chamber measurements) by evapotranspiration (resulting units were μmol CO_2 mmol H_2O^{-1}). Volumetric soil water content (θ_v) in the 0 to 15 cm profile was measured on sampling dates using TDR (model 6050XI, Soilmoisture Equipment, Santa Barbara, CA). Climatological variables were measured at a weather station located at Rocky Ford Turfgrass Research Center.

Data Analysis

Data of Pg, θ_v, g_c, and WUE were analyzed using the mixed models procedure in SAS as a completely random design (SAS Institute, 2002). Means were separated using Fisher's protected least significant difference (LSD) at p = 0.05. Regression analysis was calculated between Pnet and PAR and between ET and PAR using Sigmaplot (Systat Software, Inc., San Jose CA).

Results and Discussion

Fluxes of carbon dioxide

Gross Photosynthesis

Midday measurements of Pg revealed a seasonal change from DOY 217 (Aug. 15) to 262 (Sept. 19) in both cool season grasses. Cool season grasses Pg increased 43% between DOY 217 and 262, while the warm season grasses had a 52% decrease in Pg (Fig 5.1A). These changes in Pg were likely a result of the 12.6 °C decrease in air temperature. More generally, however, the changes in Pg among treatments from the hotter DOY 217 to cooler DOY 262 were probably caused by the respective carbon fixation pathways in cool and warm-season grasses (Fry and Huang, 2004). Warm-season C_4 turfgrasses have a higher optimum temperature range for photosynthesis than cool-season C_3 turfgrasses (Salisbury and Ross, 1991). Although the warm-season turfgrasses showed no visible signs of dormancy on DOY 262 (data not shown), measurements of Pg indicated a marked decrease in the photosynthetic capacities of their canopies compared to earlier in the summer (DOY 217). The differences in Pg among the species, while undoubtedly affected by their photosynthetic pathway (i.e., C_3 vs. C_4), may also have been affected by differences in θ_v (Fig. 5.1B). For example, on DOY 217 Pg and θ_v were lower in Kentucky bluegrass than in tall fescue. Similarly, Pg and θ_v were lower in zoysia than in bermuda.

On both sampling dates, differences in Pg were detected among the turfgrass species (Fig. 5.1A). Cool season grasses had lower Pg than warm season grasses on DOY 217 (Aug), although zoysia (warm season grass) and tall fescue (cool season grass) were statistically similar (Fig. 5.1A). The Pg for the warm-season grasses averaged 2.7 times greater than for the cool season grasses. Bermuda had the highest Pg and was almost 5 times the value of Kentucky bluegrass, which had the lowest Pg.

Temperature stress may have contributed to the differences in Pg between warm and cool season grasses on DOY 217; air temperature was greater than 36 °C at sampling. Jiang and Huang (2000) reported that Pn decreased quickly, within 3 days, in Kentucky bluegrass subjected to heat stress of 35 °C /30 °C day/night temperature. Heat stress has also been reported to reduce Pg 30% in Kentucky bluegrass and 27% in tall fescue compared to control plots with no heat or drought stress (Su et al., 2007).

Later in the summer, on DOY 262 (Sept.), Pg in the warm-season turfgrasses had decreased considerably but nevertheless remained comparable to Pg in the cool season grasses; Pg was ~27 $\mu mol^{-2}\ m^{-2}$ in tall fescue and bermuda, 12 $\mu mol^{-2}\ m^{-2}$ in zoysia, and 20 $\mu mol^{-2}\ m^{-2}$ in Kentucky bluegrass (Fig. 5.1A). Measurements of Pg in tall fescue and Kentucky bluegrass were comparable to Pg reported in other chamber studies (Bremer and Ham, 2005; Su et al., 2007; 2008; 2009). Interestingly, in the warm season grasses Pg was over twice as high in bermuda than in zoysia despite greater θ_v in zoysia. Bermuda may have a higher Pg than zoysia when θ_v is not limiting and other environmental factors are equal. Bermuda has a faster rate of growth than zoysia and therefore, bermuda would require more carbon fixation for growth (Turgeon, 1999; Christians, 2007).

CO_2 Flux Diurnals

Diurnal measurements of CO_2 fluxes (Pnet) with the uncovered (sunlit) chamber on DOY 216 (Aug. 15) and 262 (Sept. 19) revealed increases in CO_2 flux with PAR (Figs. 5.2 and 5.3). Diurnal measurements of CO_2 flux during mid-summer, on DOY 216, indicated stronger responses to light in the warm-season grasses (zoysia and bermuda) than in the cool-season grasses (tall fescue and Kentucky bluegrass) (Fig. 5.2). Maximum CO_2 fluxes were 3 times greater in warm- than in cool-season grasses on DOY 216, and maximum CO_2 flux was lowest in Kentucky bluegrass. Maximum CO_2 fluxes in cool season grasses were 10.6 μmol m^{-2} s^{-1} in tall fescue and only 3.2 μmol m^{-2} s^{-1} in Kentucky bluegrass. In the warm season grasses, maximum CO_2 fluxes were 18.4 μmol m^{-2} s^{-1} in zoysia and 25.2 μmol m^{-2} s^{-1} in bermuda. Lower θ_v in zoysia may have reduced its maximum CO_2 fluxes relative to tall fescue and bermuda(data not shown). All maximum CO_2 fluxes were measured when PAR ~1800 μmol m^{-2} s^{-1}.

By DOY 262, responses of Pnet to light had weakened in warm-season grasses, and maximum CO_2 fluxes had declined by 18% in zoysia and 24% in bermuda from DOY 216 (Figs. 5.2 and 5.3). Maximum CO_2 fluxes were 14.0 μmol m^{-2} s^{-1} in zoysia and 20.6 μmol m^{-2} s^{-1} in bermuda on DOY 262 (Fig. 5.3). In the cool-season grasses, responses of Pnet to light and maximum CO_2 fluxes were greater on DOY 262 than 216 (Figs. 5.2 and 5.3), indicating a favorable response to cooler temperatures; air temperature at sampling was 33 °C on DOY 216 and 19 °C on DOY 262. Maximum CO_2 fluxes for the cool season grasses increased by 49% (20.7 μmol m^{-2} s^{-1}) and 80% (16.4 μmol m^{-2} s^{-1}) for tall fescue and Kentucky bluegrass, respectively, between DOY 216 and 262.

Much of the previous research on diurnal light measurements has focused on light saturation. In a laboratory chamber study, light saturation at 21 ^{o}C was at a photosynthetic photon flux density of about 500-600 μmol m^{-1} s^{-1} in Kentucky bluegrass (Gaussoin et al., 2005). In another leaf level study, tall fescue reached light saturation at 1200 to 1500 μmol m^{-1} s^{-1} (Allard et al., 1989). Ribeiro et al. (2006) reported a maximum assimilation of ~30 μmol m^{-1} s^{-1} at a PAR of ~ 1700 μmol m^{-2} s^{-1} in the warm-season bahiagrass. We were unable to find any citations related to levels of light saturation for bermuda and zoysia. Our measurements were not made at a high enough resolution to make accurate determinations on light saturation. Soil respiration in our chamber may have confounded apparent light saturation as well. However, both the cool season and warm season exhibited light responses typical of their respective C_3 and C_4 photosynthetic pathways (Fry and Huang, 2004) (Fig. 5.2). Specifically, warm-season grasses have C_4 metabolism with typically higher light saturation and compensation points than cool-season C_3 plants (Salisbury and Ross, 1991).

Water vapor fluxes

Evapotranspiration Diurnals

Evapotranspiration generally increased linearly with PAR for all species on DOY 216 and 262 (Figs. 5.4 and 5.5). On DOY 216 under mid-day PAR of ~ 1800 μmol m^{-2} s^{-1}, Kentucky bluegrass had the highest ET rate (20.8 mmol m^{-2} s^{-1}) among species (Fig. 5.4). In tall fescue, the increase in ET with PAR was confounded by time of day on DOY 216, suggesting a sort of hysteretic effect. On DOY 216, ET in tall fescue was considerably lower at 1100 CST than at 1300 CST, despite having similar PAR (~1800 μmol m^{-2} s^{-1}) at both times. This transient response, however, was not observed in tall fescue on DOY 262 (Fig. 5.5). Bermuda had a higher mid-day ET rate than zoysia on DOY 217, or 16.3 and 13.0 mmol m^{-2} s^{-1}, respectively. This may have been because of lower θ_v in zoysia than bermuda (Fig. 1). The maximum ET values for all the species were about 46% lower on DOY 262 compared to DOY 217, probably because of lower air temperatures and solar radiation (Figs. 5.4 and 5.5). On DOY 262, Kentucky bluegrass had the highest ET at 12.6 mmol m^{-2} s^{-1}, then bermuda, zoysia and tall fescue at 9.0, 6.7, and 6.4 mmol m^{-2} s^{-1}, respectively.

Conductance and WUE

Canopy Conductance

Canopy conductance on DOY 216 (Aug.) averaged higher in the cool season grasses than the warm season grasses (Fig. 5.6). Average daily canopy conductances were: 3.22, 4.47, 1.88, and 0.87 cm s^{-1} in Kentucky bluegrass, tall fescue, bermuda, and zoysia, respectively. Generally, stomatal conductance increased quickly in the morning and then decreased later in the afternoon, although this pattern was not as pronounced in zoysia or bermuda. A similar pattern for whole plant conductance was described by Bremer et al. (1996) and Blonquist et al. (2009). This illustrates how the plant experiences greater water or heat stress as the day progresses. Wang and Huang (2003) found that in drought-tolerant Kentucky bluegrasses subjected to drought stress, gs declined less than in drought-susceptible cultivars. Also selecting plants with rapid closure of stomata during the early phases of drought stress may result in water savings (Hu et al., 2009).

The g_c in Kentucky bluegrass peaked at 900 CST, and was higher than any other species at that time. Thereafter g_c declined, possibly because of heat stress later in the day. In tall fescue, g_c peaked later in the day. Tall fescue probably had greater access to soil water because of its deeper rooting (Fry and Huang, 2004; Su et al., 2008), which may have minimized plant stress and allowed maintenance of a higher gc during the hottest part of the day. The low gc in zoysia compared to bermuda may have been the result of lower θ_v in zoysia on DOY 217; θ_v was 20 v v^{-1} in zoysia and 32 v v^{-1} in bermuda.

Water Use Efficiency

Midday measurements of instantaneous WUE on DOY 217 and 262 revealed seasonal changes in WUE among the grasses (Fig. 5.7). In general, WUE was greater in the warm- than the cool-season grasses on DOY 217, when air temperatures were higher. Later in the season as air temperatures decreased, WUE increased in the cool season grasses and became statistically similar to warm season grasses.

The warm-season grasses did not show as large of a change in WUE from DOY 217 (Aug.) to DOY 262 (Sept.) as the cool-season grasses although WUE increased by 158% in bermuda and 46% in zoysia. The increase in WUE in bermuda and zoysia is somewhat surprising because their respective Pg had declined from Aug. to Sept.; apparently the respective ET decreased greater still proportionally (Fig. 5.1).

Instantaneous WUE increased several fold in Kentucky bluegrass and tall fescue from DOY 217 (Aug.) to DOY 262 (Sept.) (Fig. 5.7). On DOY 217 the WUE of Kentucky bluegrass was negative, and the WUE of tall fescue was low, possibly from deleterious effects of high air temperatures (>35°C) on photosynthesis and θ_v less than 28% (Figs. 5.1 and 5.7). Cooler air temperatures on DOY 262 probably resulted in greater WUE in Kentucky bluegrass and tall fescue than earlier in the growing season (DOY 217). Cool-season C_3 turfgrasses have an optimal temperature range of 20-25°C for photosynthesis; air temperature on DOY 262 was 24^{o}C

(Fry and Huang, 1993). On DOY 217 when the warm season grasses had a higher WUE air temperature was 36°C, slightly higher than warm-season C_4 turfgrasses optimal range of 30-35°C for photosynthesis.

Conclusions

This study successfully demonstrated a number of applications for the chamber that would be useful when investigating various turfgrass stressors (e.g., drought, heat, cold, mowing height, pests). For example, declining Pg rates in warm season grasses from mid to late summer were observed before visual symptoms of dormancy had appeared. We characterized Pnet and ET light response curves in the field, and measured g_s at the canopy level in the field, and differences in WUE were detected among grasses. Field studies about the effects of θ_v, including droughty conditions, on Pg, ET, g_c, and WUE in turfgrasses needs further investigation. In addition, the investigation into diurnal patterns of turfgrass photosynthesis and its parameters is warranted, in particular with more frequent measurements than was done in this study. The transient effects of soil respiration on diurnal Pnet measurements also needs to be evaluated. Finally, data collected with the chamber could be used for model development of photosynthesis and g_c in different turfgrasses, and improving irrigations scheduling by better detection of turfgrass stress.

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Figures

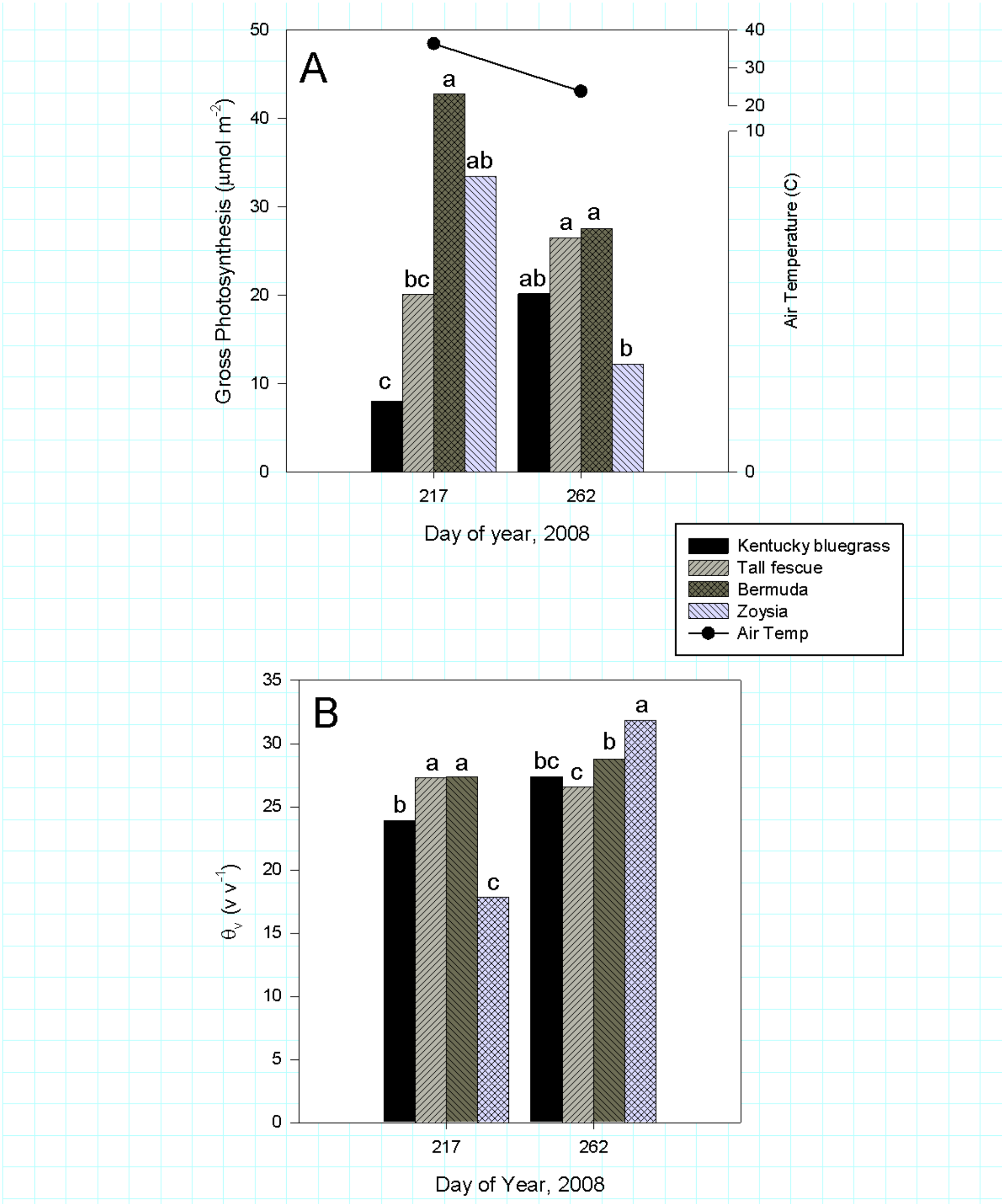

Figure 5.1 Seasonal measurements of gross photosynthesis (Pg) at midday and volumetric soil water content (θ_v) in the 0 to 15 cm profile in Kentucky bluegrass, tall fescue, bermuda and zoysia. Air temperature was measured at 2 m. Means with the same letters within each date are not significantly different (P=0.05).

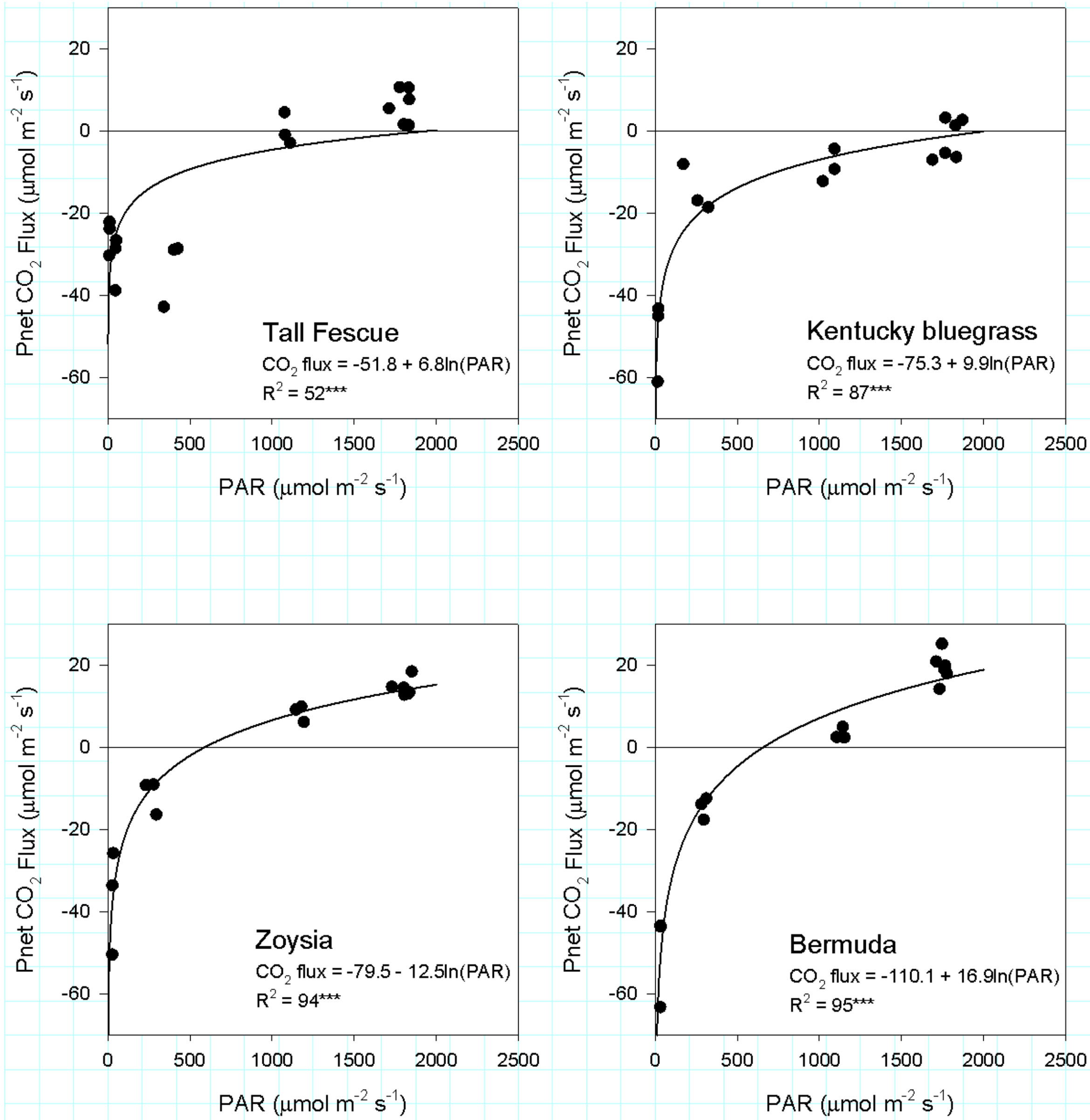

Figure 5.2 Measurements and regression lines for diurnal CO_2 flux measurements (Pnet) taken on DOY 216 in tall fescue, Kentucky bluegrass, zoysia and bermuda.

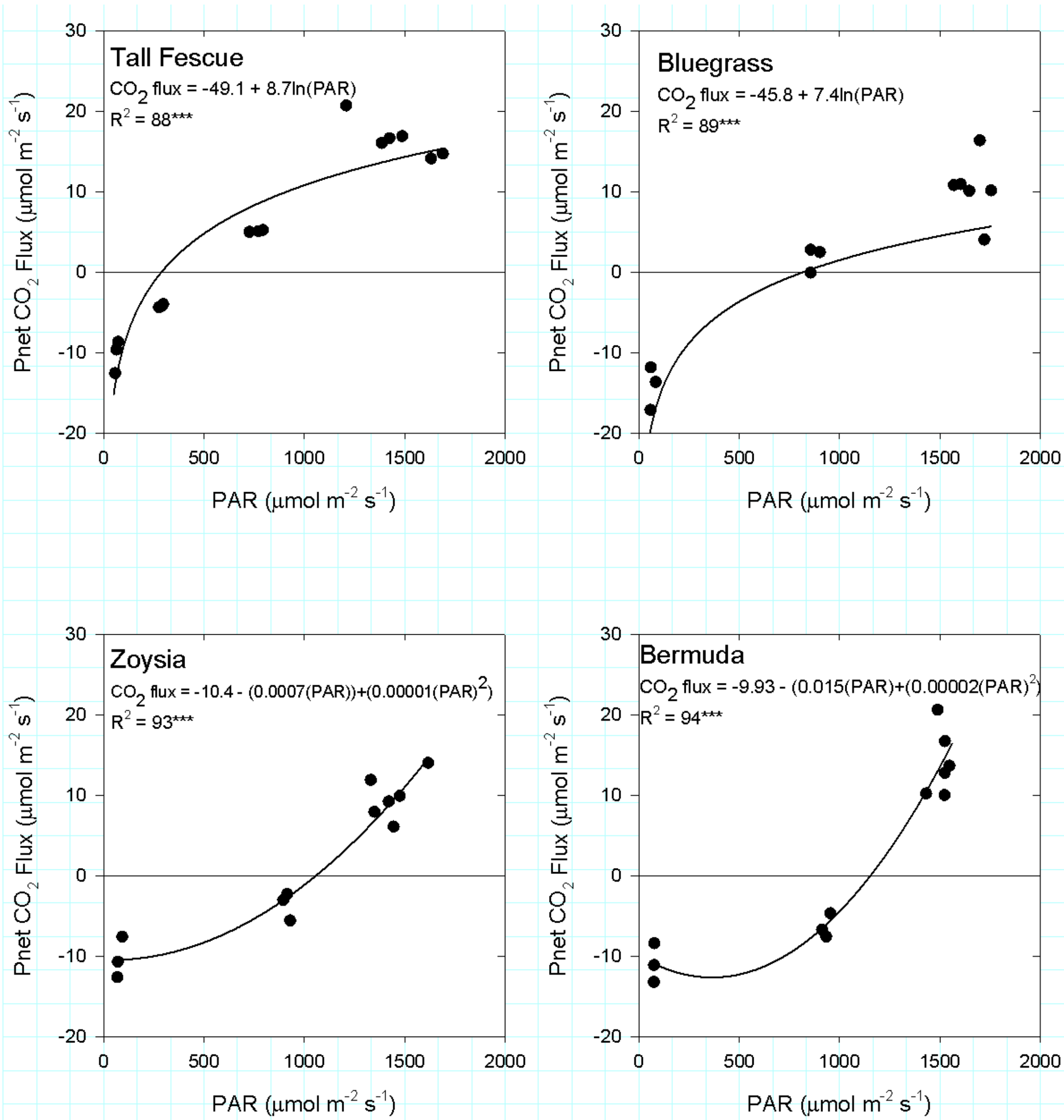

Figure 5.3 Measurements and regression lines for diurnal CO_2 flux measurements (Pnet) taken on DOY 262 in tall fescue, Kentucky bluegrass, zoysia and bermuda.

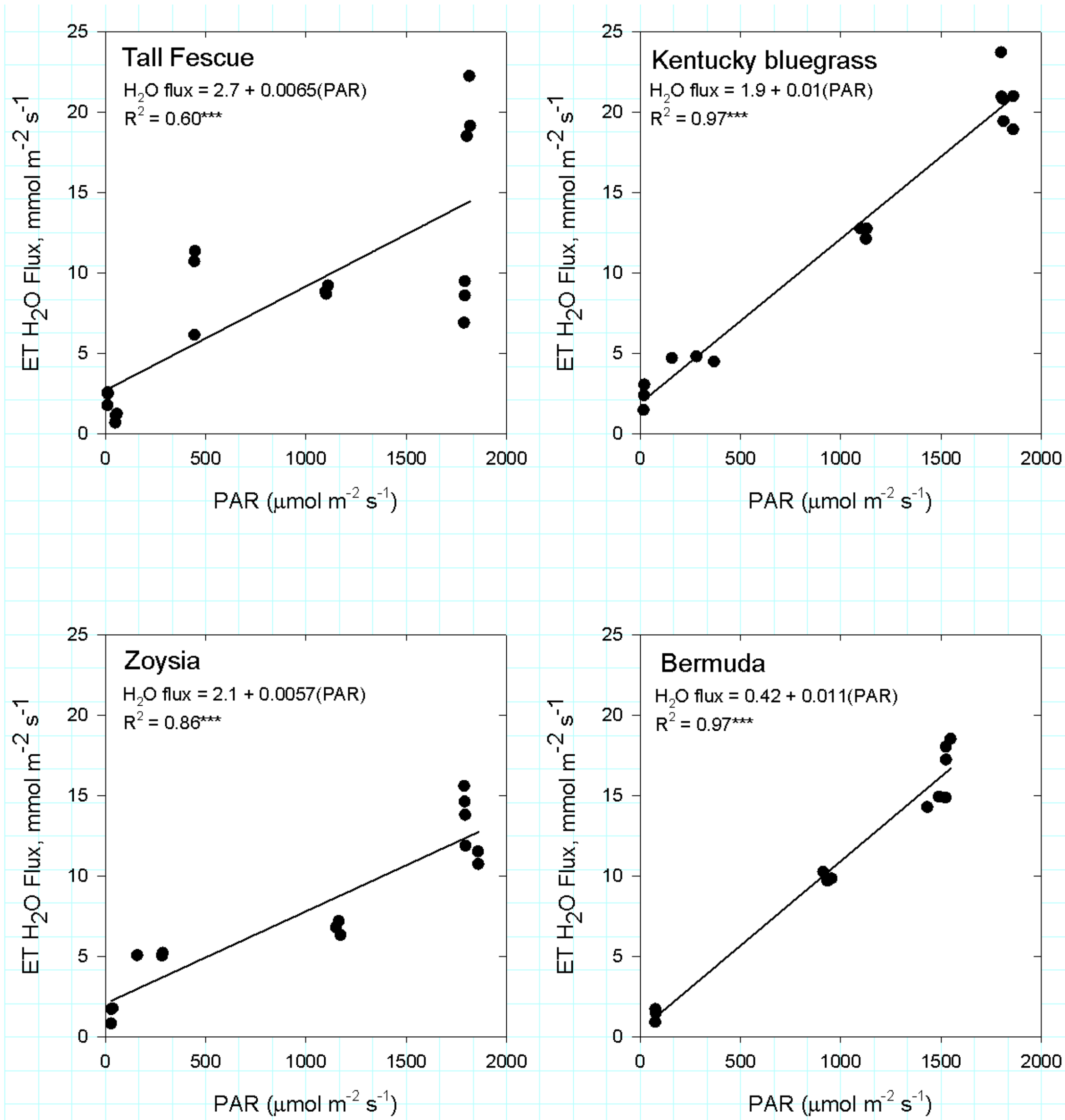

Figure 5.4 Measurements and regression lines of diurnal H_2O fluxes (ET) on DOY 216 in tall fescue, Kentucky bluegrass, zoysia and bermuda.

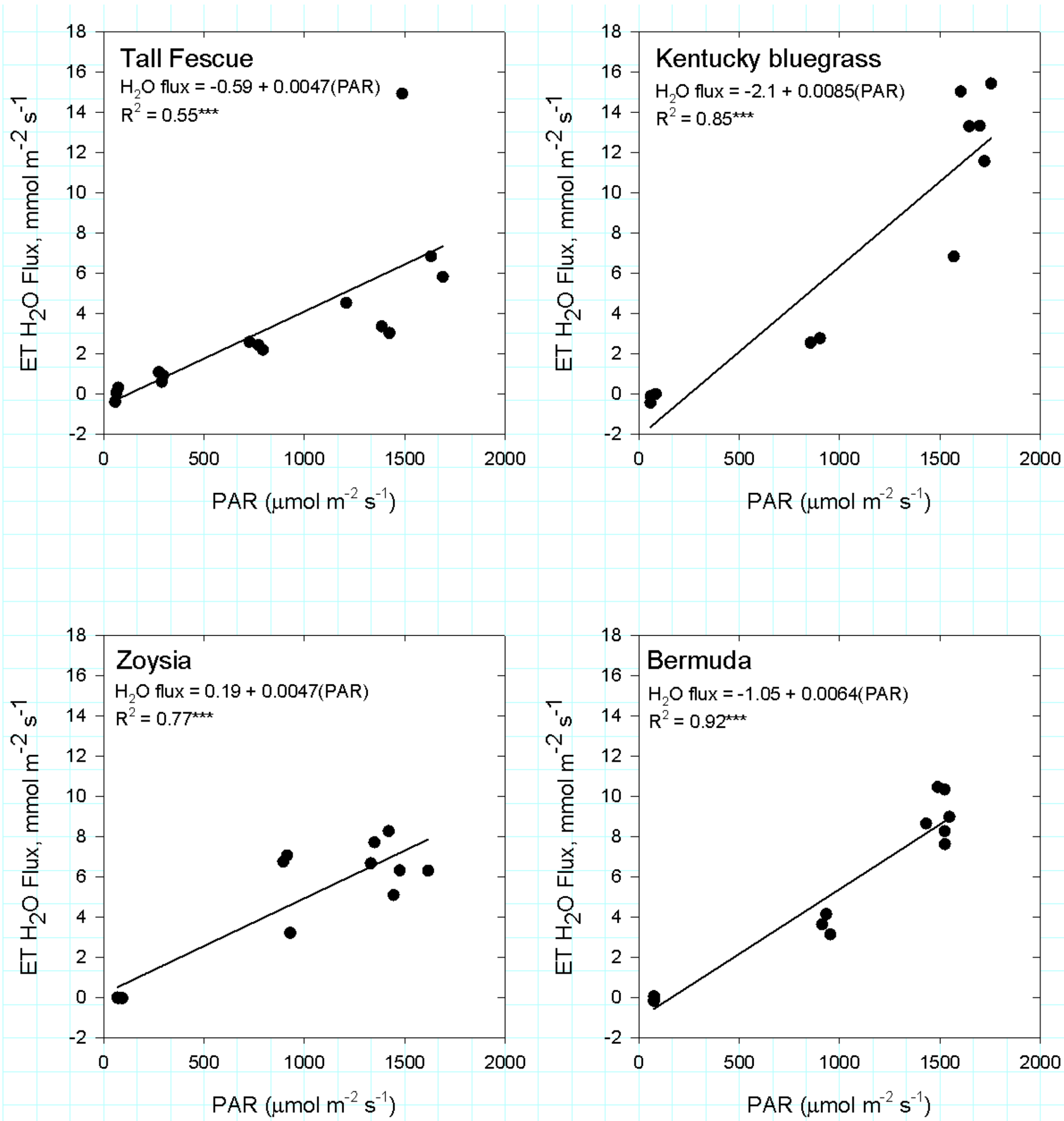

Figure 5.5 Measurements and regression lines of diurnal H_2O fluxes (ET) on DOY 262 in tall fescue, Kentucky bluegrass, zoysia and bermuda.

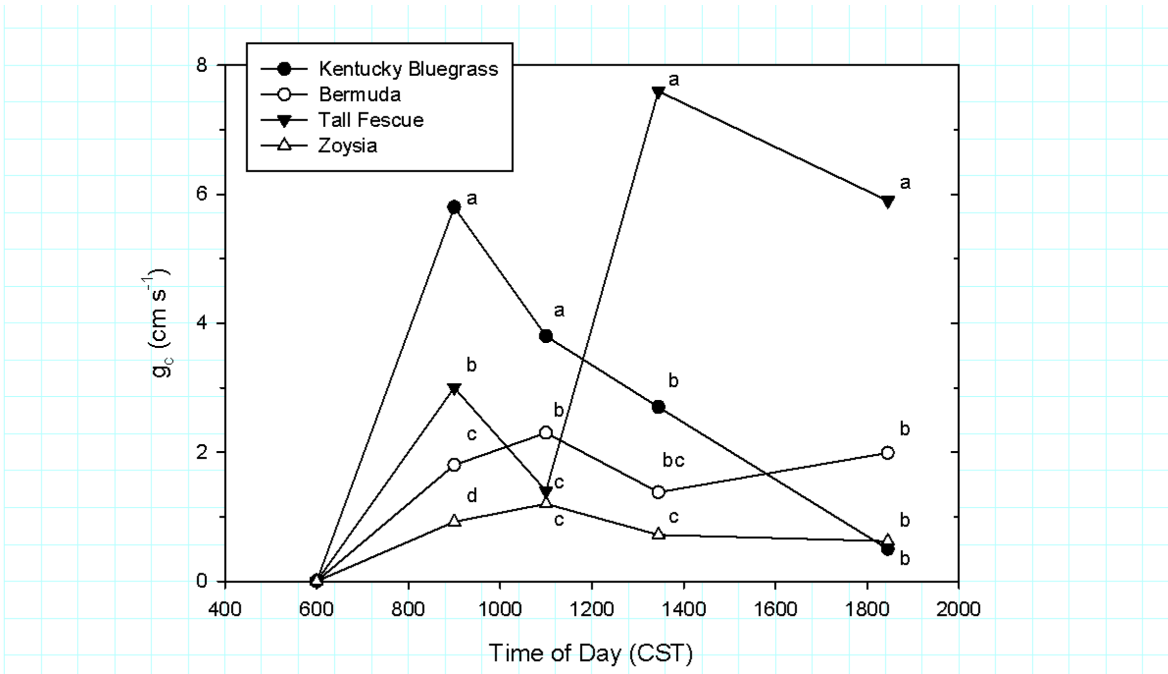

Figure 5.6 Diurnal estimates of canopy conductance (g_c) on DOY 216 in Kentucky bluegrass, bermuda, tall fescue, and zoysia. Means with the same letter within each time are not significantly different (P=0.05).

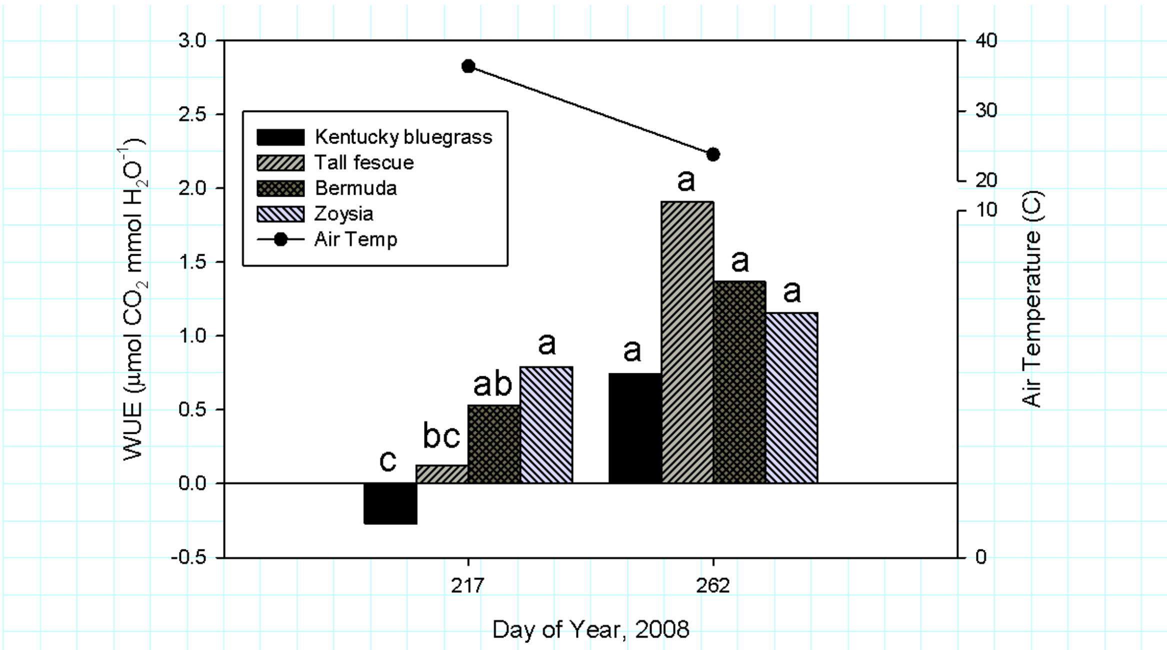

Figure 5.7 Seasonal measurements of water use efficiency (WUE) collected at mid-day in Kentucky bluegrass, tall fescue, bermuda, and zoysia. Air temperature was measured at 2 m. Means with the same letters within each date are not significantly different (P=0.05).

Appendix A - Measurements of Photosynthesis in Kentucky Bluegrass during a Progressive Drought with a Custom Surface Chamber

Introduction

Drought is a limiting factor for turfgrass growth and quality. This is certainly true for Kentucky bluegrass (*Poa pratensis* L.) KBG, which is commonly used in home and commercial lawns, on golf course roughs and fairways, and in sports fields. Significant ranges in water use have been observed in cultivars of KBG in experiments conducted in growth chambers, greenhouses, and lysimeter-based field studies (Steinegger et al., 1980; Shearman 1986; Ebdon et al., 1998a, 1998b, and 1998c; Abraham et al., 2004). Cultivars of KBG that have lower stomatal resistance and maintain cooler canopy temperatures tolerate summer heat stress better than cultivars with higher stomatal resistance and canopy temperatures (Bonos and Murphy, 1999). However, greater conductance results in increased water use, which may not equate to better drought resistance. In addition KBG cultivars that were classified as summer stress tolerant extracted more water in the 15 to 30 cm depth (Bonos and Murphy, 1999). However, responses of canopy photosynthetic capacity, evapotranspiration (ET), and canopy stomatal conductance (g_C) to soil drying among diverse KBG cultivars have not been investigated. Knowledge about physiological responses to drought stress could lead to better understanding of drought tolerance in KBG cultivars and useful in drought screening.

The objectives of our study were to characterize gross photosynthesis (Pg), ET, canopy stomatal conductance (g_C), and water use efficiency (WUE) of 5 cultivars of KBG during a dry down using our custom surface chamber. Ancillary measurements of volumetric soil water content (θ_v) were collected at 5 and 20 cm.

Materials and Methods

A field study was conducted from in the summer of 2009 under an automated rainout shelter (12 by 12 m) at the Rocky Ford Turfgrass Research Center near Manhattan, KS (39º13’53” N, 96º34’51”W). Plots measuring 1.13 by 0.61 m were bordered by metal edging (10 cm depth) to prevent lateral soil water movement. Established KBG were well watered until DOY 216, 2009. The 5 cultivars used were Apollo, Baron, Kenblue, Nu Destiny; additionally the Texas bluegrass hybrid (*P. pratensis* x *P. arachnifera* Torr.) Thermal Blue Blaze was included. Cultivars were selected to represent the wide range of water requirements in 2007 from the study described in Chapter 4. Irrigation was halted on DOY 216, 2009 and plots were allowed to dry down until DOY 242, 2009. Plots were then allowed to recover with irrigation until DOY 263, 2009 when the second dry-down cycle started, this dry-down lasted until DOY 323, 2009.

Gross photosynthesis in each plot was estimated from measurements of photosynthesis and respiration using the chamber described in Chapter 3 according to the method of Bremer and Ham (2005), which was also described briefly in Chapter (final chapter that described measurements in 2 cool and 2 warm season grasses). Evapotranspiration and g_c were measured with the chamber. Instantaneous water use efficiency was calculated from chamber measurements by dividing photosynthetic rates, determined from the (sunlit chamber measurements) by evapotranspiration (resulting units were μmol CO_2 mmol H_2O^{-1}). A negative WUE indicated that the canopy had a net loss CO_2, or that the sum of canopy and soil respiration was greater than Pg. All chamber measurements were made at mid-day on clear days.

Volumetric soil water content and temperature at 5 cm and 20 cm were measured automatically using dual-probe heat-pulse technique (Campbell et al., 1991; Tarara and Ham, 1997; Song et al., 1998). Sensors were fabricated in the laboratory as described by Basinger et al. (2003) and Bremer (2003). Measurements of WFP were logged twice daily and soil temperature was logged every 60 min. All data acquisition and control were accomplished with a micrologger and accessories (CR10x and one AM16/32 Campbell Scientific, Logan, UT). Bulk density of the soil at 5 cm was 1.35 g cm^{-3} (determined from volumetric samples 5.4 cm diam. by 3 cm) and organic matter was 4% (Soil Testing Laboratory, Kansas State University).

Measurements of Pg, ET, g_c, and WUE were analyzed by the mixed model (mixed) procedure in SAS, and means were separated using Fisher's protected least significant difference (LSD) at $p = 0.05$ (SAS Institute Inc., 2002).

Results

Dry Down 1

Measurements of Pg decreased 72% for all cultivars during the 26 day dry-down (Fig. A.1). Apollo consistently had higher Pg than the other cultivars. Conversely, Baron consistently had lower Pg than the other cultivars. Despite no irrigation for 26 days, Pg values never reached 0, which would indicate the canopy had stopped assimilating CO_2.

Measurements of ET also decreased during the dry-down (Fig. A.2). Apollo had consistently higher ET than the other cultivars, while Baron and Nu Destiny consistently had lower values of ET than the other cultivars.

Measurements of g_c decreased during the drydown, and most rapidly during the first 10 days (Fig. A.3). On the first measurement date (DOY 216), g_c was similar among cultivars; high variability resulted in no statistical differences despite a wide range of g_c. By the second measurement date, however, differences had emerged among cultivars, with Apollo having the greatest g_s. After the first 2 measurement dates, Apollo and Thermal Blue Blaze consistently had the greatest g_s among cultivars, while Baron had the lowest g_c throughout the dry-down.

Changes in WUE over the dry-down varied, depending on the cultivar (Fig. A.4). In Apollo, WUE only decreased by 5%, while WUE in Baron and Nu Destiny decreased by about 90%. The cultivar Apollo maintained a positive WUE throughout the dry-down and was consistently higher than the other cultivars. Kenblue had positive values on 4 of the 6 dates measured. The cultivars Nu Destiny and Baron had negative WUE values for all dates after DOY 224, which was 8 days after the dry-down started.

Measurements of θ_v indicated that the KBG cultivars differed in the amounts of and rates at which they extracted water at 5 and 20 cm (Fig A.5). As with Pg, ET, and g_c, θ_v decreased with time during the dry-down. The values of θ_v decreased very quickly for all the cultivars at the 5 cm depth the first 7 days. After that, the cultivars Apollo and Baron extracted more water than the other cultivars at 5 cm (Fig A.5A).

Deeper in the soil, at 20 cm, θ_v values decreased slower than at 5 cm. The cultivar Thermal Blue Blaze and Baron extracted more water by the end of the dry-down than the other cultivars, θ_v decreased by 0.10 v v^{-1} in for both (Fig A.5B). Thermal Blue Blaze had the lowest at θ_v, 0.24 than the other cultivars at the end of the dry down. Kenblue extracted the least amount of water among cultivars, with θ_v decreasing by only 0.05 v v^{-1}.

Dry Down 2

Average Pg from all cultivars decreased 52% during the second dry-down (Fig. A.6). Apollo and Thermal Blue Blaze had higher Pg than the other cultivars at the end of the dry-down. The Pg in Baron decreased faster than the other cultivars and by the second measurement date (DOY 272) was significantly lower than the other cultivars. Thereafter, Baron remained consistently lower through the end of the drydown.

Evapotranspiration decreased for all cultivars during the dry-down (Fig. A.7). Kenblue and Thermal Blue Blaze consistently had higher ET rates during the last four measurement dates than the other cultivars. Conversely, Baron and Nu Destiny had lower ET rates. The ET rates of all the cultivars increased slightly from DOY 292 to 299, possibly because the rainout shelter failed to completely shield plots from precipitation on all dates. This may also have caused an uptick in Pg at about the same time (Fig. A.6).

The g_c decreased for all cultivars, until DOY 280. By DOY 292 it had leveled off or increased slightly among cultivars but then increased substantially by DOY 299 (Fig. 8). After DOY 299 g_c decreased again and became similar values of g_c on DOY 292. Thermal Blue Blaze had higher g_c values at the end of the dry-down, while Baron had the lowest.

The WUE remained positive for all the cultivars on all dates except for Baron on DOY 311 (Fig. A.9). Apollo had higher WUE than the other cultivars at the end of the dry-down, while Baron had lower WUE after the first sampling date.

The θ_v decreased during the dry-down, and KBG cultivars differed in their extraction of soil water (Fig. A.10). At 5 cm, Thermal Blue Blaze extracted very little soil water compared to the other cultivars (Fig. A.10A). In the cultivars other than Thermal Blue Blaze, θ_v decreased quickly for the first 15 days. Apollo had extracted the most soil water by the end of the dry-down.

Deeper in the soil profile, Apollo and Baron extracted the least amount of water, while Kenblue extracted the most by the end of the dry-down (Fig. A.10B).

The second dry-down cycle did not exhibit the decrease in Pg, g_c, and WUE to the extent that the first dry down did. It is possible this was the effect of cooler temperatures during the second dry-down. Additionally some rainfall may have unintentionally irrigated the plots on DOY 294 during a12 mm precipitation event, although the θ_v at 5 cm did not show an increase. Similar trends in the graphs indicate that Pg, ET, g_c, and WUE are interdependent.

Apollo consistently had the highest Pg, ET, and WUE, indicating that it would perform better under drought stress. Conversely, Baron consistently had the lowest values of Pg, ET, and WUE, indicating it would have worse performance under drought stress.

Figures

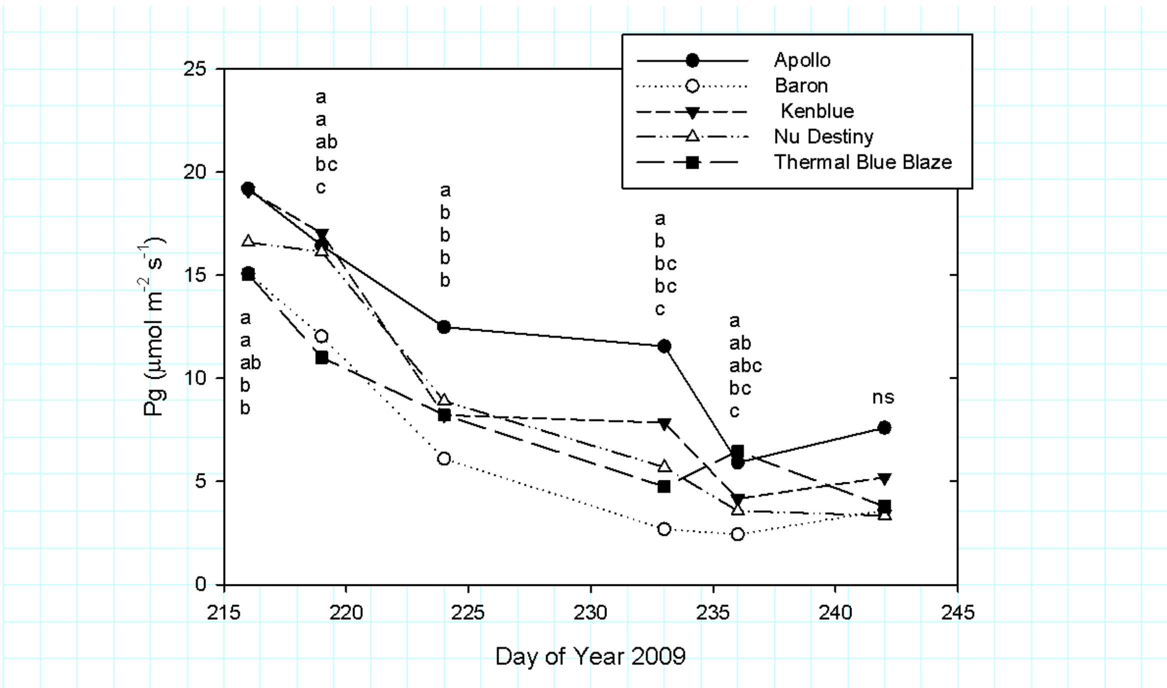

Figure A.1 Measurements of gross photosynthesis (Pg) at midday during dry-down 1 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

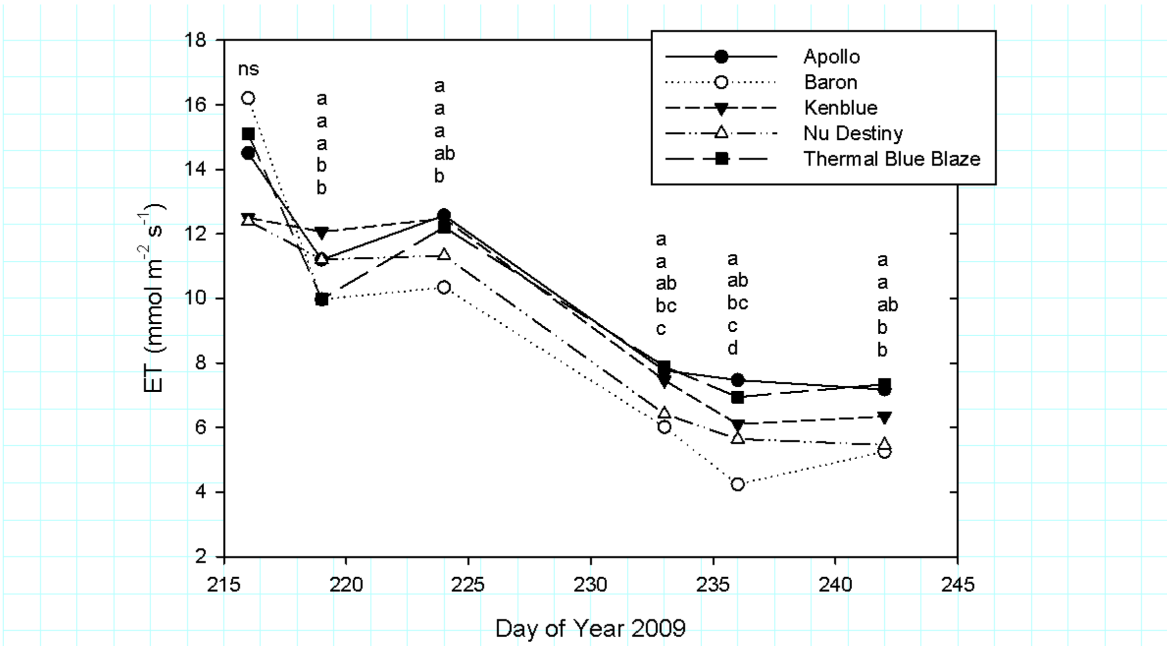

Figure A.2 Measurements of evapotranspiration (ET) at midday during dry-down 1 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

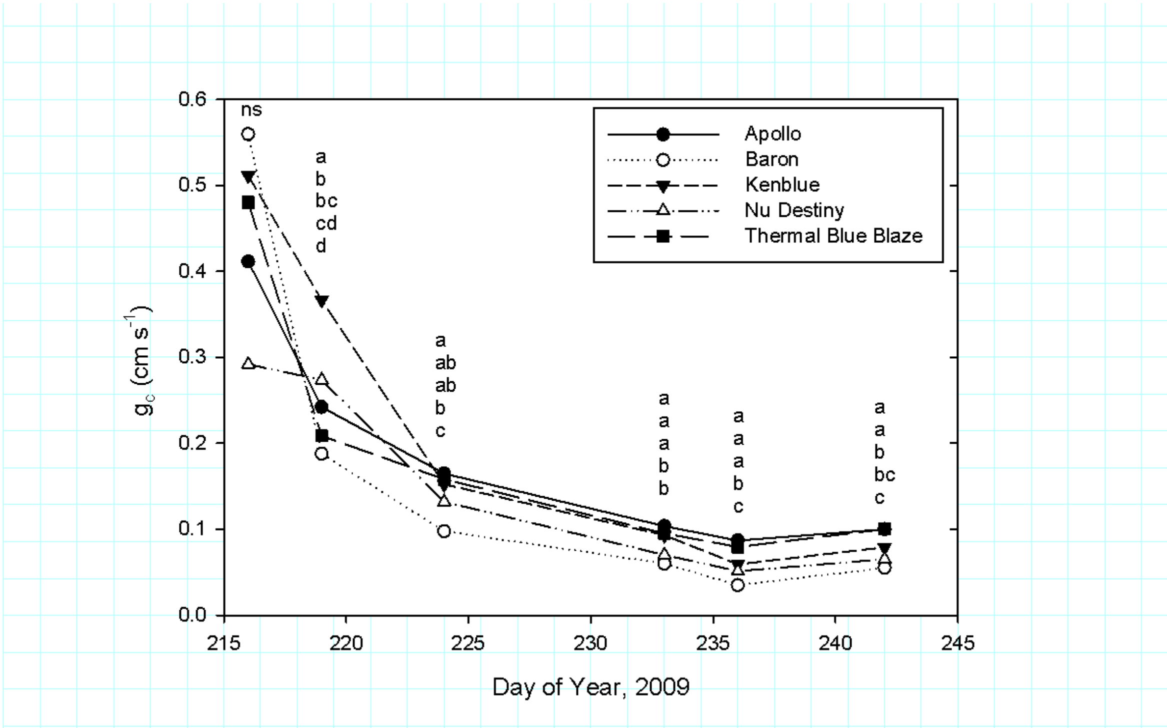

Figure A.3 Measurements of canopy stomatal conductance (g_s) at midday during dry-down 1 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

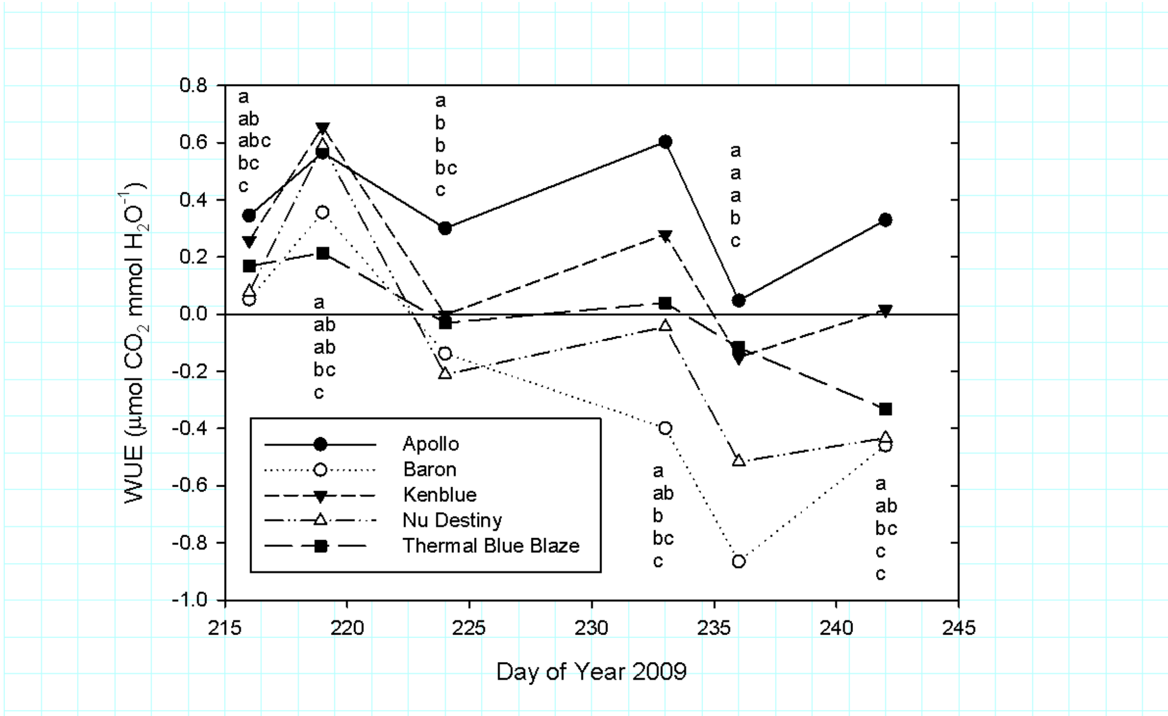

Figure A.4 Measurements of instantaneous water use efficiency (WUE) at midday during dry-down 1 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different ($p=0.05$).

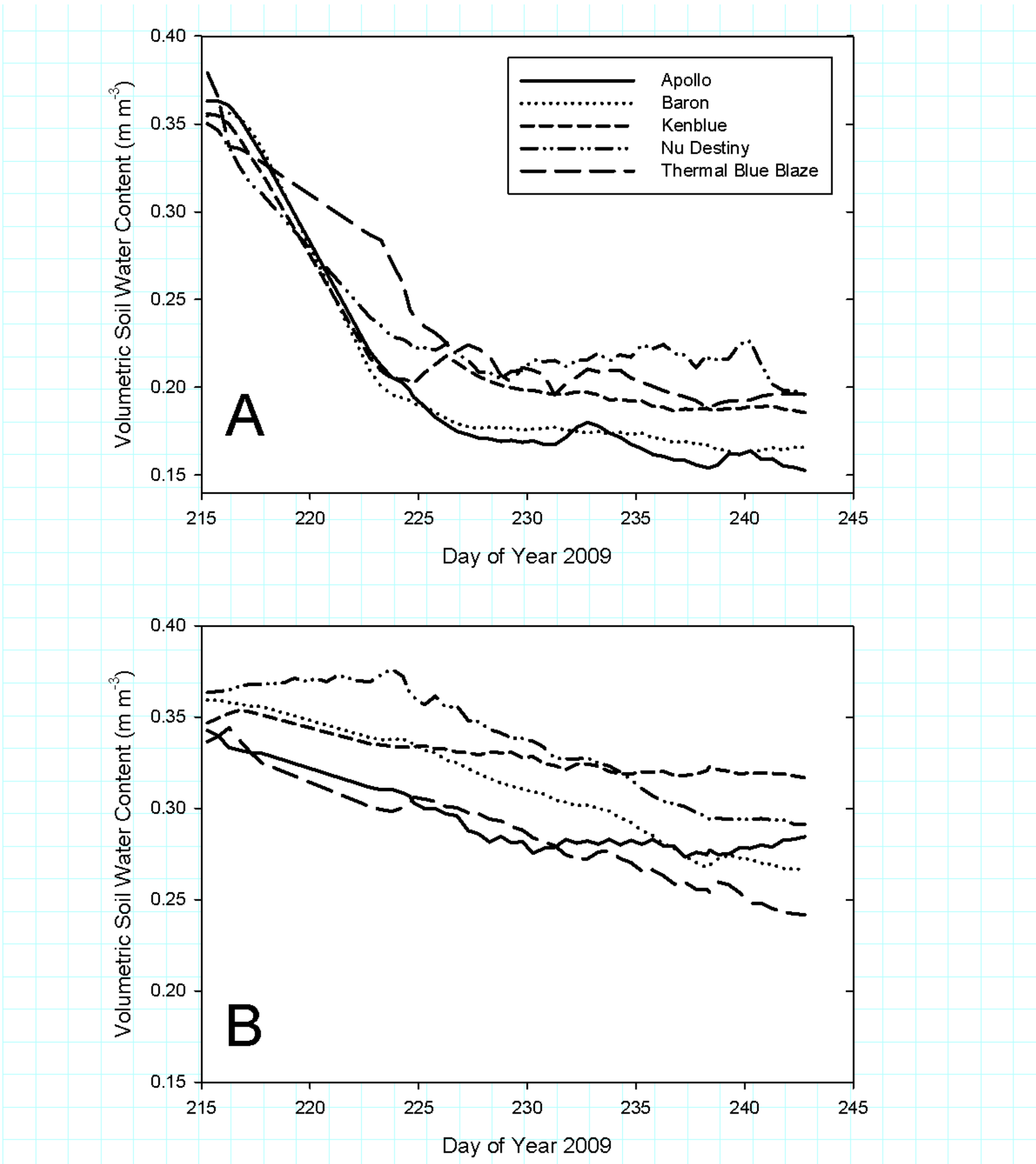

Figure A.5 Volumetric soil water content (θ_v) at 5 cm (A) and 20 cm (B) in cultivars of Kentucky bluegrass during dry-down 1.

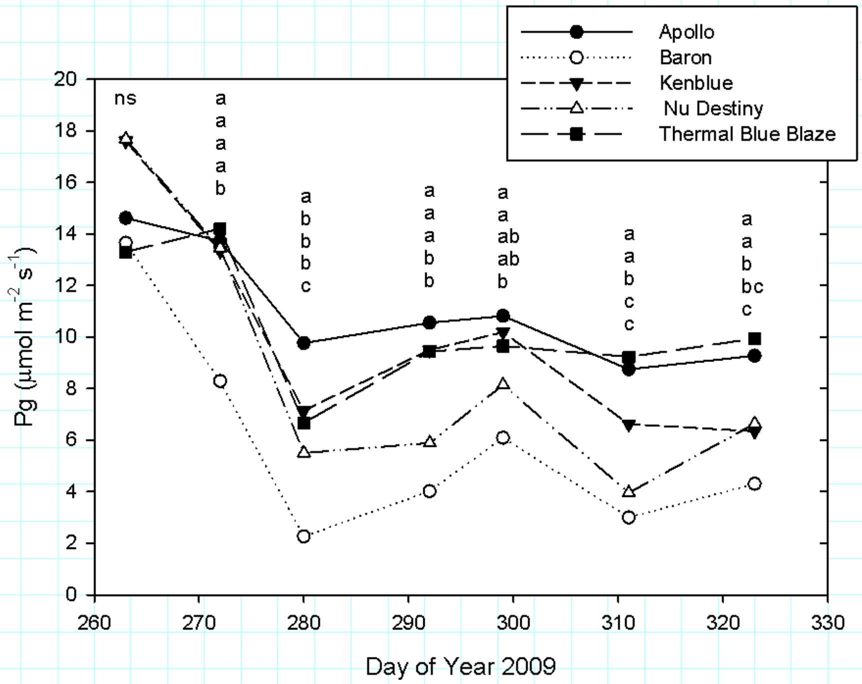

Figure A.6 Measurements of gross photosynthesis (Pg) at midday during dry-down 2 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

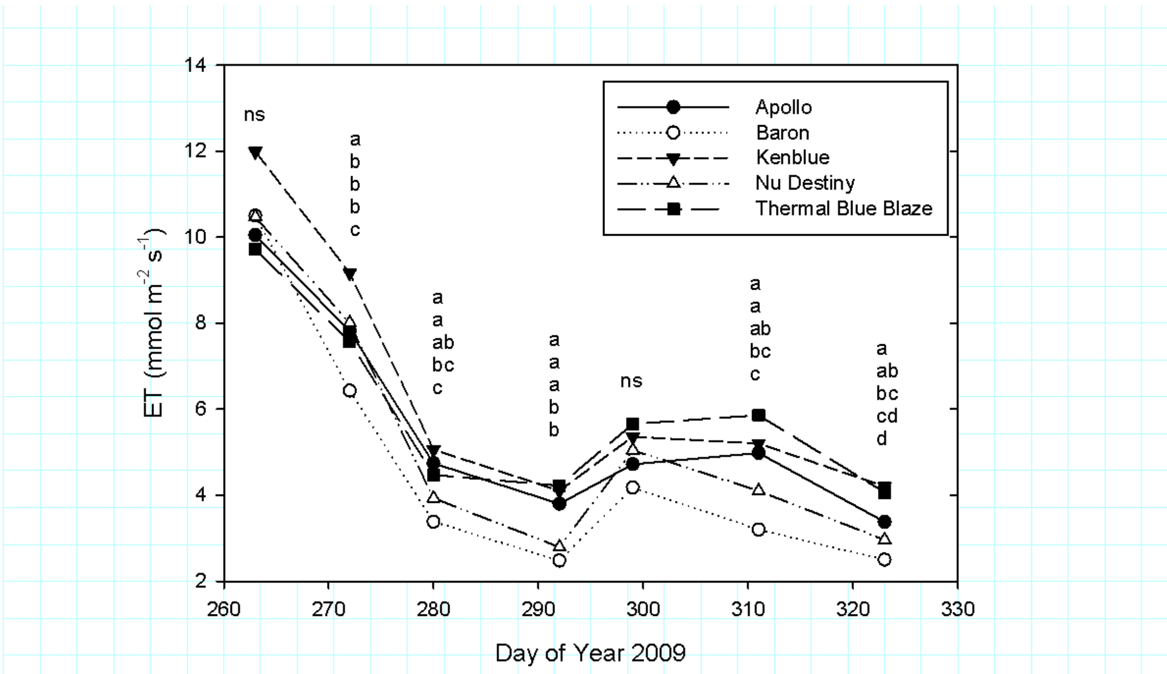

Figure A.7 Measurements of evapotranspiration (ET) at midday during dry-down 2 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

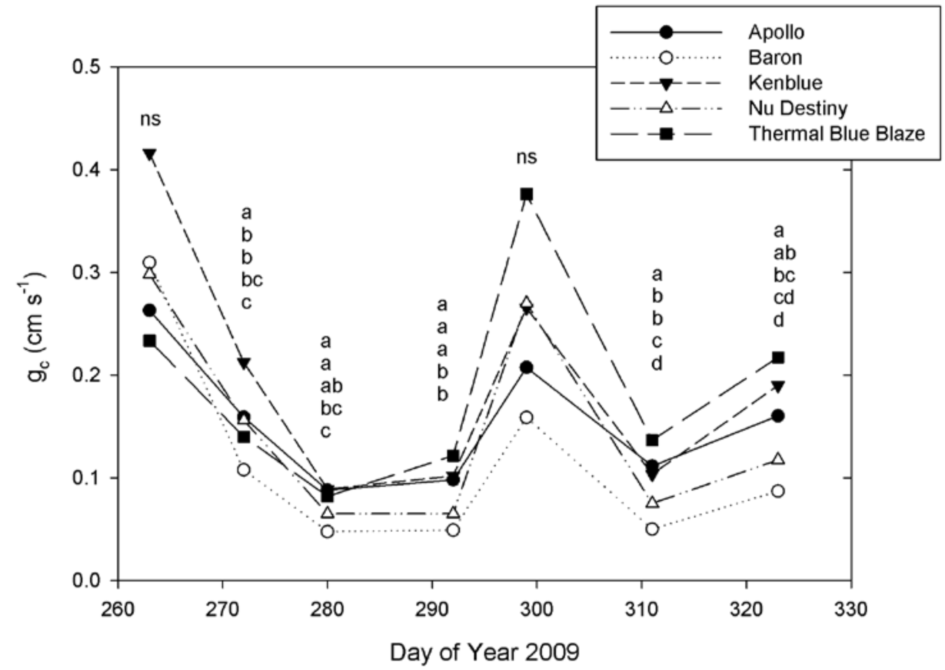

Figure A.8 Measurements of canopy stomatal conductance (g_s) at midday during dry-down 2 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

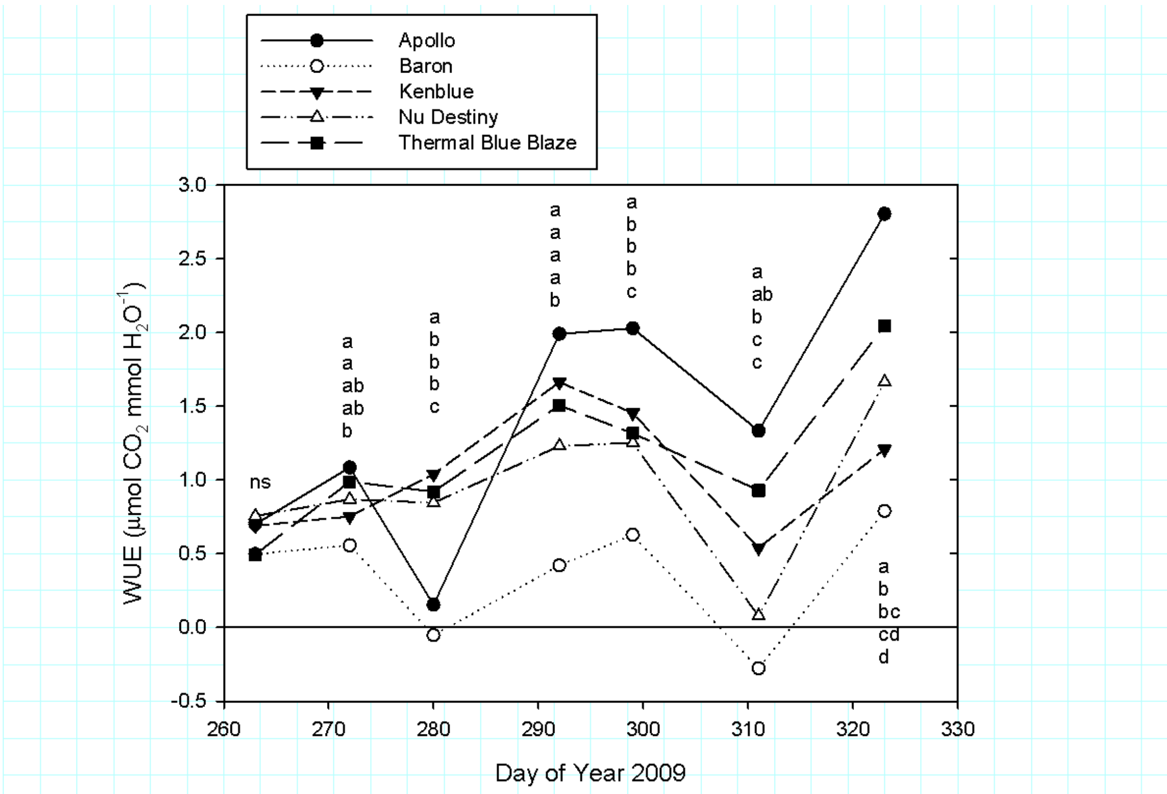

Figure A.9 Measurements of instantaneous water use efficiency (WUE) at midday during dry-down 2 in cultivars of Kentucky bluegrass. Letters are arranged in the same order as the means above or below, and means represented with the same letter within each date are not significantly different (p=0.05).

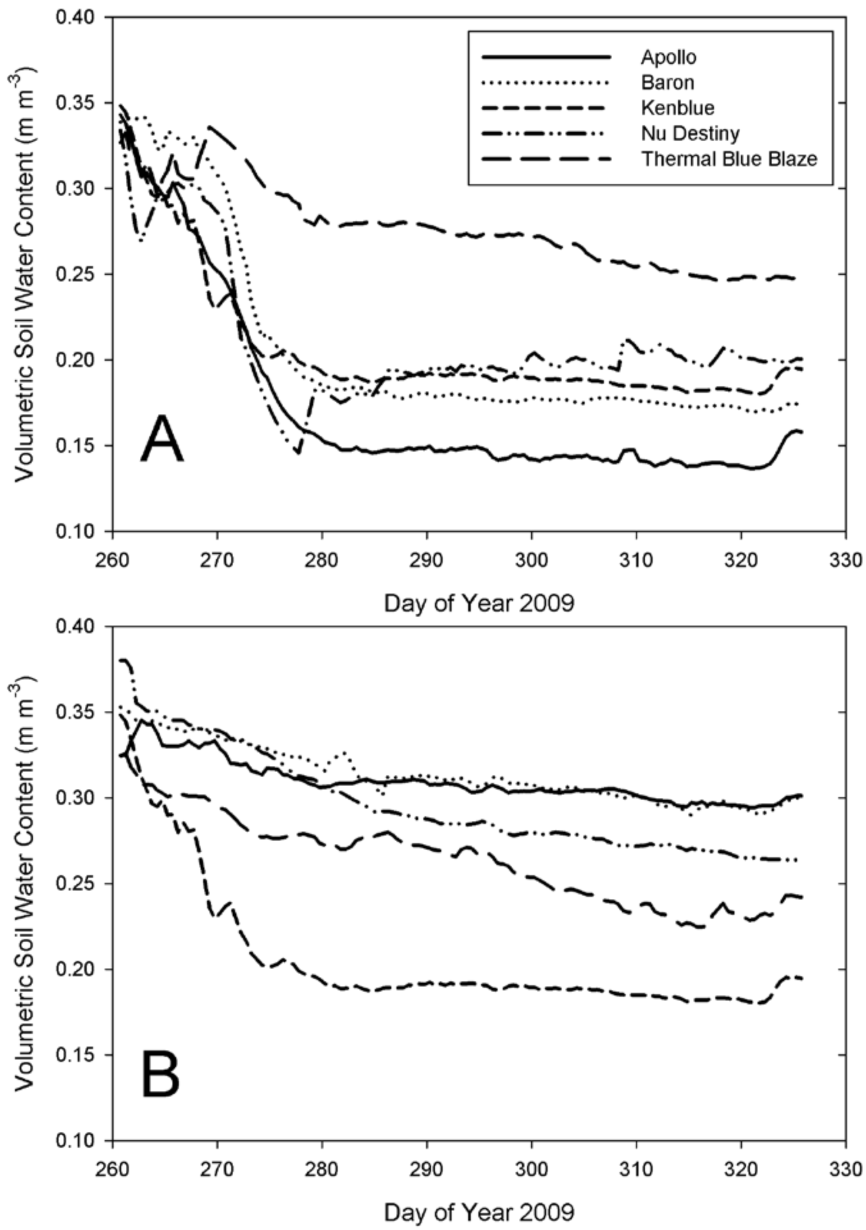

Figure A.10 Volumetric soil water content (θ_v) at 5 cm (A) and 20 cm (B) in cultivars of Kentucky bluegrass during dry-down 2.

Appendix B - Kentucky Bluegrass-ville

By Jimmy (Bill) Bugget

Nibblin' on tillers
We're bluegrass killers
Can't do no research with us around
The rain-out shelter's a beauty
A Kentucky cutie
A nicer spot for is just can't be found

Chorus:
Wastin' away again in Kentucky bluegrass-ville
Searchin' for my lost shaker of Talstar
Some people claim a mis-application's to blame
But I know, it's my own damn fault

We messed with Kemin
Harassed him all season
Ruined his research and sent him away
Now it's Jason
What were you thinking'?
Tryin' to do research in Billbug-Bombay

(Chorus)

Soak us in Merit
We'll grin and bear it
We just get fatter when you spray
You can try Talstar
But you won't get far
We lick it up like it's crème brulee
(Chorus)

Figures

Figure B.1 Jimmy (Bill) Buggett.