Title
Effects of Turfgrass Species and Irrigation Practices on Carbon Fixation and Water Use Efficiency

Permalink
https://escholarship.org/uc/item/3vv2h39s

Author
Nichols, Ryan Scott

Publication Date
2013

UNIVERSITY OF CALIFORNIA
RIVERSIDE

Effects of Turfgrass Species and Irrigation Practices on Carbon Fixation and Water Use Efficiency

A Thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Science

in

Plant Biology

by

Ryan Scott Nichols

December 2013

Thesis Committee:
Dr. James H. Baird, Chairperson
Dr. G. Darrel Jenerette
Dr. Louis S. Santiago

The Thesis of Ryan Scott Nichols is approved:

Committee Chairperson

University of California, Riverside

ACKNOWLEDGMENTS

This research was funded by the United States Golf Association and the California Turfgrass and Landscape Foundation.

I would like to thank Dr. James H. Baird and Dr. G. Darrel Jenerette for their continued support and guidance throughout the research project and composition of this manuscript. Additionally, I would like to express my appreciation to Dr. Louis S. Santiago of the University of California, Riverside and Dr. Bernd Leinauer of New Mexico State University for their advice and suggestions throughout the revision process of this manuscript.

ABSTRACT OF THE THESIS

Effects of Turfgrass Species and Irrigation Practices on Carbon Fixation and Water Use Efficiency

by

Ryan Scott Nichols

Master of Science, Graduate Program in Plant Biology
University of California, Riverside, December 2013
Dr. James H. Baird, Chairperson

Turf is an essential part of urban landscapes and an effective sink for soil organic carbon, yet little is known about the relative carbon fixation (CF) capabilities among various turfgrass species and cultivars and how CF is influenced by irrigation practices. Ten commonly used cool-season and warm-season turfgrasses were evaluated for CF and water use efficiency (WUE) rates under optimal and deficit irrigation practices. Cool-season species consisted of: Kentucky bluegrass and perennial ryegrass (KB/PR); fineleaf fescue (FF); tall fescue and Kentucky bluegrass (TF/KB); and tall fescue (TF). Warm-season species included: zoysiagrass (ZOY); St. Augustinegrass (SA); seashore paspalum (SP); bermudagrass (328B and 419B); and buffalograss (BUF). Carbon fixation was measured and calculated as gross ecosystem productivity (GEP) along with WUE using an open-path infrared gas analyzer. Kentucky bluegrass/perennial ryegrass, FF, TF/KB, TF, and SP had the highest GEP under deficit irrigation. When grouped, GEP was significantly higher during recovery under deficit irrigation ($p<0.0001$) for cool-season compared to warm-season turfgrasses, indicating that C_3 photosynthesis is labile and C_4 photosynthesis is stabile during recovery. Overall, WUE for warm-season grasses was higher than cool-season grasses ($p<0.0001$). However, species did not differ in WUE between optimal and deficit irrigation, suggesting that WUE is conserved when water is limited. Our results confirmed that warm-season turfgrasses are the most appropriate species for water conservation in regions where they are adapted.

Table of Contents

Introduction……………………………………………………………………………..1

Materials and Methods…………………………………………………………………4

Results……………………………………………………………………………………..8

Discussion and Conclusion……………………………………………………………10

References……………………………………………………………………………..14

Tables…………………………………………………………………………………….17

Figure captions………………………………………………………………………...19

Figures……………………………………………………………………………………20

Introduction

Turfgrass is the largest irrigated crop, occupying three times the land of any other crop (Milesi et al. 2005). As the use of turfgrass is common in urban landscapes, and urbanization is increasing, the land area occupied by turfgrass is also likely to rise (Pataki et al. 2006). Unlike other grassland ecosystems under drought, which rely solely on rainfall (Potts et al. 2006), turfgrasses are mainly watered through irrigation systems with some level of frequency. However, water-use restrictions have become commonplace in the arid southwestern United States (City of Albuquerque, NM, 2000; State of California, 2009). Considering the ever-growing demand for water conservation, either turfgrasses will be irrigated with less water and less frequently or their use in landscapes will diminish.

Cool-season turfgrasses, particularly tall fescue (*Festuca arundinacea*), are the most common turfgrasses used in lawns in California. Previous research has shown that cool-season turfgrasses have higher water consumption rates than warm-season turfgrasses (Biran et al. 1981). Annual crop coefficients (K_c), the ratio of evapotranspiration observed, of cool-season turfgrasses and warm-season turfgrasses have been established in California as 0.8 and 0.6, respectively (Meyer et al. 1985; Richie et al. 1997). When considering minimum water requirements for maintaining season-long acceptable turf quality, Fu et al. (2004) found that during June through September, tall fescue, and two warm-season turfgrasses, bermudagrass and zoysiagrass required 478, 247, and 359 mm, respectively. Water use efficiency (WUE), the amount of carbon fixed per unit of water lost through transpiration, has been studied to identify superior performance in Kentucky bluegrass genotypes under limiting soil moisture (Ebdon and Kopp 2004). Although not always a reliable predictor of turf performance, measuring WUE under moisture stress is more reliable for predicting turf performance than WUE under nonlimiting moisture (Ebdon and Kopp 2004). Zhou et al. (2012) found that WUE correlated strongly with survival period when evaluating eight warm-season turfgrass cultivars for drought resistance. Additionally, Fu et al. (2007) observed that zoysiagrass exhibited higher WUE than tall fescue under deficit irrigation.

Although turfgrasses are generally considered high water use plants, turfgrass provides a number of aesthetic, functional and environmental benefits that enhance the quality of human life (Beard and Green 1994). One of these benefits is carbon fixation (CF). Water use and WUE of turfgrasses are closely linked to CF, as turfgrasses require carbon (C) and water for photosynthesis. Moreover, as atmospheric C is the focus of climate change research (Pataki et al. 2006), turfgrasses have the potential to stabilize atmospheric C through long-term carbon storage as soil organic carbon (Zirkle et al. 2011). Many studies have been done to assess the carbon sequestration of turfgrass systems (Qian and Follett 2002; Bandaranayake et al. 2003; Pouyat et al. 2009; Qian et al. 2010; Zirkle et al. 2011). Qian and Follett (2002) conducted a study using long-term soil testing data from 15 Colorado golf courses, in which they concluded that turfgrass systems make substantial contributions to sequester atmospheric C, sequestering as much as 1100 kg C ha^{-1} yr^{-1}. Additionally, C sequestration was highest on well-irrigated and fertilized areas of golf course.

Since deficit irrigation can be achieved simply by returning less water than is lost through actual ET, deficit irrigation will most likely be the first step for many turfgrass managers to reduce water use. Understanding that CF and WUE are dependent on available water (Fu et al. 2007), it is increasingly important to understand turfgrass physiological responses under varying conditions. Moreover, turfgrasses managed under deficit irrigation go through a cycle of wetting, during irrigation, and drying, between irrigation events. This may result in frequent periods of recovery after irrigation events for drought sensitive turfgrass species.

As most turfgrass species can be successfully grown in California by homeowners and turfgrass managers, information is lacking on CF and WUE of many cool and warm-season turfgrasses during recovery under deficit irrigation. Our study sought to address this need by assessing relative CF and WUE among 10 commonly used cool and warm-season turfgrasses in California and determine how these factors are influenced by irrigation practices, mainly optimal and deficit irrigation during recovery.

Materials and methods

Site Description and Plant Material.

The study was conducted at the University of California, Riverside turfgrass research facility from May 2009 to April 2012. The soil was a Hanford fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents). Treatments consisted of ten turfgrasses, four cool-season and six warm-season turfgrasses (Table 1). Turfgrasses species and cultivars were selected by commercial availability and popularity in southern California and the southwestern U.S. All grasses were established by sod in August 2008 with the exception of buffalograss, which was plugged on 15-cm spacing. Plot size was 6 m^2 with 0.5-m alleys.

Cultural Practices.

All turfgrasses were maintained at or slightly above recommended mowing heights respective to each species or cultivar, and ranged from 1.3 to 6.4 cm (Table 1). Plots were mowed twice weekly, with the exception of Hillside fine fescue (Table 1). Plots were fertilized monthly during the growing season based on annual fertility requirements for each species and ranged from 98 to 195kg N ha^{-1} yr^{-1} using a complete fertilizer (Table 1). During year 1 (optimal irrigation) all treatments were irrigated based on reference evapotranspiration (ET_0) rates obtained from an on-site California Irrigation Management Information System (CIMIS) weather station that was based on a modified Penman equation with a wind function(Doorenbos and Pruitt 1984). The CIMIS reference crop was a well-watered tall fescue maintained at 11.9 cm. For cool-season turfgrasses, irrigation was 80% ET_0 yr^{-1} and for warm-season turfgrasses irrigation was 60% ET_0 yr^{-}

^{1}. Irrigation amounts were based on K_c data established in previous research (Meyer et al. 1985; Carrow 1995; Richie et al. 1997). During year 2 all grasses were subjected to deficit irrigation, ≈ 5-20% less than ET_0, to induce water stress based on a percentage of the previous week's ET_0 (Table 2).

Field Measurements.

CO_2 exchange measurements were taken monthly directly after irrigation for both years to determine performance during recovery. Additionally during year 2, measurements were taken on one occasion at 2-hour intervals to monitor a change in CO_2 and H_2O exchange during the peak stress month during the growing season. Net ecosystem CO_2 exchange (NEE), CO_2 exchange during photosynthesis and respiration, ecosystem respiration (R_e), CO_2 exchange during respiration only, and evapotranspiration (ET) were taken in a closed transparent cubic chamber ($1m^3$) seated over each plot with an open-path infrared gas exchange analyzer (LI-7500, Li-Cor Inc., Lincoln, NE, USA) installed inside (Potts et al. 2006; Harpole et al. 2007; Chen et al. 2009). The infrared gas exchange analyzer (IRGA) was mounted on a tripod fit with one 10 cm diameter fan to aid in mixing the air within the closed chamber. The chamber was constructed of 3.2 cm diameter PVC pipe frame covered by a tightly fitted transparent polyethylene sheet (Shelter Systems, Santa Cruz, CA, USA). The transparent polyethylene sheet used for the closed chamber allowed for approximately 50% photosynthetically active radiation (PAR), to pass into the plots.

Gas exchange measurements using the closed chamber were taken under clear sky conditions to maximize light penetration into the chamber, as mentioned by others (Fu et al. 2007; Harpole et al. 2007). To measure NEE, ET, and R_e, the transparent chamber was seated over each plot with the tripod mounted fan and IRGA inside. For each turfgrass plot, three measurements were taken monthly, NEE, ET, and R_e. First, the tripod was placed on the center of the plot and covering it with the transparent chamber, NEE and ET measurements were logged on a computer for 60-s. After the first measurements, the chamber was removed and vented. For the R_e measurement, the chamber was placed back over the tri-pod, which was covered by a shade cloth, allowing no light to penetrate the chamber. Data were logged for 60-s while the chamber was covered. Measurements were analyzed following procedures outlined by others (Jasoni et al. 2005). Carbon fixation was calculated as Gross ecosystem productivity (GEP) according to Harpole et al. (2007), the balance of NEE and R_e. WUE was then calculated in two ways, annual and monthly. Average water use efficiency (AWUE) was calculated similar to previous research (Steduto and Albrizio 2005), as the slope of monthly GEP plotted against monthly ET for each species/cultivar. Although WUE is not commonly calculated this way (Gulias et al. 2012), especially for turfgrasses (Ebdon and Kopp 2004; Zhou et al. 2012), when using instantaneous gas exchange measurements over time, this method gives a more reliable WUE value. Monthly or instantaneous WUE was calculated similar to other research (Gulias et al. 2012) by dividing GEP values over ET values for each treatment. Average GEP (AGEP) represent the 12-month GEP average of each year during the research period.

Statistical Analysis.

Experimental design was a randomized complete block design with three replications of each turfgrass type. Average GEP, AWUE, GEP, and WUE were analyzed separately for each year. Data were analyzed separately as cultivar/species and grouped by photosynthesis type (cool-season vs. warm-season turfgrasses). Data were subjected to analysis of variance (ANOVA) using Proc Mixed in SAS version 9.2 (SAS Institute, Cary, NC) followed by multiple comparisons of means using Fisher's protected least significant difference test (α=0.05). Figures were created using GraphPad Prism 6 version 6.0a (GraphPad Software, San Diego, CA).

Results

Environmental Data

During the study period mean annual precipitation was 217mm. Mean monthly air temperatures ranged from 11.4 °C in December 2009 to 24.4 °C in August 2011 (Table 2). Observed ET_0 for year one and year two were 1437 mm and 1539 mm respectively. Observed annual precipitation for year one and two were 243 mm and 148 mm, respectively. Annual irrigation input during year one (optimal irrigation) was 1168 mm for cool-season turfgrasses and 876 mm for warm-season turfgrasses. During year two, (deficit irrigation) annual irrigation input was 1055 mm for cool-season turfgrasses and 847 mm for warm-season turfgrasses (Table 2).

For both years one and two, July was the highest evapotranspiration month with observed ET_0 values of 193 mm and 197 mm, respectively (Table 1). Additionally, during the month of August of year 2 while under deficit irrigation WUE decreased as canopy temperature and ET increased over a 4-hour period after irrigation for cool-season turfgrasses (Fig. 1a). Conversely, for warm-season turfgrasses canopy temperature increased while ET peaked then deceased and WUE appeared unaffected over a 4-hour period after irrigation (Fig. 1b).

Annual Gas Exchange Measurements

Overall, deficit irrigation did not appear to affect the seasonal trends of GEP and WUE for cool and warm-season turfgrasses (Fig. 2). We also observed a rapid decline of GEP in warm-season turfgrasses during the months of winter dormancy in both years (Fig. 2c).

The AGEP of cool-season turfgrasses did not differ between cultivars under optimal irrigation or deficit irrigation (Fig. 3a). When grouped together, AGEP for cool-season turfgrasses was significantly higher during recovery from deficit irrigation than during recovery from optimal irrigation (Fig. 4a). For warm-season grasses, AGEP differed significantly among cultivars for both years, but there was no interaction between years (Fig. 3a). The AGEP for warm-season turfgrasses ranged from 7.67 µmole CO_2 m^{-2} sec^{-1} for BUF to 10.69 µmole CO_2 m^{-2} sec^{-1} for STA in optimal irrigation and 8.64 µmole CO_2 m^{-2} sec^{-1} for 328B to 11.44 µmole CO_2 m^{-2} sec^{-1} for SP in deficit irrigation (Fig. 3a). When considered as a group, AGEP of warm-season turfgrasses did not differ between optimal and deficit irrigation (Fig. 4a). Average ET for all turfgrasses followed a similar trend as AGEP, which was significantly higher for deficit irrigation than optimal irrigation ($p<0.001$).

The WUE of turfgrass species did not differ between optimal irrigation and deficit irrigation. Therefore, AWUE data were pooled together for both years, which made for a more powerful statistical analysis (Fig. 3b). The AWUE among all species differed significantly (Fig. 3b). The AWUE ranged from 1.40 µmole CO_2 mmole H_2O^{-1} for TF/KB to 3.83 µmole CO_2 mmole H_2O^{-1} for SP (Fig. 3b). When species were pooled together by photosynthesis type, cool-season and warm-season turfgrasses, the AWUE was higher for warm-season turfgrasses (Fig. 4b).

Discussion

Under deficit irrigation, most cool-season turfgrasses had higher AGEP, while warm-season turfgrasses did not differ (Fig. 3a). Although Fu et al. (2007) found that tall fescue had lower CF than zoysiagrass, TF and ZOY were similar under optimal and deficit irrigation in our study (Fig. 3a). This difference in results may have resulted from different irrigation amounts and environmental conditions. Fu et al. (2007) irrigated tall fescue 20% less than zoysiagrass, whereas the cool-season turfgrasses were irrigated 20% more than warm-season turfgrasses in our study (Table 2).

Previous research shows that C_4 plants as a group including warm-season turfgrasses have higher CO_2 assimilation rates and higher stomatal resistance than C_3 plants (Hsiao and Acevedo 1974; Fu et al. 2007; Zhou et al. 2012). In contrast,when pooled together our data show that cool-season turfgrasses (C_3 grasses) had higher AGEP during recovery than warm-season turfgrasses (C_4 grasses) under deficit irrigation (Fig. 4a). Higher AGEP for cool-season turfgrasses under recovery may reflect a high demand for carbon in C_3 photosynthesis to meet the carbon costs of processes linked to plant stress, one of them being photorespiration, a process that C_4 plants have evolutionarily overcome (Fry and Huang 2004; Sage et al. 2012).

In response to irrigation amount and frequency, our data infers how carbon fixation rates would most likely differ between optimal and deficit irrigation during recovery. It is estimated that carbon sequestration increases with more inputs of water and nutrients for agricultural crops (Nieto et al. 2013) and turfgrasses (Qian et al. 2010; Zirkle et al. 2011). Intuitively, reduced water availability through deficit irrigation practices should decrease carbon fixation and overall plant growth. Although the AGEP during recovery was higher under deficit irrigation for cool-season turfgrasses (Fig. 3a), gas exchange rates changed between irrigation events (Fig. 1). As environmental changes occur throughout the course of a day, and between irrigation events, we expect these changes to affect GEP, especially when under stress (Redshaw and Meidner 1972). We assume that GEP would be highest during recovery, followed by a decline to a lower but more stable GEP during stress until the next irrigation event. The assumption that deficit irrigation practices decrease *total* carbon fixation will be further supported when future experiments can definitively document this reduction in GEP between irrigation events.

Although the AGEP of cool-season turfgrasses during recovery was higher under deficit irrigation, GEP can change rapidly based on environmental queues. Therefore our data do not support that deficit irrigation is good for maximizing carbon uptake of turfgrasses, mainly because a high CF rate does not guarantee the most carbon fixed over time. Our data show that cool-season turfgrasses respond to deficit irrigation by increasing GEP when water is available, immediately after irrigation or during recovery, whereas warm-season turfgrasses do not. The benefits of C_4 over C_3 photosynthesis (Sage et al. 2012) during recovery are clearly seen in the results of our study, with C_3 photosynthesis being more labile and C_4 photosynthesis being more stable. We most likely did not observe any difference in the AGEP of warm-season turfgrasses during recovery under optimal and deficit irrigation, because C_4 photosynthesis is already an evolutionary adaptation to hot, arid conditions (Sage 2004).

While warm-season turfgrasses had higher AWUE than cool-season turfgrasses (Fig. 4b), ZOY and SP had the highest overall AWUE among all turfgrasses in the study (Fig. 3b). Higher WUE values for warm-season turfgrasses was consistent with previous findings; stating that high stomatal resistance and the more efficient C_4 photosynthetic pathway may have contributed to higher observed WUE in warm-season turfgrasses than cool-season turfgrasses (Fry and Huang 2004; Fu et al. 2007).

During recovery AGEP differed between optimal and deficit irrigation, however AWUE did not differ during recovery for optimal and deficit irrigation. Average ET during recovery followed a similar trend as AGEP, being higher under deficit irrigation. Since WUE is dependant on GEP and ET, it is expected that the AWUE would be similar between years, denoting that GEP and ET of all grasses were proportionally similar for both optimal and deficit irrigation. Similar AWUE under optimal and deficit irrigation was consistent with previous findings on agricultural crops (Hsiao and Bradford 1983; Sinclair et al. 1984; Steduto and Albrizio 2005)and turfgrasses (Fu et al. 2007), which suggests WUE is conserved, and does not vary under a wide range of conditions.

As mentioned previously, we believe that deficit irrigation would decrease overall carbon fixed. However, further research needs to be conducted to determine the irrigation level that maximizes carbon fixation. In conclusion, cool-season turfgrasses have higher carbon fixation rates than warm-season turfgrasses when re-watered after water stress at the expense of consuming more water. Warm-season turfgrasses have higher WUE, and when considering that they were irrigated with approximately 20% less water (Table 2), warm-season turfgrasses are far superior to cool-season turfgrasses for minimizing water use. Our research supports previous research (Qian and Fry 1997; Fu et al. 2004) and has shown, for the arid southwestern United States, warm-season turfgrasses are the most appropriate turfgrass for water conservation.

References

Bandaranayake W, Qian YL, Parton WJ, Ojima DS, Follett RF (2003) Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agronomy Journal 95: 558-563.

Beard JB, Green RL (1994) THE ROLE OF TURFGRASSES IN ENVIRONMENTAL-PROTECTION AND THEIR BENEFITS TO HUMANS. Journal of Environmental Quality 23: 452-460.

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

Carrow RN (1995) Drought resistance aspects of turfgrasses in the southeast: evapotranspiration and crop coefficients. Crop Science 35: 1685-1690.

Chen SP, Lin GH, Huang JH, Jenerette GD (2009) Dependence of carbon sequestration on the differential responses of ecosystem photosynthesis and respiration to rain pulses in a semiarid steppe. Global Change Biology 15: 2450-2461.

Doorenbos J, Pruitt O (1984) Crop Water Requirement, FAO. Irrigation and Drainage, Paper 24.

Ebdon JS, Kopp KL (2004) Relationships between water use efficiency, carbon isotope discrimination, and turf performance in genotypes of Kentucky bluegrass during drought. Crop Science 44: 1754-1762.

Fry J, Huang B (2004) Applied turfgrass science and physiology: Wiley.

Fu JM, Fry J, Huang BR (2004) Minimum water requirements of four turfgrasses in the transition zone. Hortscience 39: 1740-1744.

Fu JM, Fry J, Huang BR (2007) Growth and carbon metabolism of tall fescue and zoysiagrass as affected by deficit irrigation. Hortscience 42: 378-381.

Gulias J, Seddaiu G, Cifre J, Salis M, Ledda L (2012) Leaf and Plant Water Use Efficiency in Cocksfoot and Tall Fescue Accessions under Differing Soil Water Availability. Crop Science 52: 2321-2331.

Harpole WS, Potts DL, Suding KN (2007) Ecosystem responses to water and nitrogen amendment in a California grassland. Global Change Biology 13: 2341-2348.

Hsiao TC, Acevedo E (1974) PLANT RESPONSES TO WATER DEFICITS, WATER-USE EFFICIENCY, AND DROUGHT RESISTANCE. Agricultural Meteorology 14: 59-84.

Hsiao TC, Bradford KJ (1983) Physiological consequences of cellular water deficits. Limitations to Efficient Water Use in Crop Production: 227-265.

Jasoni RL, Smith SD, Arnone JA (2005) Net ecosystem CO2 exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO2. Global Change Biology 11: 749-756.

Meyer J, Gibeault V, Youngner V (1985) Irrigation of turfgrass below replacement of evapotranspiration as a means of water conservation: Determining crop coefficient of turfgrasses. 5. International Turfgrass Research Conference, Avignon (France), 1-5 Jul 1985: INRA.

Milesi C, Running SW, Elvidge CD, Dietz JB, Tuttle BT, Nemani RR (2005) Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environmental Management 36: 426-438.

Nieto OM, Castro J, Fernandez-Ondono E (2013) Conventional tillage versus cover crops in relation to carbon fixation in Mediterranean olive cultivation. Plant and Soil 365: 321-335.

Pataki DE, Alig RJ, Fung AS, Golubiewski NE, Kennedy CA, McPherson EG, Nowak DJ, Pouyat RV, Lankao PR (2006) Urban ecosystems and the North American carbon cycle. Global Change Biology 12: 2092-2102.

Potts DL, Huxman TE, Cable JM, English NB, Ignace DD, Eilts JA, Mason MJ, Weltzin JF, Williams DG (2006) Antecedent moisture and seasonal precipitation influence the response of canopy-scale carbon and water exchange to rainfall pulses in a semi-arid grassland. New Phytologist 170: 849-860.

Pouyat RV, Yesilonis ID, Golubiewski NE (2009) A comparison of soil organic carbon stocks between residential turf grass and native soil. Urban Ecosystems 12: 45-62.

Qian YL, Follett RF (2002) Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agronomy Journal 94: 930-935.

Qian YL, Follett RF, Kimble JM (2010) Soil Organic Carbon Input from Urban Turfgrasses. Soil Science Society of America Journal 74: 366-371.

Qian YL, Fry JD (1997) Water relations and drought tolerance of four turfgrasses. Journal of the American Society for Horticultural Science 122: 129-133.

Redshaw AJ, Meidner H (1972) EFFECTS OF WATER STRESS ON RESISTANCE TO UPTAKE OF CARBON-DIOXIDE IN TOBACCO. Journal of Experimental Botany 23: 229-&.

Richie W, Green R, Gibeault V (1997) Using ETo (reference evapotranspiration) for turfgrass irrigation efficiency. California Turfgrass Culture 47: 9-15.

Sage RF (2004) The evolution of C-4 photosynthesis. New Phytologist 161: 341-370.

Sage RF, Sage TL, Kocacinar F (2012) Photorespiration and the Evolution of C-4 Photosynthesis. Merchant SS editor. Annual Review of Plant Biology, Vol 63, p19-47.

Sinclair TR, Tanner CB, Bennett JM (1984) WATER-USE EFFICIENCY IN CROP PRODUCTION. Bioscience 34: 36-40.

Steduto P, Albrizio R (2005) Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea II. Water use efficiency and comparison with radiation use efficiency. Agricultural and Forest Meteorology 130: 269-281.

Zhou Y, Lambrides CJ, Kearns R, Ye CR, Fukai S (2012) Water use, water use efficiency and drought resistance among warm-season turfgrasses in shallow soil profiles. Functional Plant Biology 39: 116-125.

Zirkle G, Lal R, Augustin B (2011) Modeling Carbon Sequestration in Home Lawns. Hortscience 46: 808-814.

Table 1. Turfgrass species and cultural practices evaluated for carbon fixation and water use efficiency in Riverside, Ca, USA.

All grasses were established by sod in July 2008 with the exception of buffalograss, which was established by plugs.

Scientific name	**Commercial variety/species**	**Cultivar/composition**	**Source**	**Abbr.**	**Type**	**Fertility (kg N $ha^{-1}yr^{-1}$)**	**Mowing height (cm)**
Poa pratensis/Lolium perenne	Bayside Blend Kentucky bluegrass/perennial ryegrass	Unstated varietal mix (80% Kentucky bluegrass, 20% perennial ryegrass)	West Coast Turf, CA	KB/PR	C_3	135	6.4
Festuca rubra Ssp.	Hillside fine fescue	"Florentine GT' strong creeping red fescue, 'Seabreeze GT' slender creeping red fescue, and 'Tiffany' Chewing's fescue	West Coast Turf, CA	FF	C_3	98	No mow
Festuca arundinacea/Poa pratensis	Elite Plus tall fescue and Kentucky bluegrass	Unstated varietal mix (tall fescue, Kentucky bluegrass)	A-G Sod, CA	TF/KB	C_3	135	6.4
Festuca arundinacea	Westcoaster tall fescue	Westcoaster	West Coast Turf, CA	TF	C_3	135	6.4
Zoysia matrella x (*Z. japonica* x *Z. tenuifolia)*	Hybrid zoysiagrass	'De Anza'	West Coast Turf, CA	ZOY	C_4	135	1.3
Stenotaphrum secundatum	St. Augustinegrass	'Palmetto'	West Coast Turf, CA	STA	C_4	135	6.4
Paspalum vaginatum	Sea Spray seashore paspalum	'Sea Spray'	West Coast Turf, CA	SP	C_4	135	1.3
Cynodon dactylon x *transvaalensis*	hybrid bermudagrass	'Tifgreen 328'	A-G Sod, CA	328B	C_4	135	1.3
Cynodon dactylon x *transvaalensis*	hybrid bermudagrass	'Tifway 419'	West Coast Turf, CA	419B	C_4	135	1.3
Bouteloua dactyloides	buffalograss	'UC Verde'	Florasource, CA	BUF	C_4	98	6.4

Table 2. Environmental data collected on the research site at the University of California, Riverside, USA turfgrass research facility during year 1 (April 2009 – March 2010) and year 2 (May 2011 – April 2012) of the research period. During year 1, irrigation for was based on historical reference evapotranspiration (ET_0), 80% ET_0 yr^{-1} for C_3 grasses and 60% ET_0 yr^{-1} for C4 grasses (Richie et al. 1997). During year 2, deficit irrigation was a percentage of the previous week's ET_0 .

Climate parameters	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
						°C							
Air Temperature													
Year 1	12.7	12.6	14.5	15.8	19.7	19.6	25.3	24.4	24.7	18.5	15.9	11.4	
Year 2	14.0	12.9	13.3	16.5	17.1	19.6	23.7	24.4	22.6	19.2	13.6	11.5	
						mm							
Precipitation													
Year 1	135.1	51.6	7.9	0.1	0	0.6	0	0	0	0	3.0	45.1	243.4
Year 2	9.6	16.2	24.5	22.1	8.6	0.1	7.3	0	0	10.8	39.4	9.8	148.4
						mm							
ET_0													
Year 1	59.82	61.9	118.5	141.78	160.65	136.32	193.15	169.76	149.71	111.79	80.65	52.75	1436.78
Year 2	76.6	86.61	114.48	148.66	169.53	176.43	197.17	194.26	139.06	102.27	62.12	71.73	1538.92
						mm							
Irrigation													
Year 1 C_3	52.72	60.96	92.75	90.42	125.55	135.85	149.29	158.32	111.03	81.63	62.01	47.90	1168.4
Year 1 C_4	39.54	45.72	69.56	67.82	94.16	101.89	111.97	118.74	83.28	61.22	46.50	35.92	876.32
Year 2 C_3	41.49	43.3	50.18	79.88	147.9	143.76	173.98	196.91	128.86	98.97	8.38	21.66	1055.39
Year 2 C_4	33.95	35.43	42.46	61.09	128.42	111.05	137.36	155.45	101.73	76.77	6.99	17.71	847.32

Figure captions

Fig. 1 Canopy temperature (°C), evapotranspiration rate (ET) measured in mmole H_2O m^{-2} sec^{-1}, and water use efficiency (WUE) measured in µmole CO_2 / mmole H_2O of cool-season (a) and warm-season turfgrasses (b) measured at 2-hour intervals after irrigation.

Fig. 2 Monthly gross ecosystem productivity (GEP), measured in µmole $CO_s m^{-2} sec^{-1}$ of cool-season (a) and warm-season turfgrasses (b) under optimal and deficit irrigation. Monthly water use efficiency (WUE), measured in µmole CO_2/mmole H_2O of cool-season (c) and warm-season turfgrasses (d) under optimal and deficit irrigation.

Fig. 3 12 month average gross ecosystem productivity (AGEP), measured in µmole $CO_s m^{-2} sec^{-1}$, of all turfgrasses under optimal and deficit irrigation (a). 12 month average water use efficiency (AWUE), measured in µmole CO_2/mmole H_2O, of all turfgrasses of both years pooled together (b). Kentucky bluegrass/perennial ryegrass blend (KB/PR), fine fescue blend (FF), tall fescue/Kentucky bluegrass blend (TF/KB), tall fescue (TF), zoysiagrass (ZOY), St. Augustinegrass (STA), seashore paspalum (SA), Tifgreen 328 hybrid bermudagrass (328B), Tifway 419 hybrid bermudagrass (419B), buffalograss (BUF).

Fig. 4 Twelve-month average gross ecosystem productivity (AGEP), measured in µmole $CO_s m^{-2} sec^{-1}$ (a) of all grasses categorized into two groups, cool-season and warm-season turfgrasses under deficit irrigation. 12-month average water use efficiency (AWUE), measured in µmole CO_2/mmole H_2O (b) of all grasses categorized into two groups, cool-season and warm-season turfgrasses for both years pooled together.

Figures

Fig. 1

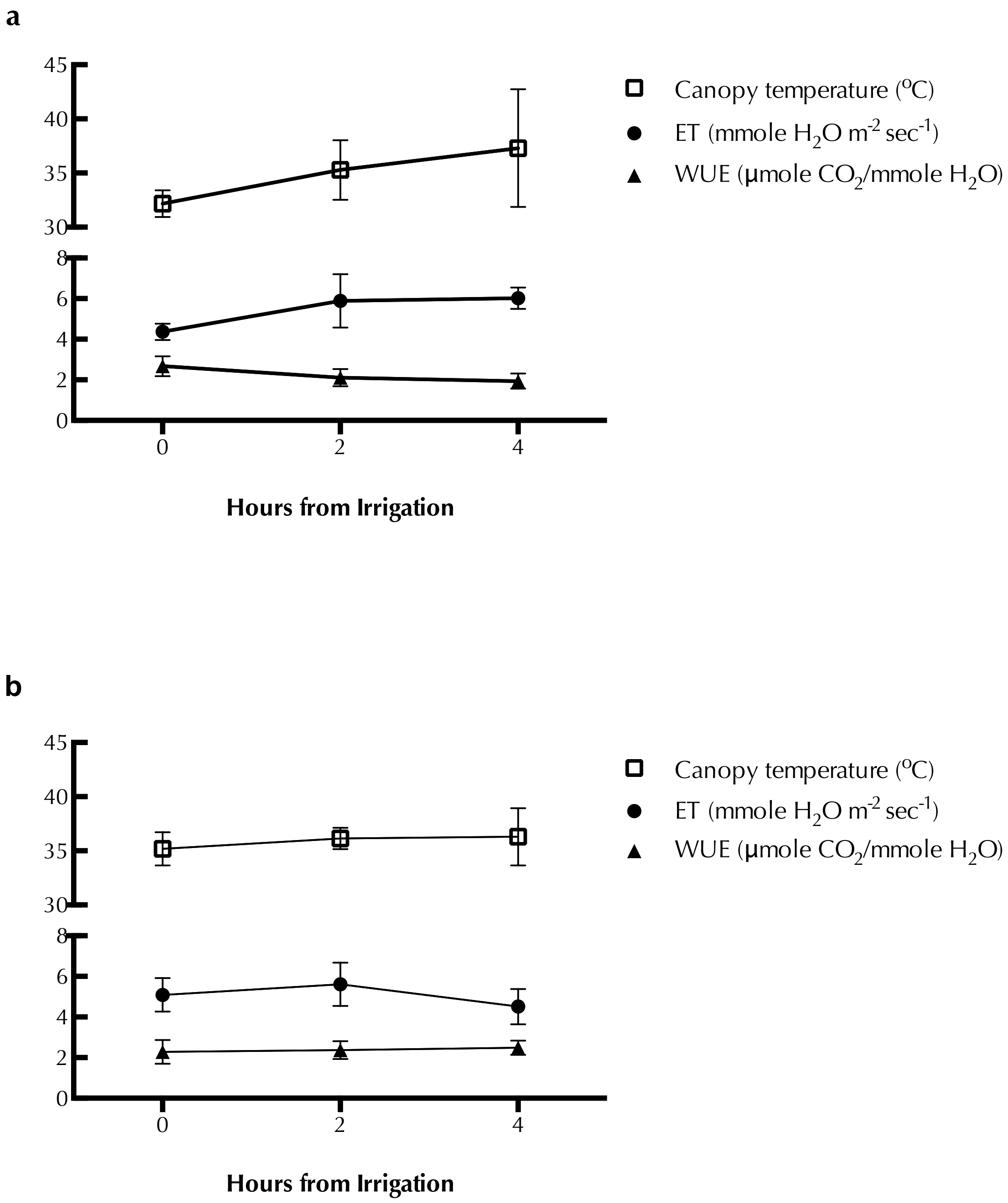


Fig. 2

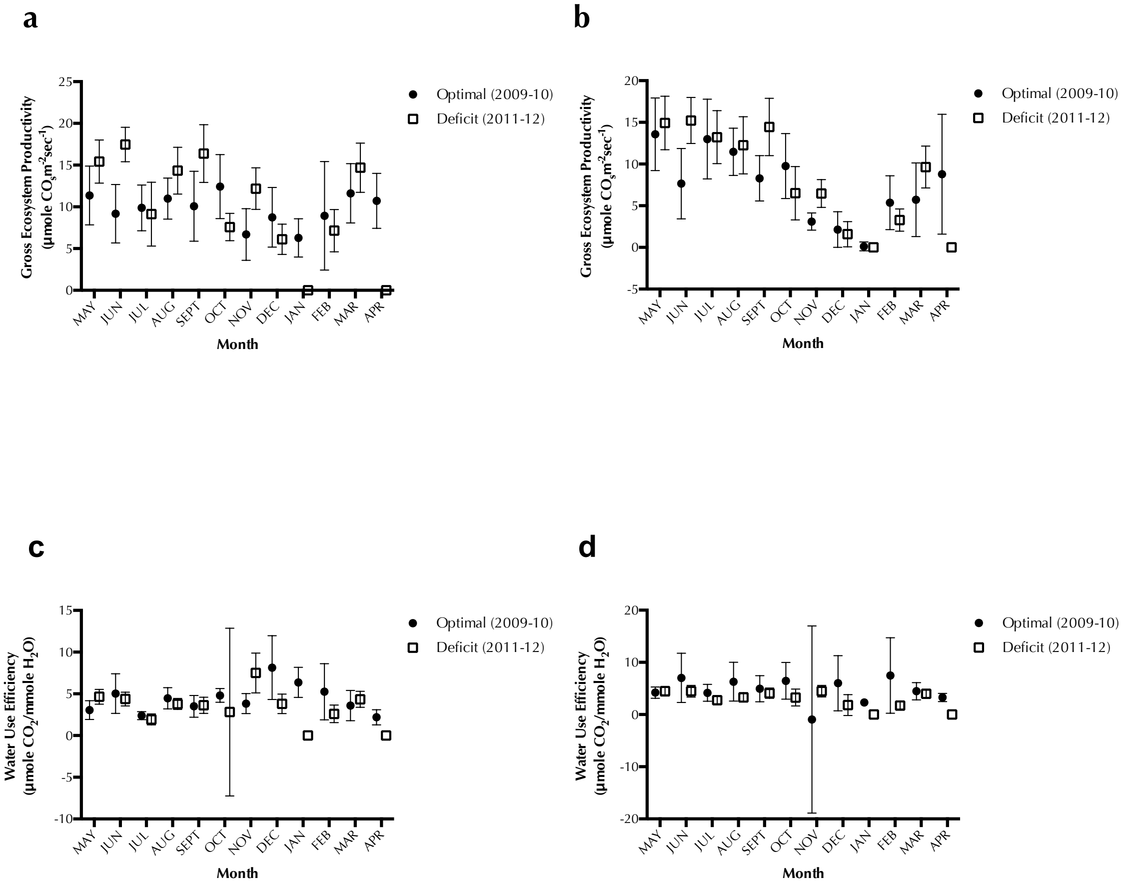
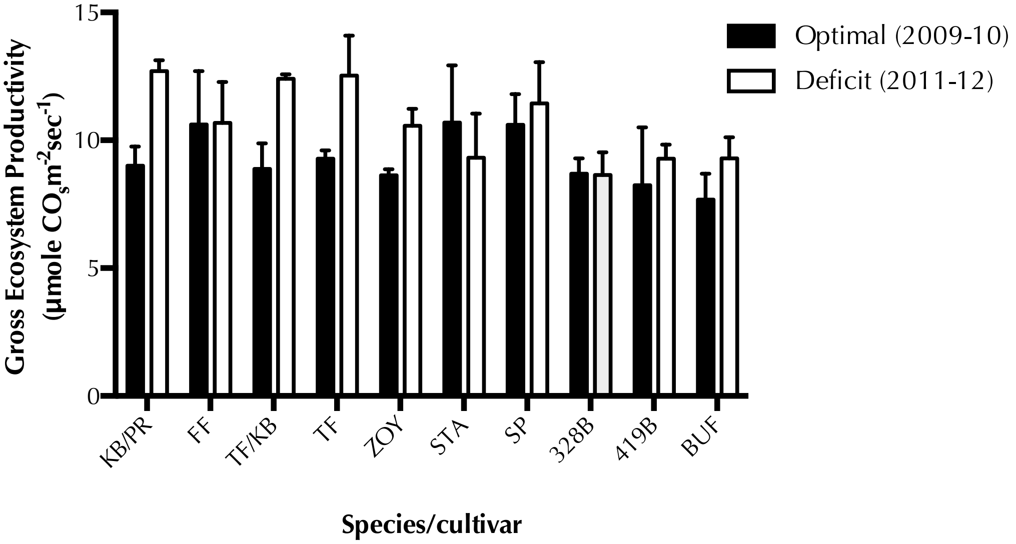

a
b
c
d
Gross Ecosystem Productivity (µmole CO$_2$m^{-2}sec^{-1})
Water Use Efficiency (µmole CO$_2$/mmole H$_2$O)
Month
MAY
JUN
JUL
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
Optimal (2009-10)
Deficit (2011-12)
25
20
15
10
5
0
-5
-10
-20

Fig. 3

a


Gross Ecosystem Productivity
(µmole CO$_s$m^{-2}sec^{-1})
15
10
5
0
Optimal (2009-10)
Deficit (2011-12)
KB/PR
FF
TF/KB
TF
ZOY
STA
SP
328B
419B
BUF
Species/cultivar

b

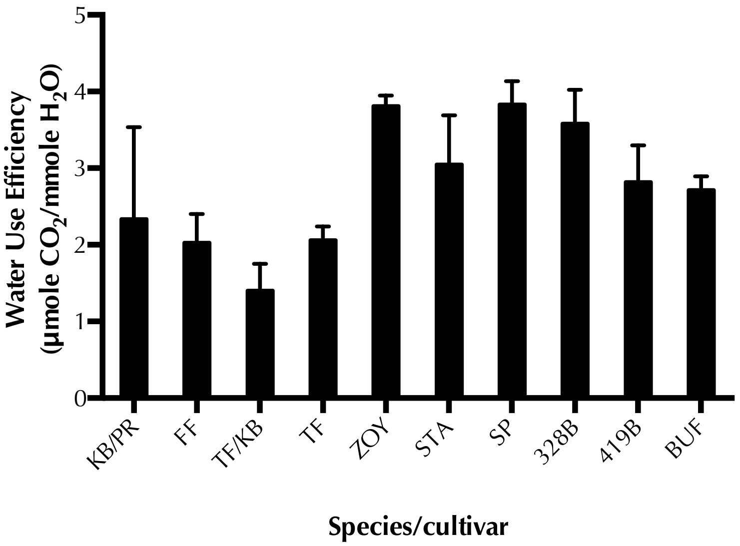
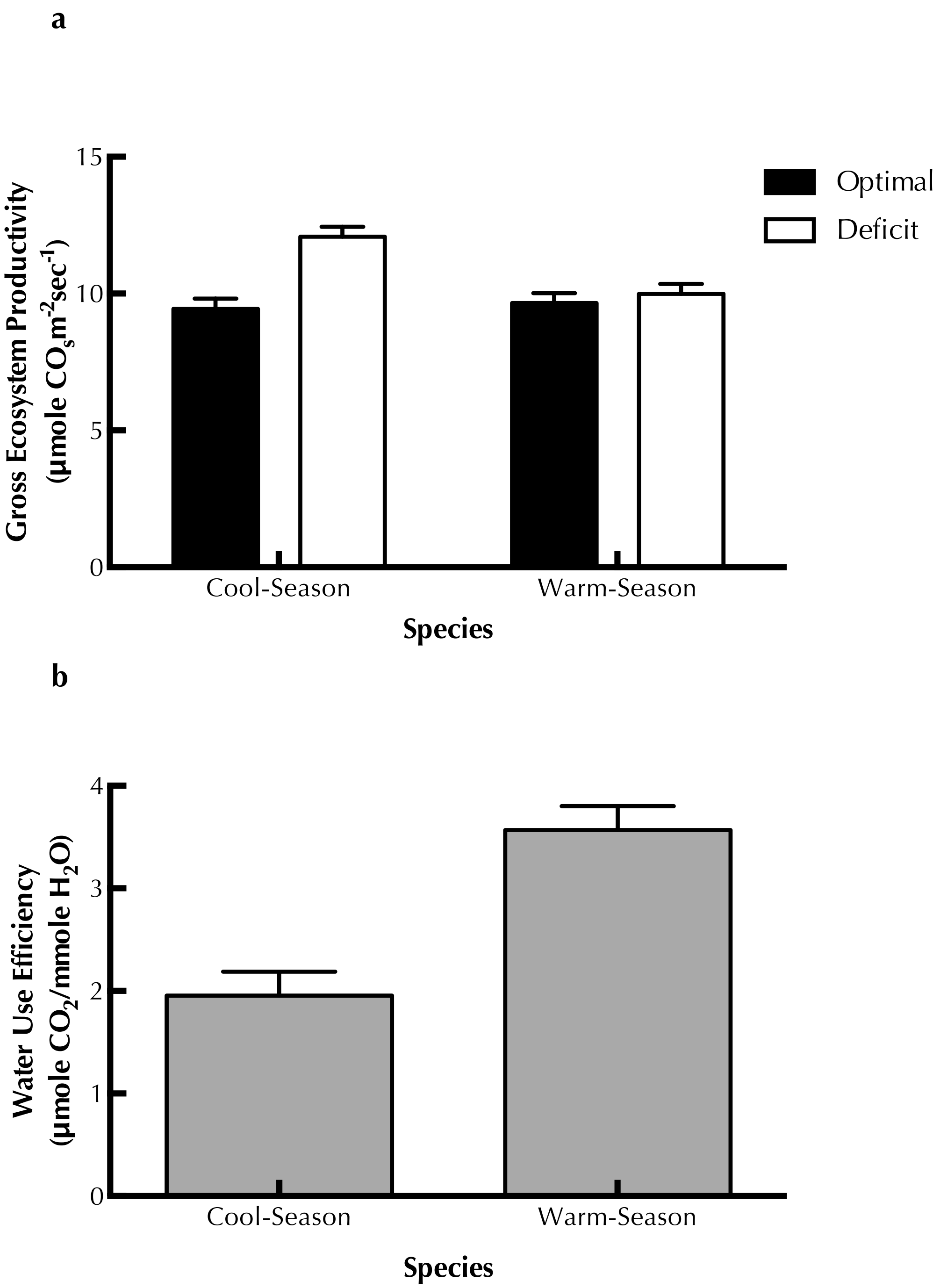

Water Use Efficiency
(µmole CO$_2$/mmole H$_2$O)
5
4
3
2
1
0
KB/PR
FF
TF/KB
TF
ZOY
STA
SP
328B
419B
BUF
Species/cultivar

Fig. 4


a
15
10
5
0
Gross Ecosystem Productivity
(µmole CO$_s$m^{-2}sec^{-1})
■ Optimal
□ Deficit
Cool-Season
Warm-Season
Species
b
4
3
2
1
0
Water Use Efficiency
(µmole CO$_2$/mmole H$_2$O)
Cool-Season
Warm-Season
Species