DEFICIT IRRIGATION PROGRAMS FOR WATER CONSERVATION IN THE

MANAGEMENT OF BERMUDAGRASS FAIRWAYS IN TEXAS

A Thesis

by

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ABSTRACT

Golf course water use in Texas has become increasingly regulated in the past decade due to persistent drought conditions, diminishing water supplies, and rapidly a growing population. Many golf courses have been faced with considerable cutbacks in irrigation allocations, but information is limited regarding critical levels needed for maintaining adequate turf quality, persistence, and recovery from divots and traffic. Furthermore, the effects of irrigation water quality on minimal irrigation requirements has not been fully resolved. A series of field and greenhouse studies were conducted over the course of two years in College Station, TX, to determine the effects of continuous reference evapotranspiration (ET_o)- based deficit irrigation levels on quality of bermudagrass fairway turf. Turf quality evaluations from both seasons showed that in the absence of traffic, irrigation levels of 0.3 x ET_o were sufficient to maintain acceptable turfgrass quality during summer months (at a 3-day per week irrigation frequency). Canopy temperatures increased considerably as irrigation was reduced; with up to a 20°C increase detected between irrigated and unirrigated plots. Upon resumption of full irrigation levels in September, unirrigated and deficit-irrigated plots quickly recovered to ~90% green cover within 8 weeks in year 1. However, unirrigated plots were much slower to recover in the second season, only reaching ~30% green cover by 8 weeks. The delayed ability of unirrigated plots to rebound following successive years without irrigation suggests a cumulative effect of drought stress on bermudagrass health and vigor. Traffic treatments delayed recovery across all irrigation levels. Greenhouse investigations into irrigation water quality (reverse osmosis (RO), saline, and sodic) and plant growth regulator trinexapac-ethyl (TE) effects on bermudagrass evapotranspiraton and tolerance to deficit irrigation were also undertaken. Irrigation water quality failed to significantly influence minimal irrigation requirements, but turf irrigated with sodic irrigation did exhibit considerably higher evapotranspiration (ET) rates relative to those receiving saline or RO irrigation. TE improved bermudagrass quality and delayed leaf firing under the soil moisture stress from deficit irrigation. The findings from this research provide timely and practical information for turf managers who must increasingly utilize ET-based irrigation scheduling and/or low-quality water sources in the management of golf course turfgrass systems.

DEDICATION

To my late grandparents, whose legacy keeps me pushing forward.

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INTRODUCTION

Golf's Use of Water in Texas

During the last decade, Texas has experienced one of the harshest droughts on record and, in 2011, the state endured the worst drought since the drought of 1956. Rainfall throughout the state was at a record low as well as record high temperatures and these trends are predicted to continue.

This water shortage coupled with rapid population growth has placed great strains on water supplies throughout the state. Population growth in Texas is predicted to continue and according to the 2012 Texas State Water Plan, over the next 50 years, the state's population will increase by 82% (Texas State Water Plan, 2012). As population increases so does the demand for water. According to the Texas Water Development Board, in 2011 the state needed 18 million acre-feet of water per year to support the current population. With current growth trends, the board predicts by 2060, 22 million acre-feet of water will be required to support the state's population (Texas State Water Plan, 2012). This growing demand for water has caused reservoir storage to drastically decline since 1980 (Texas State Water Plan, 2012).

To ensure adequate water supplies throughout the state, there is a major emphasis on water conservation, a key component of which is tighter regulation on turfgrass and amenity landscape irrigation practices. In 2011, about 1,000 water systems implemented watering restrictions throughout the state (Thomas, 2012). Most were day-of-the-week restrictions, which limit the number of days per week customers are allowed to water.

According to the 2012 Texas State Water Plan, there are over 1000 golf courses in Texas representing an area of nearly 115,000 acres. It is estimated that water use for irrigation of these golf course accounts for nearly 2% of the state's total water allocations (Texas State Water Plan, 2012). According to a recent national survey of golf course operations conducted by the Environmental Institute for Golf, 25% of 18-hole golf course facilities have been subject to 'recurring annual water allocations' (Throssell, 2009). For survey purposes, Texas was divided east to west, primarily based on differences in annual rainfall amounts. In East Texas, 36% of facilities reported experiencing recurring annual water allocations, while in West Texas, nearly 40% of facilities face similar challenges (Throssell et al, 2009).

Water Conservation Efforts

Given these water allocation changes, golf course superintendents must be prepared to modify irrigation practices to meet conservation goals while still producing the quality turfgrass playing surface golfers demand. Currently, the majority of golf course superintendents manage irrigation essentially 'by feel', relying on skill and experience to maintain quality. Greater than 90% of managers of 18-hole golf course facilities in the United States still make irrigation decisions based on turfgrass or soil observations, (Throssell, 2009). As greater strains are placed on irrigation supplies in the future, and mandatory restrictions and allocation reductions become the norm; however, it may become even more challenging for superintendents to manage irrigation in this way.

Therefore, the challenge for golf course superintendents is to meet conservation goals set forth by water purveyors while maintaining acceptable turf quality and playability standards desired by membership. As such, superintendents must increasingly become familiar with and adopt technology-based strategies for budgeting and managing water use, irrigating only when the plant needs it and at amounts that don't surpass plant irrigation requirements.

ET-Based Irrigation

Evapotranspiration (ET)-based irrigation is one strategy that can lead to greater water use efficiency on the golf course. Weather based-ET feedback systems or ET irrigation controllers allow for greater precision in irrigating to the exact needs of the turf. These systems initially calculate potential evapotranspiration (ET_o) from temperature, solar radiation, relative humidity, and wind velocity, and then adjust this value by a coefficient particular to the consumptive water use of the crop being irrigated, or crop coefficient (K_c) (Devitt et. al.,1992).

Previous research has sought to identify appropriate K_c for turfgrass species. By summarizing the results from a series of applied water studies, Meyer and Gibeault (1987) and Snyder and Pruitt (1985) using a modified Penman equation, suggested a K_c of 0.6 for irrigation of warm-season grasses. This has become a widely accepted value for irrigation of warm-season grasses; however, more recent studies have indicated higher K_c values may more accurately reflect warm-season grass water use. Allen et al (1998) recommend a K_c value of 0.80 to 0.85 for irrigating warm season grasses.

Another important consideration of turfgrass water use is that K_c values have been shown to vary up to 25% from one geographic location to another (Brown et al., 1998). For a K_c value to be widely accepted, it should be matched to a specific ET_o procedure that ensures accurate estimation of actual plant water usage ET_a (Brown et al., 1998). Brown et al. (2001) concluded that in the desert southwest (using the Penman-Monteith method) a constant K_c value of 0.8 was appropriate for bermudagrass in summer months, considering monthly variation (Brown et al, 2001). Similarly, Zhang et al. (2007) determined that K_c values ranged from 0.66 to 0.92 during a 2007 study involving multiple warm-season turfgrasses in Beijing, China (Zhang et al., 2007).

While seasonal and climatic differences exist, previous research aimed at identifying consumptive water use for warm-season turf has generally resulted in Kc values within the .60 to .80 range for summertime growth periods. These data offer turf managers the ability to calculate and apply water to meet the maximal demand of turfgrass on a daily, weekly, or monthly basis; however, as of 2009 only 18% of superintendents in the U.S. utilize reference evapotranspiration data for ET-based of golf course irrigation management (Throssell, 2009).

Deficit Irrigation for Periods of Water Conservation

Meeting the maximal water use rates of a given turf through use of ET-based irrigation and K_c data is an important strategy in properly managing irrigation water during times when water is plentiful. However, there are increasingly periods or seasons when diminishing water supplies or mandatory allocation reductions force golf course superintendents to reduce irrigation to below consumptive water use (K_c) levels. For example, in times of severe drought, golf courses in the San Antonio area are required to reduce irrigation amounts by 20% of daily ET_o (San Antonio Water System, 2013). Deficit irrigation is the agronomic term used to describe the practice of intentionally maintaining turf at below the maximal water use of the turf (Fu et all, 2004; Wherley, 2011). Deficit irrigation can be used as a viable water conservation tool, especially on golf course fairways, which occupy the largest acreage of irrigated turf on a golf course. However, irrigation levels must be sufficient to produce quality that meets golfer expectations in terms of aesthetic and functional characteristics. The degree of stress or deficit level a turf is able to withstand could be affected by species, environment, geographic location, and the intensity of cultural management at which the turf is maintained. In a Kansas study, tall fescue watered twice weekly at 0.5 x ET_o exhibited exceptional drought resistance, resulting in only small reductions in visual quality (Fry et al, 1989). In a transition zone study evaluating turfgrass response to season long deficit irrigation, zoysiagrass (*Zoysia japonica)* and Kentucky bluegrass (*Poa pratensis)* maintained at a 5 to 6 cm mowing height were both found to be sensitive to deficit irrigation, and both species maintained acceptable quality levels only at their maximal water use rates (Fu et al., 2004). However, in the same study bermudagrass and tall fescue maintained at the same mowing height exhibited acceptable quality at levels below maximal water use rates (Fu et al., 2004). These differences were attributed to drought avoidance characteristics of bermudagrass and tall fescues and their ability to form extensive root systems and explore more of the soil profile (Qian et al., 1997).

A study evaluating Tifway bermudagrass response to deficit irrigation in the arid southwest found dramatic loss of turf quality at irrigation levels below 0.6 x ET_o (Bañuelos, 2010). These results differed from those found in 1999 by Quian and Engelke in Dallas, TX where Tifway bermudagrass was found to exhibit acceptable quality at irrigation levels of 0.17 to 0.5 x ET_o (Bañuelos et al., 2011; Qian and Engelke, 1999). These differences would likely be attributed to differences in seasonal precipitation and soil textural differences between the two locations. Thus, the amount of deficit irrigation turf is able to withstand while exhibiting acceptable quality appears to be influenced by many factors including species, environment, and maintenance level.

Given the growing importance of water conservation in Texas and the lack of data on minimal irrigation requirements for maintaining bermudagrass fairways in the sub-humid to humid regions of Texas, a more detailed understanding of deficit irrigation management on bermudagrass could be highly useful at this time.

Bermudagrass Recuperative Capacity from Irrigation Stress

When water supplies become severely limiting, golf courses sometimes are forced to eliminate fairway irrigation entirely, directing any available water to higher priority areas such as greens and tees. The United States Golf Association (USGA) Green Section has termed this concept 'maintenance up the middle'. This management approach was widely adopted across Texas golf courses during the 2011 drought. Information on the capacity of bermudagrass fairways to tolerate and/or recover from these periods is limited. Steinke and Chalmers (2011) found that all warm-season turf species they tested were able to recover from a 60-day drought to levels greater than

80% green cover within 10-20 days of irrigation, so long as topsoil depth was not restricted. The time required for bermudagrass fairways to recover to acceptable quality and cover levels following deficit- or unirrigated conditions, or how this is affected by successive years of irrigation stress has not been evaluated.

Effects of Traffic Stress on Irrigation Requirements

Turfgrass wear injury is characterized by the crushing and tearing of leaf tissues caused by foot and vehicular traffic (Shearman, 1988). Golf course turf is routinely subject to wear injury due to golf cart traffic, foot traffic, and/or divots. Depending on other environmental factors, traffic injury can lead to an inhibition of growth from chlorophyll degradation and an overall increased susceptibility to pathogens (Trenholm et al., 2000). If deficit irrigation becomes a common approach to water management on golf courses, the influence of traffic or wear injury should be better understood. It would seem likely that grasses managed under deficit irrigation would have lower capacity to recover from injury or withstand traffic, simply due to diminished rates of growth (Wherley, 2011). In previous deficit irrigation research, traffic has been an often-overlooked factor that may have considerable impact on the minimal levels of irrigation a turf can tolerate. Therefore, more detailed examination of traffic impacts on minimal irrigation requirements should be considered.

Impacts of Water Quality on Deficit Irrigation Practices

As potable water supplies for golf course irrigation become strained, those supplies available for irrigation are typically of lesser quality. To alleviate some of the demands placed on potable water and groundwater supplies, an increasing number of golf courses are irrigating with reclaimed or recycled water (King et al., 2000). Additionally many of these water sources contain high levels of salts, making them either saline and/or sodic in nature (Qadir, 2010). Saline irrigation water has potential to cause adverse impacts on plant health by lowering the osmotic potential within the soil solution, and thereby making the water in solution less available to the plant (Qadir, 2010). High salt concentrations can also indirectly reduce plant growth by ion antagonism (Deifel et al., 2006). Sodic irrigation impacts soil physical structure, resulting in decreased soil aggregation among clay particles causing an adverse effect of soil structure over time (Halliwell et al, 2001). High sodium concentrations can also have a toxicity effect in plants.

For golf courses using irrigation of marginal quality, the ability to 'flush' the soil of salts using higher than needed amounts of irrigation (leaching fraction) has traditionally been important in managing salts. Therefore, when lower water quality is used in combination with deficit irrigation practices, a complexity of challenges may arise. It seems likely that water quality could influence the level of deficit irrigation tolerable by turfgrass, however, research is also lacking in this area.

Influence of Trinexapac-ethyl (Primo) on Plant Water Stress

Trinexapac-ethyl (TE) [4-(cyclopropylα-hydroxy-methylene)-3,5dioxocyclohexanecarboxylic acid ethyl ester] is a plant growth regulator (PGR) that when applied to turfgrasses suppresses clipping yield by inhibiting giberillic acid synthesis. TE inhibits the conversion of GA_{20} to GA_1 (Reid and Ross, 1991; Rademacher, 2000); therefore, decreasing cell elongation and increasing the total number of nonstructural carbohydrates (TNC) (Han et al., 1998, Han et al., 2004; Tan and Qian, 2003). While leaf length is reduced, mesophyll cell density, chlorophyll concentration, and leaf area are enhanced (Ervin and Koski, 1998; Ervin and Koski, 2001; Stier and Rogers, 2001; Bunnell et al., 2005; Beasley et al., 2007). These physiological alterations brought about by TE have been found to produce turfgrass color enhancement, visual quality enhancements, and may also influence plant response to stress during times of drought (McCann and Huang, 2007).

Previous research has, to a limited extent, evaluated the effects of (TE) on creeping bentrgrass (*Agrostis palustris*) during onset of drought stress. In one study, TE was applied to creeping bentgrass (*Agrostis palustris*) every two weeks for forty-two days prior to the onset of drought, and was found to improve turf quality compared to untreated controls as plants entered into water stress (McCann and Huang, 2007). In this study, TE was reported to improve heat and drought tolerance of creeping bentgrass by promoting higher photosynthetic activity levels as well as higher cellular hydration compared to the untreated controls (McCann and Huang, 2007). However, the potential benefit of TE in regards to improving warm-season turfgrass quality and vigor under water stress have not been explored.

TE applications to turf are typically made on frequent, 2 to 3 week, intervals (Kreuser, 2010), but use of TE in the context of deficit irrigation programs may allow for less frequent application schedules, especially if metabolism of TE within the plant is suppressed by water stress. Information is lacking concerning metabolism of TE as it relates to irrigation. Under ideal conditions, the time required for plants to metabolize

TE appears to range from 2 to 3 weeks in annual bluegrass (*Poa annua*) to 3 to 4 weeks in bermudagrass (Fagerness and Yelverton, 2000; Fagerness et al., 2004; Kreuser, 2007; McCullough et al., 2007). Knowledge of the effects of irrigation level on metabolism of TE could aid in developing appropriate application schedules for turf managed under differing amounts of irrigation. However, characterization of the response of bermudagrass to TE under increasing drought stress or deficit irrigation has yet to be explored.

CHAPTER II

IMPACTS OF DEFICIT IRRIGATION AND TRAFFIC STRESS ON BERMUDAGRASS FAIRWAYS

Abstract

Texas golf course water use has become increasingly regulated due to persistent drought conditions, diminishing water supplies, and population growth. Golf courses are increasingly faced with reductions in water allocation, but information is limited regarding minimal levels needed for maintaining adequate quality, persistence, and recovery. The objectives of this 2-year study were to 1) characterize the response of ‘Tifway’ bermudagrass (*Cynodon dactylon x C. traansvalensis* Burt. Davy) managed similarly to golf course fairways to season-long irrigation at crop coefficients 0.6, 0.45, 0.3, and 0 x reference evapotranspiration (ET_o), 2) determine the impacts of simulated traffic on irrigation requirements, and 3) quantify divot recovery as a function of irrigation amount and traffic. Digital analysis was used to quantify changes in turf canopy through the multiple seasons of irrigation stress. Without the influence of traffic, an irrigation level of 0.3 x ET_o was adequate to maintain acceptable quality, where there were only a few rating dates that quality fell below acceptable levels. Traffic stress reduced turf quality under all irrigation levels in both years. Canopy temperatures increased considerably with reduced irrigation, with up to a 20°C difference between irrigated and non-irrigated plots observed. Upon resuming full irrigation levels in October, all deficit and unirrigated treatments rebounded to ~90% green cover after the first summer, but were much slower to recover following the subsequent year of

irrigation stress, particularly in unirrigated plots. Divot recovery times were also noticeably delayed by deficit irrigation practices. Root development was not affected by irrigation levels during the first season, but was during the second.

Introduction

As drought and population growth continue to place greater strains on water supplies, golf course turf managers are confronted with decisions of how to best allocate irrigation water to meet the demands of the turf. One approach is to reduce overall irrigated acreage while irrigating high-priority areas at full irrigation levels. Another strategy is to irrigate turf at deficit, or stress levels of irrigation, which involves intentionally irrigating a plant below its maximal water use rate (Wherley, 2011).

In order to accurately meet turfgrass water requirements, it is necessary to understand its consumptive water use rate (evapotranspiration under fully irrigated, ideal conditions), also referred to as the crop coefficient (K_c), as it relates to reference ET for a particular species and a given location. Previous researchers have sought to determine crop coefficients (K_c) for turfgrass species. Meyer Gibeault et al. (1987) suggested a year-long K_c value for warm-season grasses of 0.6. This has become a widely accepted value for irrigation of warm-season grasses; however, more recent studies have indicated higher K_c values may more accurately reflect warm-season grass water use. In a comprehensive study evaluating various turfgrass K_c values, Carrow (1995) found that using a FAO modified Penman equation Tifway Bermudagrass' K_c value varied from 0.53 to 0.97 (Carrow, 1995). Allen et al. (1998) recommended a K_c value of 0.80 to 0.85 for irrigating warm season grasses (Allen et al., 1998). Furthermore, Brown et al. (1998)

concluded that K_c values can vary up to 25% from one geographic location to another. For a K_c value to be widely accepted the K_c value should be matched to a specific ET_o procedure that ensures accurate estimation of ET_a (Brown et al., 1998). Brown et al. 2001 concluded that in the desert southwest (using the Penman-Monteith method) a constant K_c value of 0.8 was appropriate for bermudagrass in summer months, considering monthly variation (Brown et al, 2001). Similarly, Zhang et al. (2007) determined that K_c values ranged from 0.66 to 0.92 during a 2007 study involving multiple warm-season turfgrasses in Beijing, China (Zhang et al., 2007). While seasonal and climatic differences exist, previous research aimed at identifying consumptive water use for warm-season turf has generally resulted in K_c values to be within the 0.6 to 0.8 x ET_o range for summertime growth periods. These data offer turf managers the ability to calculate and apply water to meet the maximal demand of turfgrasses on a daily, weekly, or monthly basis; however, as of 2009 only 18% of superintendents in the U.S. implement reference evapotranspiration for ET-based management of golf course irrigation (Throssell, 2009).

For the Southern United States where warm season turfgrasses are used, consumptive water use rates of warm season turf can be estimated using K_c values that range from 0.58 for low use sites to 0.83 for maintenance intensive sites (Romero, 2010; Zhang et al., 2007). However, since turfgrass is a crop maintained for an aesthetic purpose, in theory it could be irrigated at deficit levels that would decrease biomass production while still maintaining acceptable appearance. Replacing 0.6 x actual evapotranspiration (ET_a) has been suggested to produce acceptable bermudagrass turf quality; however, it is difficult to relate this value to season long irrigation programs on intensely managed turfgrass like golf course fairways where traffic injury can influence plant water needs in regards to durability and recovery (Fu et al, 2004; Qian and Engelke, 1999).

During times in which irrigation is to be limited, it is advised to limit traffic as drought stress will increase with plant injury from traffic; however, limiting traffic might not always be possible for high traffic turf areas such as golf course fairways. While theory could suggest that turfgrass quality would rapidly decrease under situations of traffic stress with limited irrigation, little is known of the minimal water requirements for turfgrasses receiving traffic. In 2000, Brown et al. concluded that warm-season turf irrigated below 0.6 x ET_o would produce water stressed conditions and suggested that irrigating above the 0.6 K_c level is suitable for turf conditions where traffic is high (Brown et al., 2000). However, further research is needed to evaluate turf conditions produced by irrigation levels below 0.6 x ET_o where turf is subjected to regular traffic.

Golf course fairways are also subjected to turf injury caused by the removal of turf due to the striking of a golf ball, which is termed “divots”. The ability of turf to recover from divots has been studied in relation to species and fertilization (Horgan, 2007; Karcher, 2005; Patton, 2009; Trappe, 2011), but information is lacking regarding the effects of deficit irrigation on divot recovery rates. Effects of irrigation frequency on divot recovery has been evaluated on creeping bentgrass, but the rate of divot recovery did not differ between plots irrigated daily and those receiving less frequent irrigation every 3 to 4 days (Walker, 2003).

While irrigating turf at a stress level may prove to be an effective water conservation strategy, allowing turf to go dormant by not irrigating at all during drought has been employed by turf managers in situations where providing supplemental water is not possible. In this situation, turf managers rely on rainfall to be the only water source during this time in hopes of turf recovery when supplying supplemental water will be possible. Most established, warm season grasses possess the ability to withstand prolonged drought by entering dormancy (Steinke et al, 2011). In a 2006-2007 study evaluating the ability warm-season turfgrass species and cultivars to survive 60 days of drought, all warm-season grasses tested were able to survive and recover following return of irrigation (Steinke et al, 2011). It should be noted, however, that separate plots were used for both years of the study, so cumulative effects of successive drought years could not be evaluated. The ability of bermudagrass fairway turf to persist and recover to acceptable quality and cover levels following multiple seasons of deficit or unirrigated conditions has not been fully investigated.

The objectives of this 2-year field study were to 1) evaluate the effects of 4 irrigation levels (0.6, 0.45, 0.3, and 0 x ET_o) on Tifway bermudagrass fairway quality, 2) monitor soil moisture and salinity in plots to determine the relationship with quality decline in the field, 3) characterize the ability of bermudagrass to withstand and recover from simulated traffic at each irrigation level, and 4) evaluate the extent of recovery possible following resumption of full irrigation levels during September and October.

Materials and Methods

Research Location and Design

This study was conducted over the 2012 and 2013 growing seasons at the Texas A&M Turfgrass Research Laboratory in College Station, Texas. Plots of established 'Tifway' bermudagrass (*Cynodon dactylon x C. transvaalensis* Burt. Davy) were used for the study. Soils at the site were a Boonville fine sandy loam (fine, montmorillonitic, thermic, Vertic Albaqualf). The study was arranged as a completely randomized design with three replicate plots per treatment.

Irrigation main plots (6.1 m x 6.1m) received irrigation based on K_c values of 0.6, 0.45, 0.3, or 0 x ET_o, based on an onsite weather station that was part of the Texas ET network. This network used the Penman-Monteith equation for calculating ET_o. Irrigation was supplied 3 times weekly from April through August. From September through October of each season, all plots received full irrigation at K_c levels of .60 x ET_o so that recovery from drought stress could be evaluated within plots. On-site rain gauges were used for determining contributions from rainfall, with rainfall amounts of up to 1" accounted for when determining weekly water requirements.

The turf was mowed 3 times weekly throughout the season using a triplex reel mower and fertilized at an annual rate of 147 kg N ha^{-1} using (21-0-0) ammonium sulfate. Fertilizer was applied every six weeks at a rate of 36.8 kg N ha^{-1} from April through September.

Simulated Traffic

The plots were further subdivided into two 6.1 m x 1.5 m sub plots, one of which received traffic. A modified Kady traffic simulator (Williams et al., 2010) was used to supply traffic stress. Soft spike golf shoes were mounted to the unit to attempt to simulate golfer foot traffic. Traffic treatments were applied from July through August of both seasons. Trafficking took place 2 times weekly with 3 passes over a plot per each traffic event, for a total of 6 passes weekly. This is the first time this type of machine has been used to simulate golf traffic so the traffic amounts were chosen arbitrarily.

Divot Recovery

Recovery rates of divots as influenced by irrigation level and infill mixture were also determined during the study. A divot simulator (Fry et al., 2008) was constructed using a modified edger with a stacked series of blades. This unit was used to remove two uniform 5 cm wide x 10 cm long x 1.3 cm deep divots from each untrafficked plot in July of 2012 and 2013. Divots were then backfilled with either straight sand or an 85:15 [(v:v) sand:peat] divot mixture. Thirty days after divots were made, digital image analysis (Richardson et al., 2001) was used to evaluate percent green cover of divots to determine the subsequent rate of turf recovery within each irrigation and divot mix treatment.

Evaluation of Seasonal Turf Performance

Turfgrass performance was evaluated during the study through visual ratings of turfgrass quality, digital image analysis for green color retention, and canopy to air temperature ratios. Turfgrass plots were visually rated on a scale from 1 to 9 with 5 representing minimal acceptable quality. These quality ratings took into account both functional and aesthetic aspects of the turf and were based on a combination of color, density, uniformity, texture, and also perceived playability. For reference, a value of 1 would indicate completely brown turf, and 9 would indicate perfect green turf, i.e. uniform, dense, dark green turf. Visual quality ratings were taken mid-to-late-morning, prior to any afternoon wilt occurring in plots.

Each irrigation treatment were also analyzed for percent green cover using the digital image analysis software SigmaScan (SigmaScan, SPSS, Chicago, IL) (Richardson, 2001). Digital images were taken twice monthly from May through December using a Nikon Coolpix camera coupled to a 0.6 m x 0.6 m square light-box that was randomly positioned within each plot. The light box cancelled out outside light and created uniform light within the box (Karcher, 2005). The SigmaScan software operates by creating an average hue saturation and brightness level (HSB), a color space based upon human perception of color level for each image (Karcher, 2003).

Canopy temperatures for treatments were also obtained twice monthly as an early indicator of turf stress using a handheld infrared thermometer (Model 2956, Spectrum Technologies, Aurora, IL). Readings were taken during mid-afternoon on cloudless days.

Evaluation of Root Development

In September of both seasons, a truck-mounted Giddings Probe (Giddings Machine Company, Windsor, CO) was used to remove two root/soil samples (5 cm diameter x 30 cm deep) from non-trafficked plots within each irrigation level. These samples were rinsed using water and sieved to separate roots from soil. Roots were then oven-dried for 72 hours and weighed.

Soil Evaluations

Irrigation water at the site originates from a municipal source characterized by high sodium bicarbonate levels. Therefore, over the course of the season, sodium adsorption ratio (SAR) and salt accumulation were monitored to determine the extent of sodium accumulation as it relates to irrigation level. Soil samples (0-15 cm depth) were obtained at the start of each season, prior to irrigating (May), as well as the end of the study period (September). Samples were analyzed for SAR at the Texas A&M Agrilife Soil, Water, and Forage Testing laboratory. Soil salinity in plots was also monitored through bi-weekly measurements obtained using a handheld electrical conductivity (EC) meter (FieldScout EC 110, Spectrum Technologies, Aurora, IL). EC readings were obtained for the 7.6 cm depth in plots. Wireless Pro soil moisture sensors (Ugmo Inc., King of Prussia, PA) were also installed at a 7.6 cm depth in each plot for documenting changes in volumetric water content and its relationship with visual quality changes over the season.

Analysis of Data

Data for each parameter were subjected to analysis of variance using the general linear model, univariate test procedure using SPSS ver. 21.0 (IBM Corp, Armonk, NY) to determine statistical significance of the results. Where analysis of variance indicated a significant study effect, parameters were presented separately by study. Mean separation procedures were performed using Tukey's HSD at the $P \leq 0.05$ level.

Results

Annual precipitation at the site was close to normal for both seasons, although little rainfall was received during the summer months, particularly for the 2013 season (Figure 2.1, 2.2). Following a wet late winter in 2012, intermittent rain was received for the first half of the summer, while August and September became very hot and dry. In 2013, a wet May was followed by 3 months with little to no rainfall. Evapotranspiration rates fluctuated from ~0.5 to 0.8 centimeters per day during the 2012 summer, and up to 1.1 centimeters per day for 2013 (Figure 2.3 and 2.4, respectively).

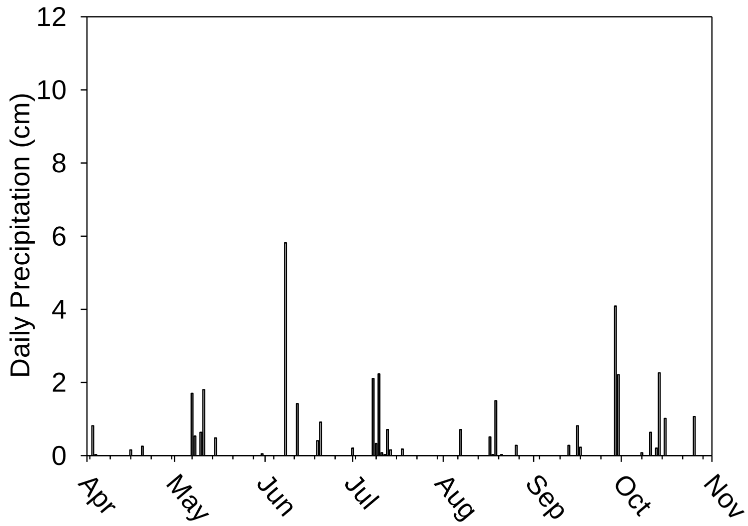

Figure 2.1. Daily percipitaion (cm) throughout the 2012 season. Data from the Texas ET network, Texas A&M Golf Course Weather Station.

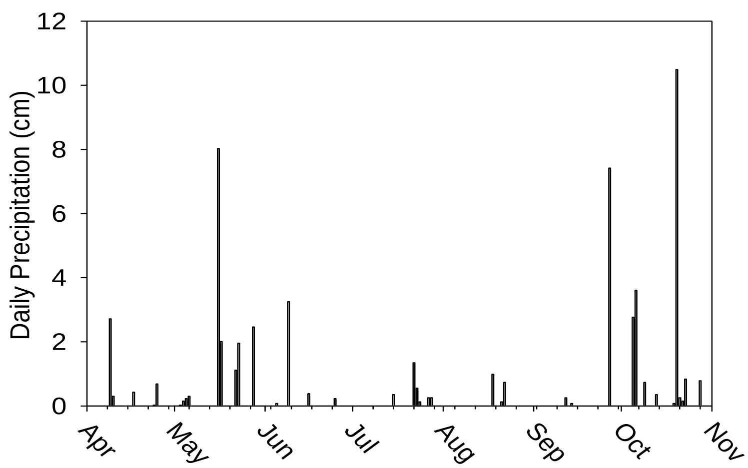

Figure 2.2. Daily percipitation (cm) throughout the 2013 season. Data from the Texas ET network, Texas A&M Field Lab Weather Station.

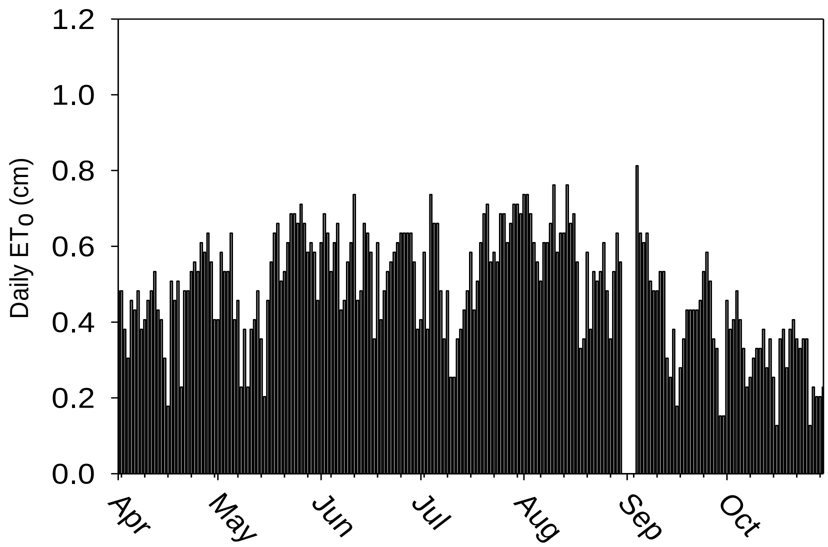

Figure 2.3. Daily ET$_o$ throughout the 2012 season. Data from the Texas ET network, Texas A&M Golf Course Weather Station.

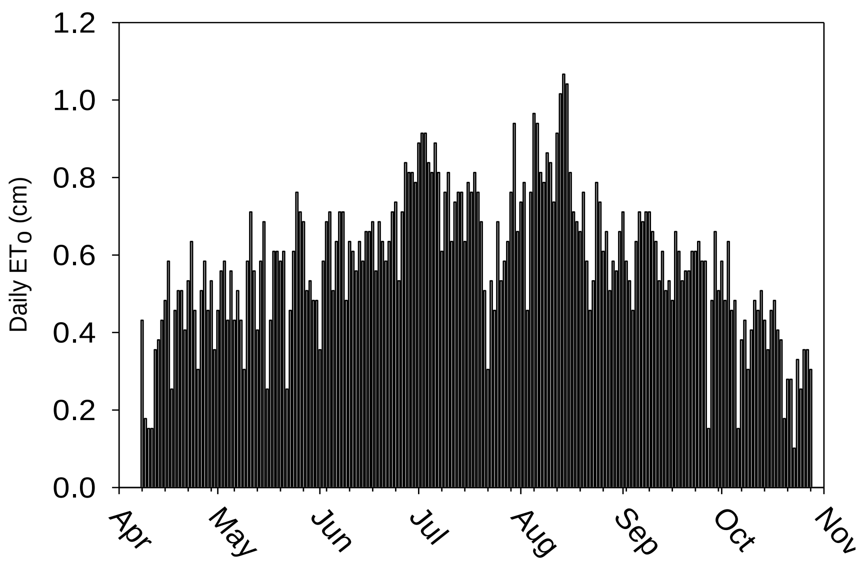

Figure 2.4. Daily ET$_o$ throughout the 2013 season. Data from the Texas ET network, Texas A&M Field Lab Weather Station.

Table 2.1. Analysis of variance table for week, irrigation level, and week x irrigation level. Where year main effects were significant ($P \leq 0.05$), years have been presented separately.

	P-values										
	Visual Quality		Percent Green Cover		Canopy Temperatures		Total Root Mass		Electrical Conductivity	Sodium Adsorption Ratio	
	2012	2013	2012	2013	2012	2013	2012	2013		2012	2013
Week (W)	***	***	***	***	***	***			***	NS	NS
Irrigation (I)	***	***	***	***	***	***	NS	***	***	NS	*
W x I	***	***	***	***	***	***			NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001, respectively

Deficit Irrigation Effects on Turf Quality and Cover

The week by irrigtion level interaction effect on turf quality was significant for both years of the study (Table 2.1). This was primarily due to the progressive summer decline in quality of deficit and non-irrigated plots relative to fully irrigated controls. While plots began both seasons at statistically similar levels of quality, the 0.6 x ET_o treatment maintained superior visual quality relative to all other irrigation treatments during the summer months (Figure 2.5). Deficit irrigation levels of .45 x ET_o and .3 x ET_o resulted in significantly lower turf quality than the fully irrigated treatment on only 2 of 21 and 3 of 21 dates, respectively. On all other dates, irrigation levels as low as 0.3 x ET_o were sufficient to sustain acceptable visual quality (≥5) in the context of this 3 day per week irrigation schedule throughout both seasons. However, unirrigated plots rapidly declined to unacceptable quality levels by June of both years, indicating natural precipitation was not adequate to maintain acceptable turf quality.

Digital image analysis for percent green cover confirmed visual quality ratings (Figure 2.6). As such, green cover values of 75% closely aligned with the minimal quality threshold of 5. In general, irrigation of .30 x ET_o or greater supported >75% green cover over the entire first season, however, slightly diminished amounts of green cover were detected in these plots in the second season (Figure 2.6).

Fall Recovery

Full irrigation amounts (0.6 x ET_o) were resumed in all plots in early September of both years. As with turf quality, green cover rebounded following return of full irrigation levels to deficit and unirrigated plots in year 1, but unirrigated plots were noticeably delayed in recovering the second season, only reaching ~25% green cover by the late October rating date (Figure 2.5, 2.6).

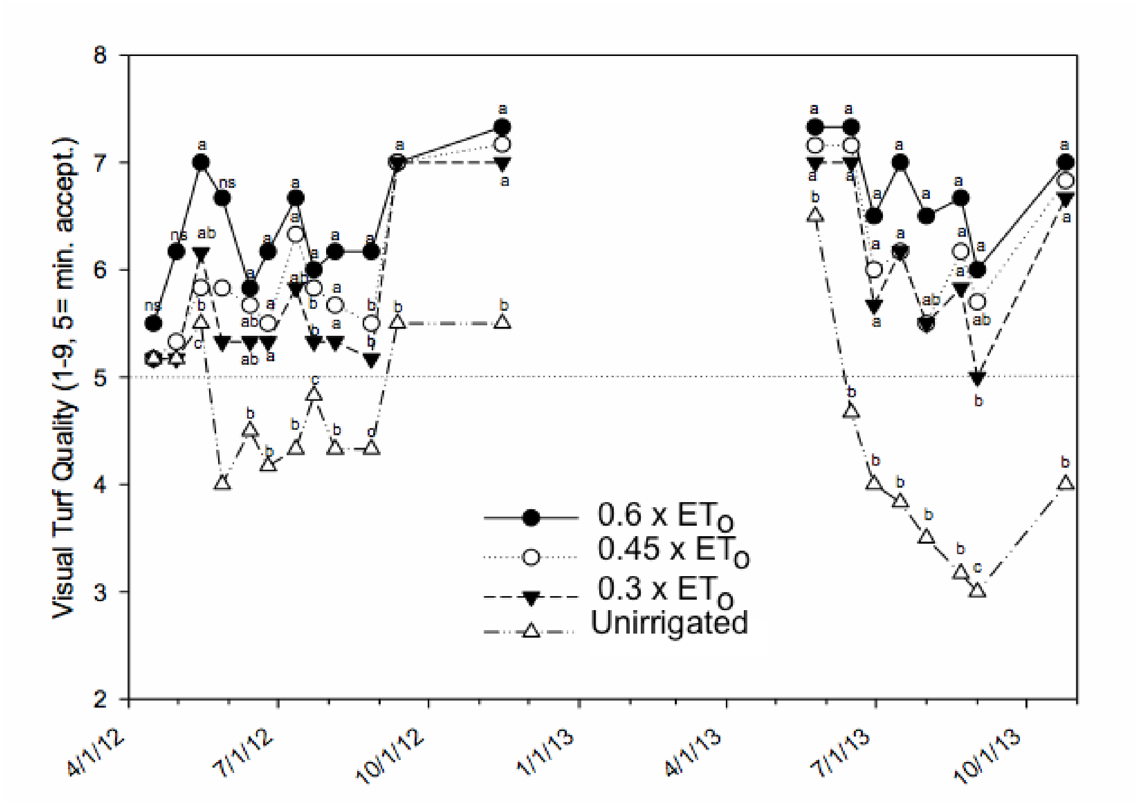

Figure 2.5. Visual quality as affected by irrigation level in 2012 and 2013. Data were pooled across traffic treatments. Means with the same letter at the same date are not significantly different based on Tukeys HSD at p≤ 0.05. Dotted horizontal line indicates minimum acceptable turf quality.

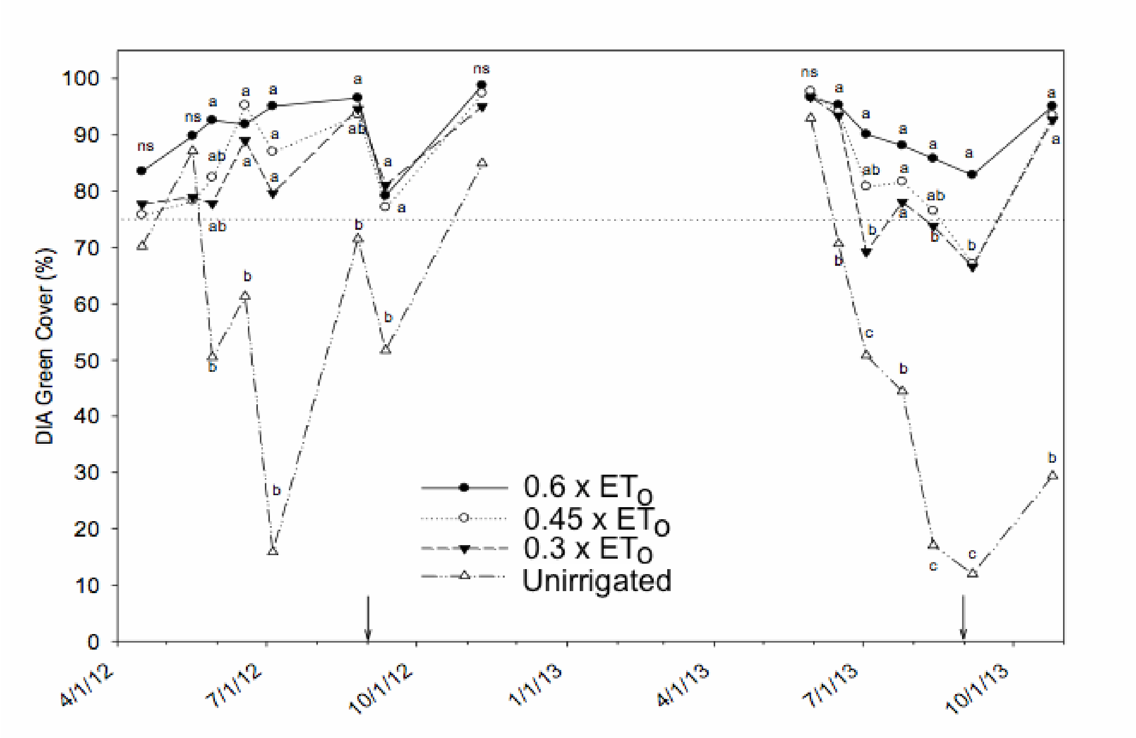

Figure 2.6. Percent green cover as affected by irrigation level in 2012 and 2013. Data were pooled across traffic treatment. Means with the same letter at the same date are not significantly different based on Tukeys HSD at P≤ 0.05. Dotted horizontal line indicates minimum acceptable percent green cover.

Canopy Temperatures

A significant week x irrigation interaction effect also occurred for canopy temperatures both seasons (Table 2.1). Generally, canopy temperatures within the fully .60 x ET_o irrigation treatments were at or slightly above ambient air temperature (data not shown). However, as evaporative demand increased in early summer, reflective canopy temperatures noticeably increased (Figure 2.7). This was most apparent where irrigation was being withheld entirely, as temperatures increased by as much as 20°C for the non-irrigated compared to the other irrigation treatments. Greater canopy temperature differences were observed in the second season, likely due to higher temperatures, less rainfall, and overall higher evaporative demand on the turf (Figures 2.2, 2.4).

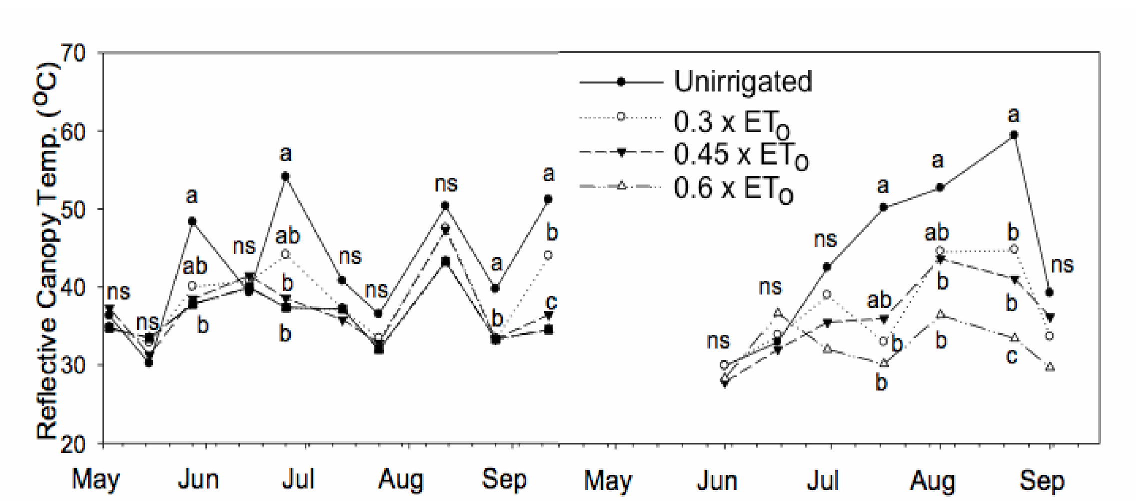

Figure 2.7. Reflective canopy temperatures as affected by irrigation level in 2012 and 2013. Data were pooled across traffic application. Means with the same letter at the same date are not significantly different based on Tukeys HSD at P≤ 0.05.

Impacts on Root Development

There was no detectable effect of irrigation on root development within the 0 to 25 cm depth in year 1; however, irrigation level did impact root mass in the second season (Table 2.1, Figure 2.8). Root dry weight increased as irrigation level increased, with exception that the .45 x ET_o and .60 x ET_o irrigation treatments were similar (Figure 2.8). Since there were no differences in root dry mass among irrigation levels during the 2012 season but differences were observed among irrigation treatments during the 2013 season, this may demonstrate the long-term cumulative effect of deficit irrigation.

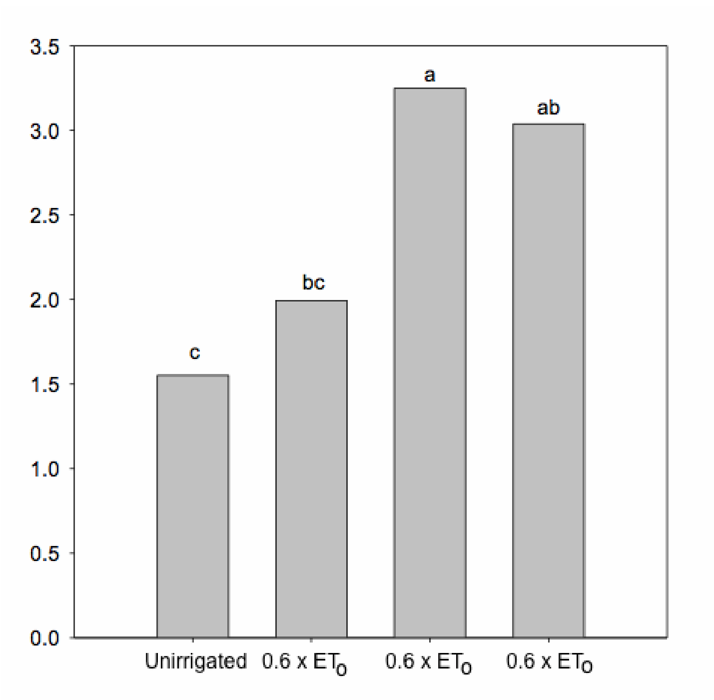

Figure 2.8. Root dry weights (grams) as affected by irrigation level in 2013. Data are for non-trafficked plots. Means with the same letter at the same date are not significantly different based on Tukeys HSD at P≤ 0.05

Irrigation Effects on Salinity

Electrical conductivity readings were variable in the first year of the study, and no differences occurred among irrigation level was detected (Table 2.1, Figure 2.9). In the second season, however, a significant irrigation treatment effect on EC occured. As such, EC measurements increased with increasing irrigation (Figure 2.9). The EC values ranged from about 0.1 at the initiation of the study to as high as 0.9 in the 0.60 x ET_o treatments during year 2. The EC never exceeded levels of 1 dS m^{-1} in either season, indicating that salinity levels never reached a stressful or damaging threshold in these soils for bermudagrass. Bermudagrass tolerates salinity levels above 10 dS m^{-1} (Harivandi, 1992).

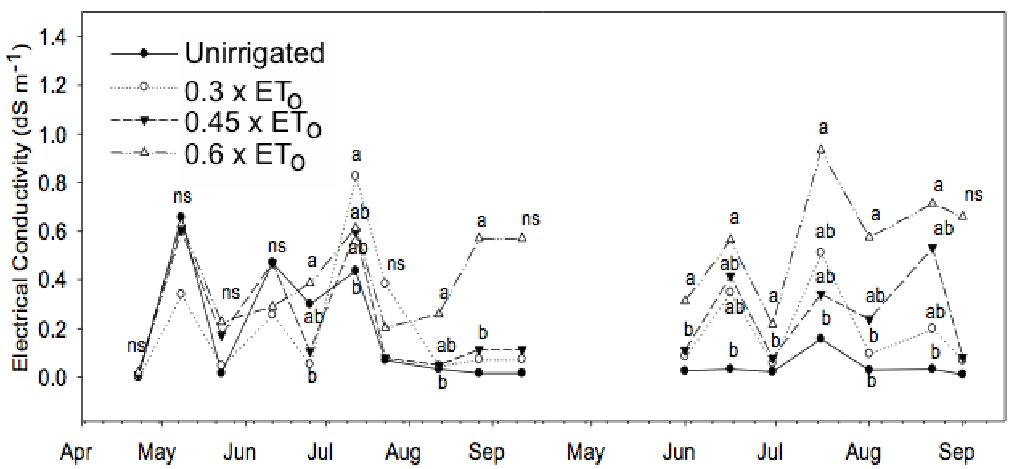

Figure 2.9. Electrical conductivity (dS m^{-1}) as affected by irrigation level for the 2012 and 2013 seasons. Data are for non-trafficked plots. Means with the same letter at the same date are not significantly different based on Tukeys HSD at $P \leq 0.05$.

There was no detectable effect of irrigation on SAR in year 1, but there was a significant irrigation main effect on SAR in the second season (Table 2.1, Figure 2.10). It should be noted that composite sampling across the plots revealed that SAR values were relatively elevated, and sodic (SAR>13), at the project initiation prior to irrigation treatment levels being imposed. These increased to even higher levels in all irrigated plots by the end of the first season (Figure 2.10). A noticeable decrease in SAR occurred from addition of gypsum to plots during the dormant season. Generally, the highest SAR was associated with the 0.6 x ET_o treatment, with a gradually decreasing SAR as irrigation level decreased.

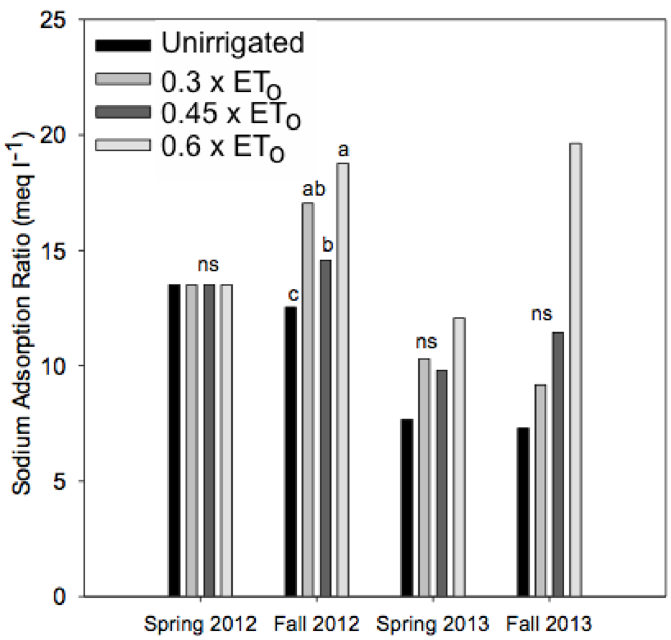

Figure 2.10. Sodium Adsorption Ratio (SAR) as affected by irrigation level for the 2012 and 2013 seasons. Data are for non-trafficked plots. Bars with the same letter are not significantly different based on Tukeys HSD at P≤ 0.05.

Irrigation Effects on Soil Moisture (SVWC)

Soil volumetric water content was monitored continually throughout the study by sensors in each plot at a 7.6 cm depth. The SWC was variable during the first season, likely due to acclimation and soil settling following installation of sensors in March 2012. Data from the 2013 season were much less variable and the relationship between SVWC and turf quality were determined (Figure 2.11). Soil moisture ranged from as low as 4% in unirrigated plots to as high as 29% in .6 x ET_o plots. Regression analysis indicated a fairly strong relationship between turf quality and soil moisture (R^2=0.49). The results of this study suggest that when managing bermudagrass fairways on fine sandy loam soil, maintaining SVWC at the 7.6 cm depth above ~12% volumetric water in order to sustain acceptable levels of turf quality. When SVWC fell below this level, turf quality was generally below acceptable levels in this study.

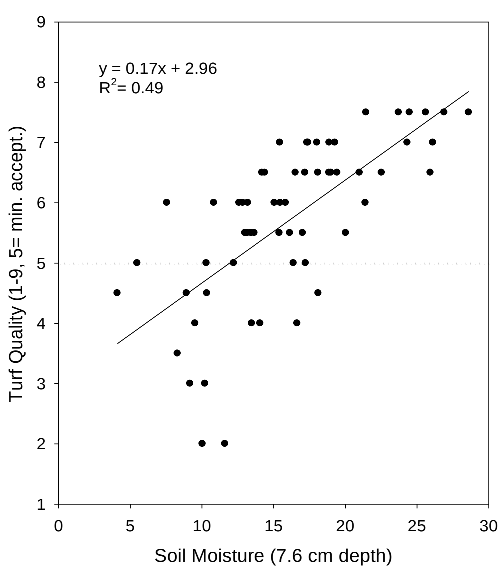

Figure 2.11. The relationship between soil moisture at 7.6 cm below the soil surface visual turf quality ratings during the 2013 growing season.

Traffic Effects on Percent Green Cover

Traffic was imposed beginning in early July and continued through August of both years. Significant week x traffic and week x irrigation effects occurred for percent green cover in both 2012 and 2013 (Table 2.2, Figure 2.12). In 2012, traffic caused a nearly 50% reduction in percent green cover (Figure 2.12). Despite this, the bermudagrass in all treatments recovered to similar levels of green cover by early, due to adequate availability of moisture from rainfall and irrigation.

In the 2013 season, traffic showed significant, but less substantial effects on green cover, with only a ~10% decline in green cover occurring due to traffic. Again, bermudagrass in trafficked and non-trafficked treatments recovered to similar levels of green cover by the final fall evaluation.

Table 2.2. Analysis of variance table for week, irrigation, and traffic effects on turf visual quality and percent green cover. Year main effect was significant for both parameters ($P \leq 0.05$).

P- values		
	Summer Traffic % Green Cover	
	2012	2013
Week (W)	**	**
Irrigation (I)	***	***
W x I	**	**
Traffic (T)	***	***
W x T	**	**
I x T	NS	NS
W x I x T	NS	NS

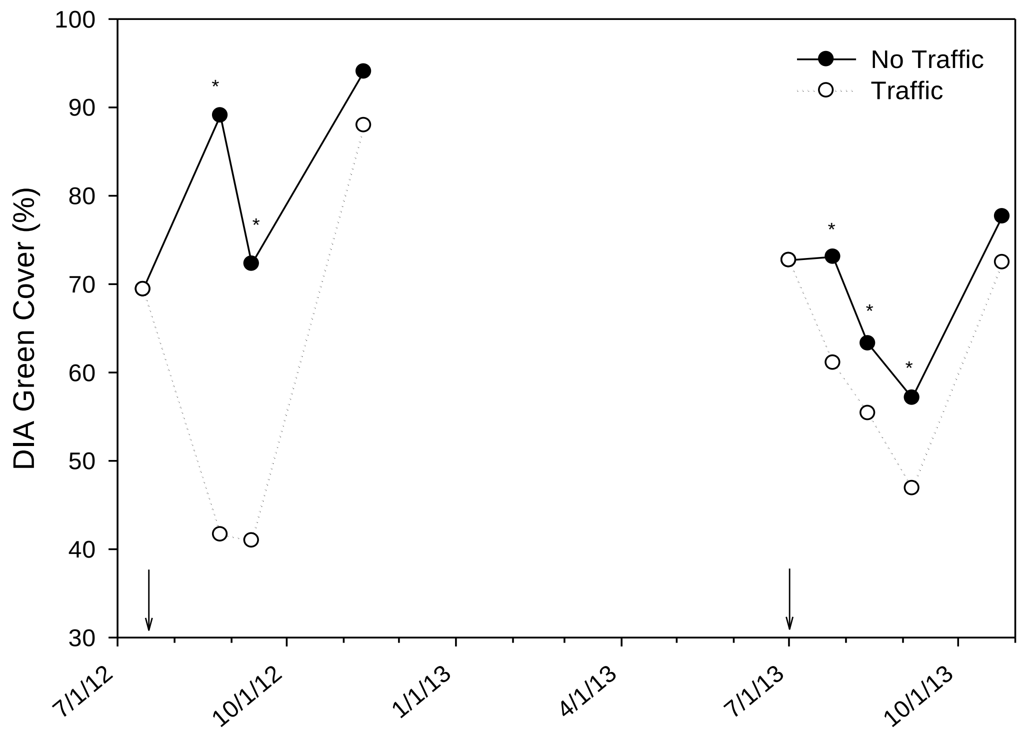

Figure 2.12. The digital image analysis (DIA) of percent green cover as affected by traffic in 2012 and 2013. Data were pooled across irrigation levels. Means with astericks at the same date are not significantly different based on Tukeys HSD at P≤ 0.05.

Divot Recovery

Irrigation main effects on divot recovery were significant in both years of the study (Table 2.3, Fig. 2.13). Divot recovery varied from as low as 10 to 20% green cover for unirrigated treatments to nearly 80% green cover in the 0.6 x ET_o treatment. Lower irrigation amounts resulted in significantly increased divot recovery time (as indicated by lower amounts of green cover in divots 30 days after divots were made) during 2012, but not 2013 (Figure 2.13). The unirrigated treatment exhibited the slowest divot recovery time in both years. In 2012, after 30 days of recovery, the turf coefficient of 0.6 x ET_o irrigation treatment had 76% percent green cover within divots compared to 40 and 60% green cover for the 0.3 and 0.45 x ET_o treatments. In 2013, all irrigated plots recovered at similar rates, with only unirrigated plots exhibiting severely increased recovery time. When comparing between sand vs. sand/peat divot mix infills, there were no statistical differences in rates of recovery, as irrigation alone was the primary factor affecting divot recovery time (Table 2.3).

Table 2.3. Analysis of variance table for irrigation level and divot mix effects on divot recovery rate. Year main effect was significant ($P \leq 0.05$).

P-values		
	Divot Recovery	
	2012	2013
Irrigation	***	***
Divot Mix	NS	NS
Irrigation x Divot Mix	NS	NS

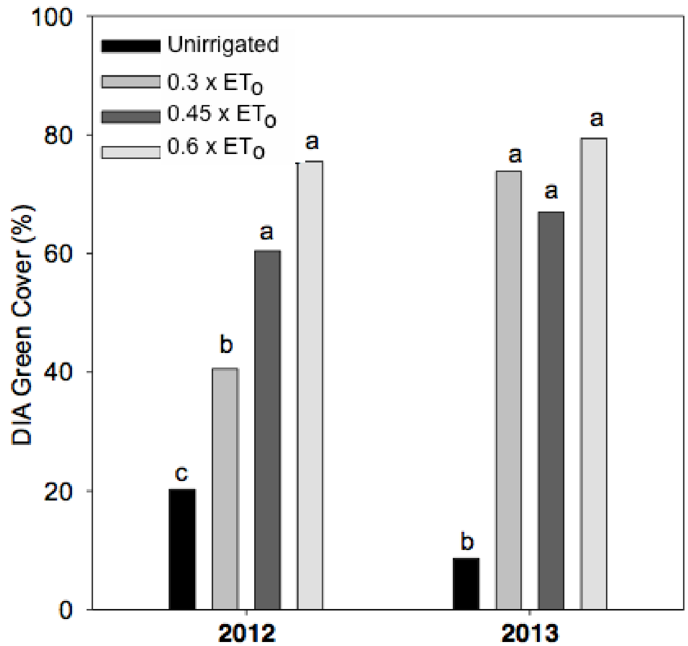

Figure 2.13. Divot recovery in relation to irrigation treatments for 2012 and 2013. Data were pooled across divot mix. Bars with the same letter are not significantly different based on Tukeys HSD at $P \leq 0.05$.

Discussion

Deficit Irrigation Effects on Bermudagrass Fairway Turf Quality

In this experiment conducted over two seasons, where irrigation was supplied at a three time per week frequency, Tifway bermudagrass maintained acceptable quality for most of the season when irrigated at levels substantially less than the commonly recommended K_c of 0.6. Our results therefore are in agreement with Fu et al. (2004) who reported that bermudagrass grown in Manhattan, Kansas could maintain acceptable quality throughout summer months while being irrigated with as little as 60% x actual evapotranspiration (ET_a). This 60% x ET_a treatment would theoretically correspond to irrigating at 0.36 x ET_o in our experiment, 20% higher than our lowest deficit treatment of 0.3 x ET_o. The results also agree with those of Qian and Engelke (1999), who reported minimal bermudagrass irrigation requirements of 0.17 to 0.50 x ET_o in a Dallas, TX study.

The ET_a for bermudagrass could vary during the summer months. However, 0.6 x ET_o has been widely accepted as an industry standard crop coefficient for warm-season turfgrass and would likely be the baseline amount for golf course superintendents using an ET based irrigation program.

Bermudagrass Fall Recovery Following Drought Stress

The first season's fall recovery results were consistent with Steinke et al. (2011). They reported that upon applying irrigation during the fall following a 60-day drought, bermudagrass had greater than 80% recovery of plots. In the second year of the study, after irrigation was returned to full levels in September, bermudagrass exhibited delayed recovery, reaching only 30% green cover and not attaining acceptable quality levels (Figure 2.5, 2.6). The delayed recovery in year 2 suggests a possible cumulative effect of irrigation treatments. It should also be noted that ET demand was much higher in the second growing season (2013), which also may have compounded the degree of stress for the bermudagrass. Regardless, the recovery of bermudagrass in all irrigation treatments was similar in both years. These data indicate that deficit irrigation of bermudagrass fairways is a feasable way to conserve water while maintaining turfgrass performance long-term.

Irrigation and Traffic Effects on Green Cover and Recovery

Although no traffic x irrigation interaction effects occurred, traffic did negatively impact turf at all irrigation levels by reducing green cover. Surprisingly there was no detectable difference between traffic treatments in terms of fall recovery, during 8 weeks after resuming uniform irrigation (Figure 2.12).

Whether or not to allow traffic under periods of drought has always been a difficult decision for golf course superintendents, and information of this type regarding irrigation x traffic effects on bermudagrass are lacking. It is common that many golfers driving carts onto fairways will enter the fairway in the same location, causing a heavy traffic area at the edge of the fairway. While our traffic applications were representative of traffic golf courses might receive in the middle of the fairway, one might expect these “entrance points” to be more severely impacted by traffic if irrigation levels are reduced or withheld entirely, and therefore results may not be representative of more highly trafficked areas of turf on golf courses.

Irrigation Effects on Divot Recovery

It is difficult to explain why delayed divot recovery was observed with lower irrigation in year 1 but not year 2, especially since less rainfall was received in year two (Figures 2.2 and 2.13). However, divot recovery results within the unirrigated treamtents were consistent from year one to year two, emphasizing the importance of at least some supplemental irrigation for promoting healing of divots. Surprisingly, divot infill mix also did not affect divot recovery time. Our results indicate that addition of peat moss to the infill mix provided no benefit compared to sand alone. Based on these results, irrigation level was the primary factor influencing divot recovery. These results differ from an Environmental Institute for golf study in 2001 in Urbana, Illinois in which divot recovery time was impacted by different infill mixes; however, irrigation level was not included as a factor in that particular study, as all plots received similar levels of irrigation (Schmitz et al, 2005).

Canopy Temperatures

One of the benefits offered by turfgrass systems is their significant cooling capacity. Through transpirational cooling irrigated turfgrasses dissipate thermal energy and have a positive impact on human comfort. While deficit irrigation may help sustain water resources, it could substantially increase turfgrass heat loading, and therefore negate some of turf's positive benefits. We observed a definite increase in reflective turf canopy temperatures between the 0.6 x ET_o compared to the unirrigated irrigation treatments; however, this was only observed during a few dates late in each season (Figure 2.7). Our findings for bermudagrass agree with those of Wherley (2011) who reported that so long as adequate green cover was present in Empire zoysiagrass (*Z. japonica*), only minor increases in canopy temperatures occurred.

Irrigation Level Effects on SAR and Salinity

Elevated salinity can impact turfgrass growth by causing ion toxicity, rendering water present in the soil "unavailable", and over time can cause detrimental impacts on soil structure. Furthermore, salts can quickly accumulate near the soil surface when irrigating with salt-laden water, and this can be exacerbated by high evaporative demand (Marcum, 2006). In this study, we found that higher amounts of salt (both sodium and total salts) accumulated as irrigation K_c increased. High salinity is usually managed by applying high levels of irrigation to "flush" or leach out salts, and therefore one might expect the highest salt accumulation while irrigating at or just below the turf coefficient. In this study, we observed the highest salt accumulation occurring for the 0.6 x ET_o treatment. Also, salts never accumulated to damaging levels for bermudagrass, which was reported to tolerate EC levels of 10 dS m^{-1}. This is likely because the irrigation water used in this study was not saline to begin with, and also because numerous rain events possibly flushed some of the added salts below the root zone.

Elevated SAR was the primary issue occurring in these soils resulting from high levels of sodium bicarbonate in the irrigation water. Elevated soil SAR (>13) has the potential to reduce soil permeability and infiltration due to its dispersive effects on soil colloids (Marcum, 2006). As with EC, SAR exhibited a trend toward elevated levels with increasing irrigation K_c, with all irrigation treatments at the end of the first season reaching sodic levels. At the end of the second season, soil SAR for the 0.6 x ET_o

treatment reached levels above 20 (Figure 2.10). It should also be noted that gypsum applied during the winter, between the two years failed to effectively reduce SAR to non-sodic levels, and likely, a much more aggressive gypsum application program would be a recommended practice.

Summary and Conclusions

As golf courses are faced with greater reductions in water allocations, there is limited information for golf course superintendents regarding the minimal irrigation amounts that will allow them to meet acceptable quality. The hypothesis of this study was that bermudagrass fairways could sustain adequate growth and persistence while irrigating at levels less than the turfs maximal water use rate, this being done by using ET-based weather data to theoretically calculate plant water use. For this study we considered 0.6 x ET_o to be the turfs maximal water use rate and evaluated turf performance at this level as well as 0.45, 0.3 x ETo, and unirrigated conditions. Under the 3-day per week irrigation used in this study, irrigating at a K_c of 0.3 provided the turf adequate water to sustain acceptable quality. However, for golf course fairways that receive a high level of traffic, the K_c would need to be raised slightly as traffic was found to have an influence on quality by consistently decreasing quality at all irrigation levels. It is worth noting that all treatments that received deficit irrigation during the summer were able to recover to greater than 90% green cover at the end of each season while non-irrigated treatments only recovered to acceptable levels after the first season. This emphasizes a possible cumulative effect of not irrigating during the summer months over consecutive seasons. The effects of deficit irrigation were also observed in root development. Irrigation K_c did not affect root mass during the first season, but in the second season root mass showed a decreasing response with decreasing K_c.

The effects of decreasing K_c on canopy temperatures were also evaluated, since a significant benefit of turfgrass systems has been shown to be mitigation of heat loading. In this regard, we found that turfgrass canopy temperatures increased substantially with decreasing irrigation Kc.

Soil EC did not reach damaging levels in any treatment throughout either season. This is likely due to the fact that the irrigation water was high in sodium and sodium bicarbonates rather than total salts. In this case, a high SAR could be observed in the soil since irrigating at or below the maximal water use rate could cause elevated sodium accumulation.

Overall, this experiment confirms that ET-based irrigation practices are a viable tool that golf course superintendents can take advantage of in achieving water conservation goals while maintaining acceptable levels of quality on their golf courses. This study documented that bermudagrass turf performed at an equally acceptable level for golf course fairways at K_c values of 0.3, 0.45, and 0.6.

CHAPTER III

WATER QUALITY AND GROWTH REGULATOR EFFECTS ON TIFWAY BERMUDAGRASS MANAGED UNDER IRRIGATION STRESS

Abstract

As the need for landscape and golf course water conservation continues to increase, use of poor-quality irrigation water combined with deficit irrigation practices become commonplace. Information is lacking concerning the relationship between water quality and minimal irrigation requirements, as well as the extent to which plant growth regulators may aid in ameliorating warm-season turfgrass quality under irrigation stress. The objectives of this 10-week greenhouse study were to 1) characterize growth and quality response of 'Tifway' bermudagrass (*Cynodon dactylon x C. traansvalensis* Burt Davy*)* to irrigation replacement of 1.0 and 0.3 x actual turfgrass evapotranspiration (ET_a), 2) determine whether application of trinexapac-ethyl (TE) aids turf quality under water stress, and 3) determine whether minimal irrigation requirements are impacted by water quality (reverse osmosis, sodic, and saline). Results demonstrated that irrigation water quality failed to significantly affect minimal irrigation requirements, but turf irrigated with sodic irrigation water exhibited considerably higher ETa rates in both studies than those receiving saline or RO irrigation. The TE application resulted in improved quality and delayed firing under soil moisture stress. As expected, higher canopy temperatures were observed across treatments with decreasing irrigation amounts. There was much higher salt accumulation observed in saline irrigated

lysimeters; however, salt accumulation did not reach levels that would be considered damaging.

Introduction

Since some turfgrasses are grown and maintained with the purpose of aesthetic appearance, one means of achieving greater water conservation in turf management is by providing water at rates lower than the maximal consumptive water use for a species, otherwise known as deficit irrigation (Feldhake et al, 1984; Fry and Butler, 1989; Qian and Engelke, 1999). Relative to their cool-season counterparts, warm-season turfgrasses possess superior water use efficiency due to their lower transpiration rates and tolerance of heat and drought (Brown, 2000; Fu et al, 2004).

Bermudagrass is a widely used warm-season turfgrass that has shown the ability to maintain acceptable appearance at irrigation levels below its maximal water use rate (Fu et al, 2004). While irrigating turf at these levels has been shown to produce acceptable quality, little is known as to how water quality may affect the extent of deficit irrigation tolerable by turfgrass. This has become an increasingly important consideration, especially in light of the growing number of maintained turf sites utilizing non-potable or low-quality irrigation sources (Throssel, 2009).

Non-potable water sources often contain high levels of sodium that may cause plant and/or soil related problems. Saline water sources often contain high levels of sodium chloride (NaCl) and can cause direct osmotic injury to turf shoots and/or roots. Elevated soil salinity can ultimately render the plant unable to absorb water present in the soil (Marcum, 2006; McFarland et al, 1998). Another common problem in low quality irrigation water is the presence of sodium bicarbonate ($NaHCO_3$), which ultimately can lead to deterioration of the soil structure due to dispersion of soil colloids (Marcum, 2006). As the amount of water available for turfgrass irrigation becomes more limited, it is important to understand plant tolerance to drought conditions as well as to explore ways to reduce water consumption without sacrificing turfgrass quality. Plant growth regulators such as trinexapac-ethyl (TE) reduce turfgrass shoot growth by inhibiting the biologically active forms of giberillins (King et al, 1997; Turgeon, 2002). The application of TE has was reported to enhance heat and drought tolerance of cool season turf species perennial ryegrass (*Lolium perenne L.*) and creeping bentgrass (*Agrostis stolonifera L.*) (Jiang and Fry, 1998; McCann and Huang, 2007). However, in the previously mentioned work with bentgrass, TE was applied weeks prior to the onset of drought conditions. Since turfgrasses metabolize TE within 2 to 6 weeks (Kreuser et al, 2011), the benefit of applying TE to enhance tolerance to water stress might be enhanced if repeat applications of TE are made prior to and during progressive water stress. Information is lacking regarding the effects of TE on tolerance of warm season turfgrasses to drought conditions.

The objectives of this 10-week greenhouse study were to 1) characterize growth and quality response of 'Tifway' bermudagrass (*Cynodon dactylon x C. traansvalensis* Burt Davy) to irrigation replacement of 100 and 30% of actual turfgrass evapotranspiration (ET_a), 2) determine whether application of trinexapac-ethyl (TE) aids turf quality under water stress, and 3) determine whether minimal irrigation requirements are impacted by water quality (reverse osmosis, sodic, and saline).

Materials and Methods

Research Location and Design

This study was conducted at the Texas A&M Agrilife Research greenhouses, in College Station, Texas. The experiment was initiated on March 6, 2013 and repeated on June 17, 2013. Greenhouse temperatures were set to 30/23˚C (day/night) for both studies. Six weeks prior to each study, 10.2 cm diameter washed sod plugs of Tifway bermudagrass (*Cynodon dactylon x C. transvaalensis* Burt. Davy) were established in lysimeters constructed from polyvinyl chloride (PVC) pipe (30.5 cm tall x 10.2 cm i.d.). Soil in the lysimeters was a medium-textured washed sand amended with complete starter fertilizer (21-7-14) containing sulfur-coated urea (BCF Products, Greenville, TX) applied at a rate of 4.9 g N m^{-2} as well as micronutrients (Step Hi-Mag, Andersons, Inc.).

The study was arranged in a completely randomized design with 3 replicates, and accommodated a factorial arrangement of all possible combinations of two irrigation levels, three water sources (RO, Saline, and Sodic Potable), and two TE levels (+ or - TE).

Growth Regulator Treatments

The effect of the growth regulator trinexapac-ethyl (Primo Maxx; Syngenta Crop Protection, Greensboro, NC.) on turf quality under water deficit was evaluated by applying TE to half of the lysimeters within each irrigation level and water quality regime using a CO_2 powered backpack sprayer calibrated to deliver 28 mg m^{-2} a.i. in 81.5 mL of H_2O m^{-2}. Treatments were made at 3-week intervals during the study, at weeks 1, 4, and 7.

Irrigation Water Quality

The effects of water quality on tolerance to deficit irrigation was evaluated using three water quality treatments including 1) reverse osmosis, 2) sodic-potable, 3) saline-potable (Table 1). The sodic-potable water source originated from a local municipal source for College Station, Texas, and was found to pose a potential Na hazard (Table 3.1). The saline-potable treatment was produced by mixing 4.8g of NaCl per liter of reverse osmosis water. This water produced a final EC of 7.5 dS m^{-1}.

Table 3.1. Quality analysis of the 3 water types used in the greenhouse study, along with their respective USSL classification.

	USSL Classification	**Na Hazard**	**Salinity Hazard**	**pH**	**EC (dS m^{-1})**	**Bicarbonates (ppm)**	**Na (ppm)**	**Cl (ppm)**
Reverse Osmosis	C1-S1	Low	Low	5.9	0	0	<1	<1
Saline	C3-S4	High	High	6.6	7.5	0	1972	3030
Sodic Potable	C1-S4	High	Low	8.4	<1	509	234	81

Irrigation Levels

Immediately prior to initiating the experiment, all lysimeters were brought to field capacity by fully submerging in water for 1 minute and then allowing lysimeters to drain overnight. Eighteen hours later, after drainage had ceased, the field capacity weights of lysimeters was recorded. Twice weekly over the 10-weeks, irrigation was applied to the lysimeters. Irrigation levels included controls (full ET replacement)= 1.0 x actual evapotranspiration (ET_a) or moderate water stress = 0.3 x ET_a. Irrigation amounts were determined by weighing and calculating the mass change of the 3 fully watered control lysimeters (receiving 1.0 x ET_a replacement) using a balance with a resolution of 15,000 g x 0.5 g (Ohaus EB15, Ohaus Corporation, Parsipanny, NJ). Irrigation was then supplied at either full ET replacement (1.0 x ET_a) or a deficit fraction (0.3 x ET_a) to each lysimeter, similar to that previously reported by Wherley (2011).

Turfgrass Performance Evaluation

Turfgrass was evaluated during the study through bi-weekly visual assessments (rating scale of 1-9, minimal acceptable rating = 6). These quality ratings took into account the color, density, and uniformity of the turf canopy. A rating of 1 indicated 100% brown leaf canopy and a rating of 9 represented fully dense, dark green perfectly uniform turf. The turf canopy within each treatment was also analyzed for percent green cover using digital image analysis software (SigmaScan,SPSS, Chicago, IL) (Richardson, 2001). Digital images were taken every 2 weeks using a Nikon camera attached to a light-box positioned over each lysimeter, cancelling out any outside light and creating uniform lighting within the box (Karcher, 2005). The SigmaScan software operates by creating an average hue, staturation, and brightness level (HSB) for each image (Karcher, 2003). Reflective canopy temperature readings were also taken within each lysimeter on a bi-weekly basis using a handheld infrared thermometer (model 2956, Spectrum Technologies, Aurora, IL). These measurements serve as an indicator of physiological drought stress.

Shoot Growth Measurement

The grass in each lysimeter was trimmed to 1.9 cm at 7 to 10 day intervals during the study using scissors and ruler. After trimming, clippings were oven dried for 72 h at 65° C before weighing.

Soil and Leaf Tissue Salinity Measurement

Salt accumulation was measured at the 7.6 cm depth within lysimeters during the middle (week 5) and end (week 10) of the study using an electrical conductivity probe (Spectrum Technologies, Aurora, IL).

Analysis of Data

Data for each parameter were subjected to analysis of variance using the general linear model, univariate test procedure using SPSS ver. 21.0 (IBM Corp, Armonk, NY) to determine statistical significance of the results. Where analysis of variance indicated a significant study effect, parameters were presented separately by study. Mean separation procedures were performed using Tukey's HSD at the $P \leq 0.05$ level.

Results

Evapotranspiration

In both studies, plants receiving sodic potable irrigation water exhibited significantly higher daily rates of ET_a compared to the RO and Saline treatments (Figure 3.1). These values representing daily ET_a are derived from the weights taken twice per week to calculate water loss and are only representing the fully irrigated non-PGR treated lysimeters. The percent differences were fairly consistent across studies when comparing sodic potable to either the RO and Saline treatments. Overall, these ET_a rates were higher during the summer study due to longer days and more intense radiation.

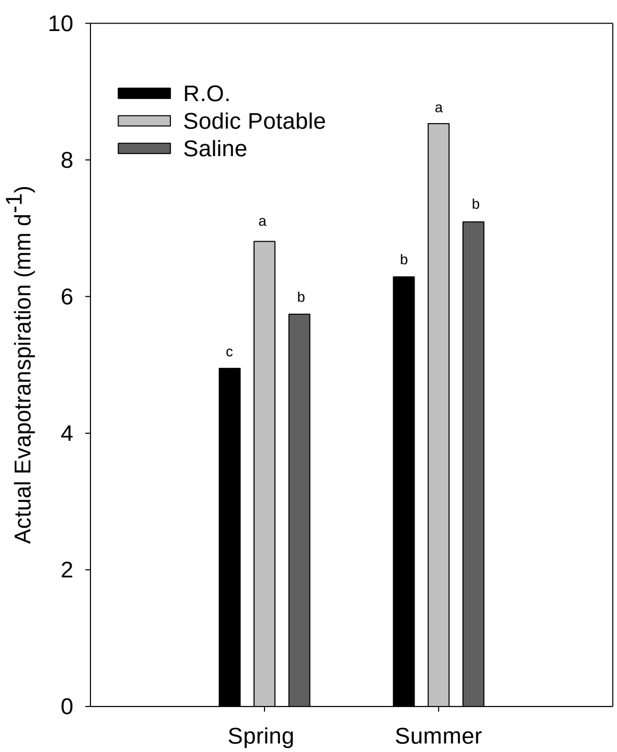

Figure 3.1. Daily average evapotranspiration (ET_a) of fully irrigated (1.0 x ET_a) treatments. Irrigation was applied twice weekly. Bars with same letter within each study are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Table 3.2. Analysis of variance table for water source, irrigation level, and trinexapac-ethyl effects on various parameters during studies 1 and 2. Where studies have been presented separately, study main effect were significant ($P \leq 0.05$).

	P values													
	Visual Quality		Percent Green Cover		Clipping Dry Weight		Soil Electrical Conductivity		Final Root Dry Weight		Canopy Temperatures		Evapotranspiration	
	Study 1	Study 2	Study 1	Study 2	Study 1	Study 2	Week 5	Week 10	Study 1	Study 2	Study 1	Study 2	Study 1	Study 2
Week	***	***	***	***	***	***					*	*	***	***
Source (S)	***	***	NS	NS	NS	***	***	***	NS	NS	**	*	***	***
Level (L)	***	***	***	***	NS	***	***	***	**	*	*	***		
Trinexapac-ethyl (TE)	***	***	***	NS	***	***	***	NS	NS	NS	NS	NS		
S x L	***	***	NS	NS	NS	***	***	***	NS	NS	NS	*		
S x TE	NS	NS	NS	NS	NS	***	***	NS	NS	NS	NS	NS		
L x TE	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS		

[NS, *, **, ***] Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively

Visual Quality as influenced by Water Source and Irrigation Level

There was a water source x irrigation interaction effect on visual qualty, as well as an irrigation level x TE interaction for the spring study (Table 3.2). Significant differences in visual quality were not observed until week 6 of the spring study, but occurred by week 4 in the summer study.

Spring study

No differences were observed due to water source at the 1.0 x ET_a level, and at the 1.0 x ET_a water application amounts, were sustained above-acceptable quality levels for the duration of the 10-week study (Figure 3.2). Visual quality ratings declined slightly for the 1.0 x ET_a irrigation treatments from during the 10 weeks, possibly due to early N fertilization and periodic removal of clippings during the study. At the deficit irrigation level 0.3 x ET_a), saline and sodic-potable irrigated treatments sustained at or above acceptable levels of quality across the 10-week study. However, R.O. irrigated turf decreased to below acceptable quality levels (~5.5 out of 9) at week 6 (Figure 3.2).

Summer Study

During the summer study, longer days and more intense radiation prevailed, producing generally higher levels of stress in deficit irrigated treatments. Unlike spring, significant differences in visual quality occurred between water sources at both the 1.0 and 0.3 x ET_a levels (Figure 3.2). At the 1.0 x ET_a irrigation level, saline-potable irrigation resulted in significant reductions in visual quality relative to R.O. and sodic-potable on 3 of the 5 rating dates. No significant differences occurred at the 0.3 x ET_a

level between water sources, as all treatment means fell to below the minimal acceptable quality level 6 at week 4 and beyond (Figure 3.2).

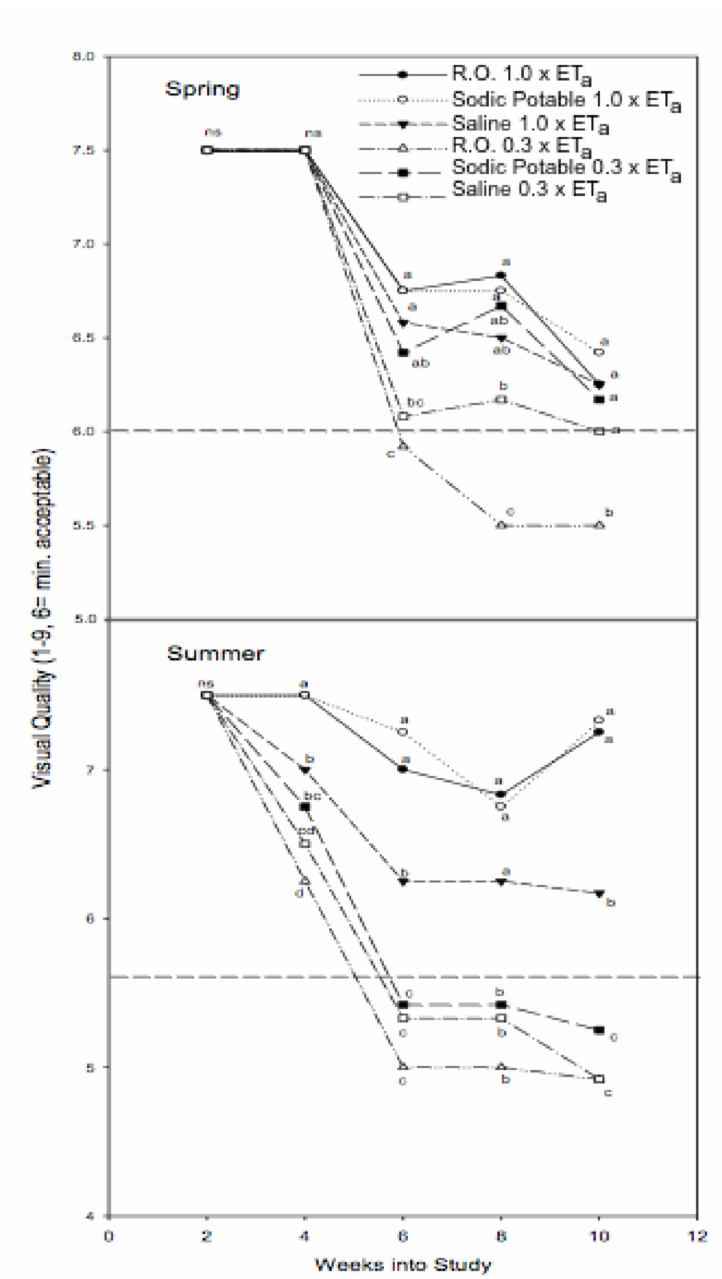

Figure 3.2. Spring and Summer study visual quality as affected by water source and irrigation level. Data have been pooled across TE application. Means with the same letter on the same date are not significantly different based on Fishers LSD at $P \leq 0.05$. Dotted line denotes acceptable quality.

TE application Quality Effects

There was an interaction of irrigation level x TE on visual quality during the spring study as well as a significant main effect of TE during both studies. TE application noticeably influenced visual quality under deficit irrigation (0.30 x ET_a) during the spring, and showed positive quality benefit at both levels during the summer (Figure 3.3). During the spring study, within deficit irrigation, TE led to delayed leaf firing and sustained acceptable quality levels during all weeks, while without TE turf quality decreased to below acceptable quality after week 6 (Figure 3.3). During the summer study, although TE treated plants exhibited higher mean quality at both irrigation levels, both TE and non-TE treated plants fell below acceptable quality by week 6 (Figure 3.3).

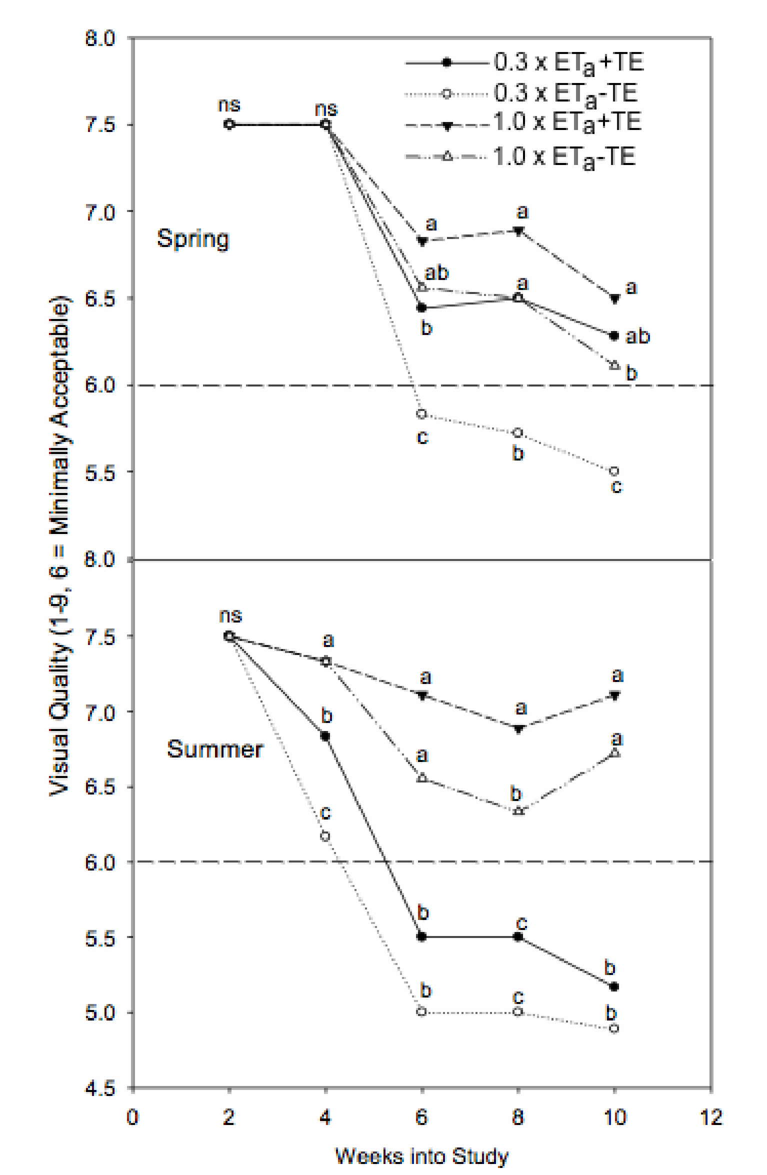

Figure 3.3. Bermudagrass turf quality in the spring and summer studies as affected by TE application and irrigation level. Data were pooled across water source. Means with the same letter on the same date are not significantly different based on Fishers LSD at P≤0.05.

Water Quality Effects on Salinity

No study interaction was found between the spring and summer study for EC so data were pooled across studies. The EC at the 7.5 cm depth in saline-irrigated lysimeters approached ~2 and 3 dS m^{-1} (0.3 and 1.0 x ET_a, respectively) by the end of the 10 weeks (Figure 3.4). The EC was much lower within the R.O. and sodic irrigated lysimeters. In these treatments, EC remained below 0.25 dS m^{-1} at weeks 5 and 10 of both studies (Figure 3.4).

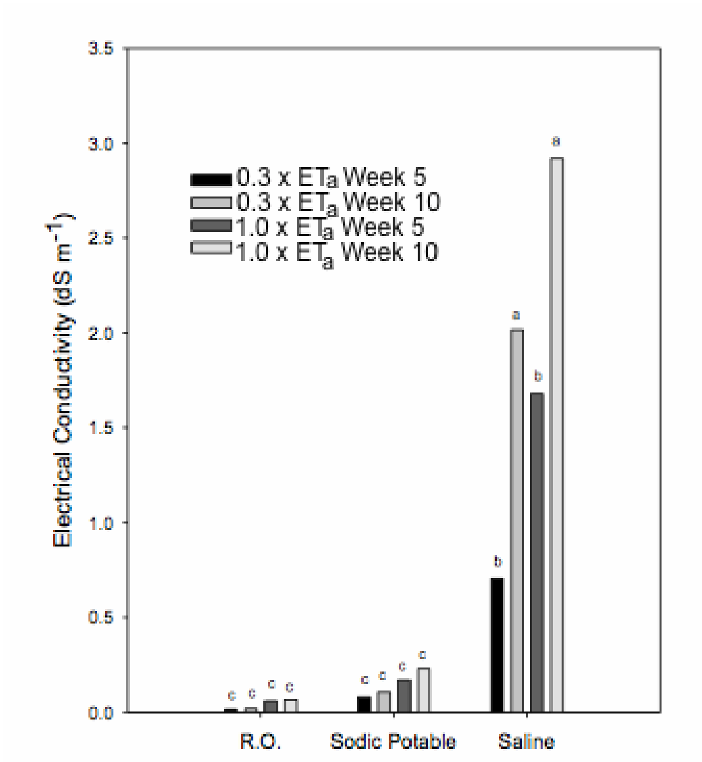

Figure 3.4. Week 5 and 10 electrical conductivity as affected by water source and irrigation level. Means were averaged across studies. Means with the same letter at the same week and irrigation water are not significantly different based on Fishers LSD at $P \leq 0.05$.

Water Quality, TE, and Irrigation Effects on Bermudagrass Shoot Growth

There was a main effect on bermudagrass shoot growth among TE treatments in the spring study (Table 3.1). Plants without TE maintained ~62% more daily shoot growth compared to TE treated plants, within the spring study (Figure 3.5).

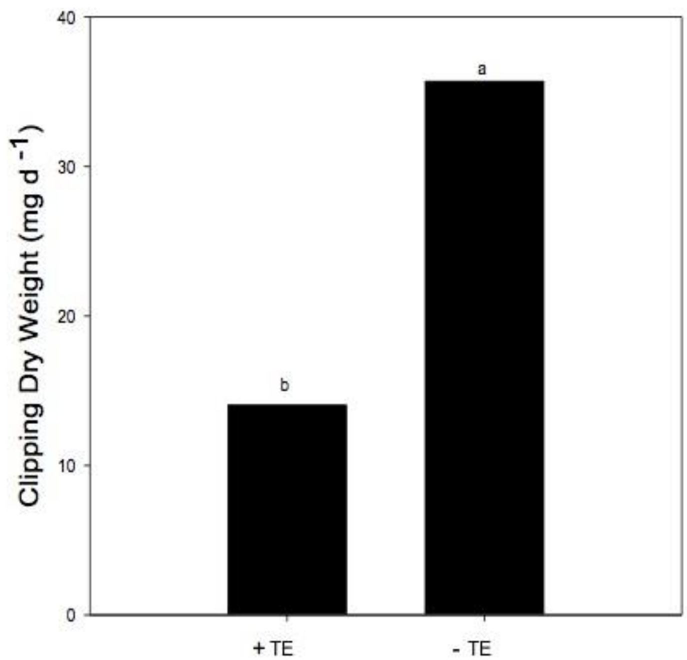

Figure 3.5. Bermudagrass clipping dry weight as affected by trinexapac-ethyl treatment during the spring study. Data are pooled across irrigation levels and water sources. Bars with the same letter are not significantly different based on Tukeys HSD @ $P \leq 0.05$.

While considering TE application and irrigation level, twice the amount of shoot growth occurred in sodic-irrigated turf as compared to saline or R.O. water sources (Figure 3.6). Within the summer study, TE caused the greatest levels of suppression in sodic-irrigated turf while there were no differences within TE and non-TE growth rates of R.O. and saline irrigated turf (Figure 3.6).

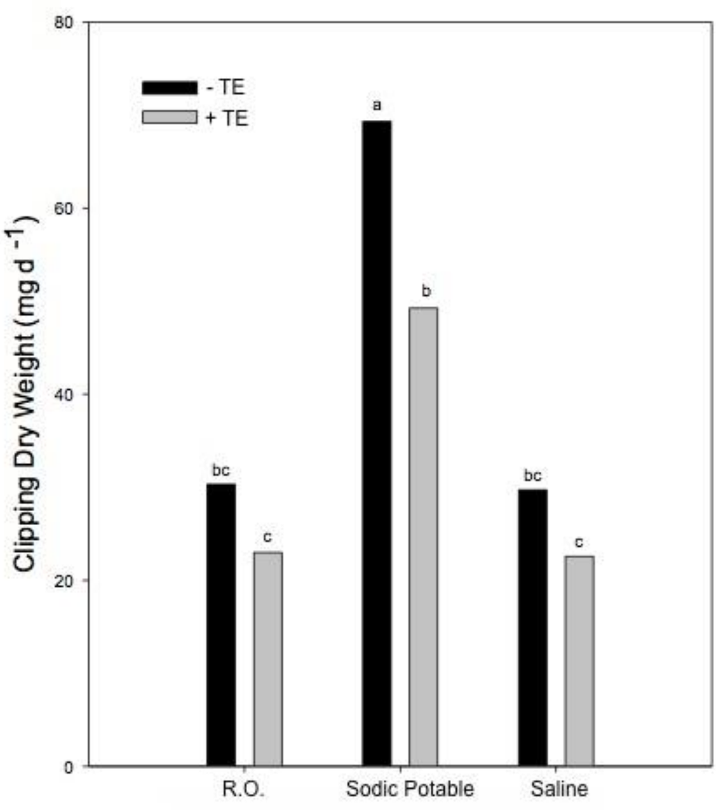

Figure 3.6. Clipping dry weights as affected by trinexapac-ethyl treatment (PGR) for the summer study. Bars with same letter are not significantly different based on Fishers LSD at $P \leq 0.05$.

Reflective Canopy Temperatures

Within both studies, higher canopy temperatures were observed at lower irrigation levels with ~15˚C increase in canopy temperatures from the spring to summer study at both irrigation levels (Figure 3.7). In the summer study, the saline 1.0 x ET_a treatment maintained higher canopy temperatures than the sodic potable and R.O. treatments at that level (Figure 3.8).

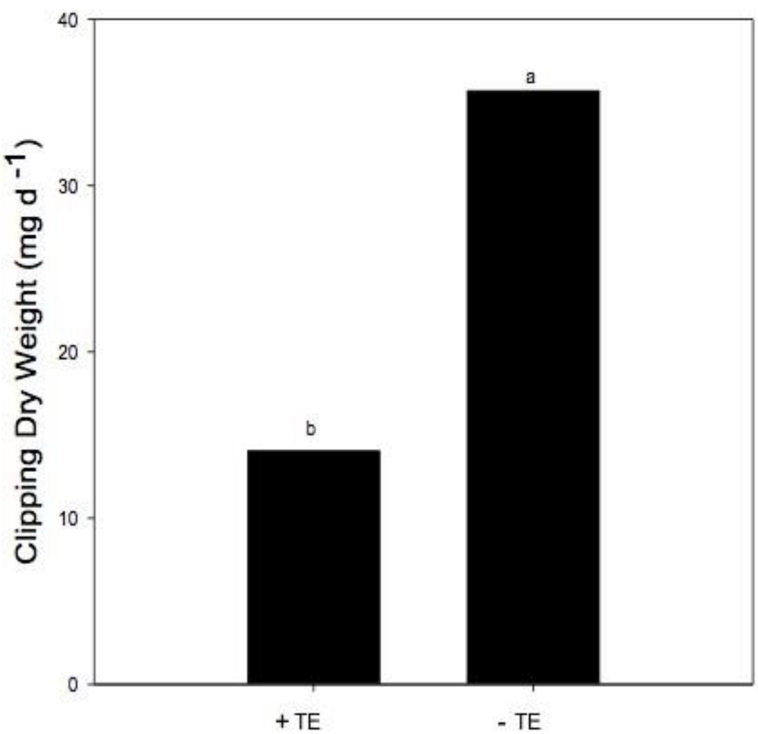

Figure 3.7. Canopy temperatures for the 1.0 and 0.3 x ET_a treatments for both the spring and summer study. Data were pooled across TE and water source. Bars with the same letter within the same study are not significantly different based on Tukeys HSD at P≤ 0.05.

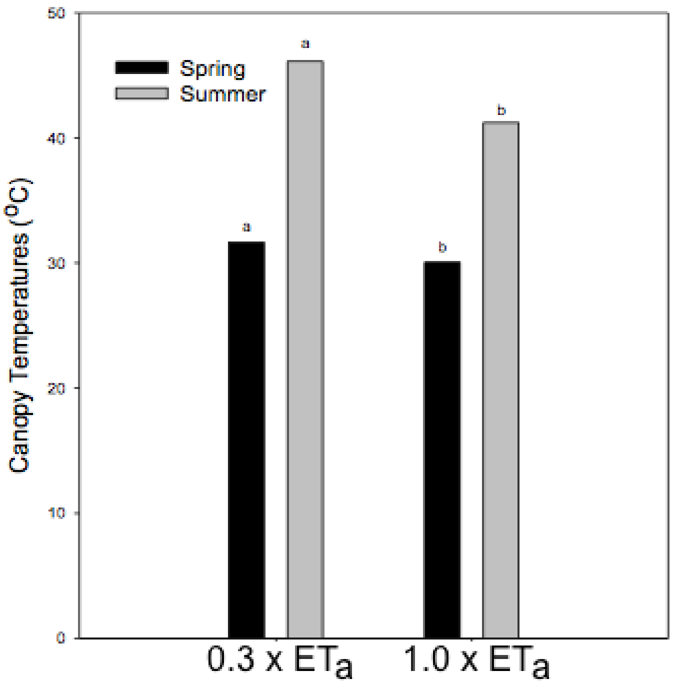

Figure 3.8. Summer study canopy temperatures for the three water sources and two irrigation levels. Data were pooled across TE. Bars with the same letter are not significantly different based on Tukeys HSD at P≤ 0.

Discussion

Turf Quality as Influenced by TE Application Under Irrigation Stress

When irrigation stress became apparent, TE treated bermudagrass maintained higher turf quality levels than did the untreated at the 0.3 x ET_a level. These results are consistent with Jiang and Fry (1998) and McCann and Huang (2007) that TE can enhance turf quality during periods of water deficit. McCann and Huang found that plants pre-treated with TE maintained higher quality compared to untreated plants up to 21 days after onset of drought. Unlike McCann and Huang (2007) who pre-treated bentgrass plants with TE every 14 days for 42 days before exposing them to drought, bermudagrass in this study was treated every 3 weeks beginning with the onset of water stress. The theory behind this method was that Tifway Bermudagrass was found to metabolize TE within 4-6 weeks (McCullough et al., 2007; Fagerness and Yelverton, 2000; Fagerness et al., 2004) so re-applying TE before to the plants could fully metabolize the TE, could strengthen the benefit of TE improving turf quality during irrigation stress. While McCann and Huang saw a positive response of TE application with creeping bentgrass up to 21 days of drought, beyond this point TE would likely have metabolized within the plant and the benefit would no longer have been appaent. Whether it is more beneficial to pre-treat with TE or apply TE in subsequent applications during drought would likely depend on how long the drought conditions persisted. Since TE had a positive impact within the fully irrigated treatment compared to non-treated plants, pre-treating before being exposed to drought may have a positive impact on bermudagrass since plants would be of higher quality.

Visual Quality as influenced by Water Source and Irrigation Level

While the saline irrigation treatment caused the greatest increases in EC within the 1.0 x ET_a irrigation treatment, the only significant differences in visual quality observed during the summer study at 3 of the 5 rating dates. The explanation for this could be some salinity stress caused by salt accumulation within the saline treatment during the summer study as a result of replacing higher water volumes. The reason we did not find more significant differences within the water quality treatments is likely due to EC levels not reaching damaging levels during the 10 week studies. Bermudagrass is a turf species fairly tolerant to soil salinity over 10 dS m^{-1} (Harivandi, 1992), in both of the studies salinity did not exceed 3 dS m^{-1}.

At the deficit level, sodic treatment bermudagrass was superior for the saline and R.O. treatments during the spring study. This was likely due to the sodic treatments receiving higher water volumes due to higher ET_a within the fully irrigated sodic treatment, since water amounts applied to the deficit treatments were a percentage of the ET_a in the fully irrigated treatment of the same water type. During the summer study the sodic treatments again outperformed other treatments through week 4. From week 6 on, all deficit treatments performed relatively the same.

Trinexapac-ethyl and Water Quality Effects on Bermudagrass Shoot Growth

While TE application was found to enhance turf quality, TE caused an overall reduction in turfgrass shoot growth. A reduction of ~60% in daily growth while considering the mean of all treatments was found during the spring study. This reduction in growth was fairly consistent across water sources.

Overall, higher shoot growth occurred within the sodic potable treatment compared to the R.O. and saline treatments. This is likely due to the observed higher ET_a within the sodic-potable treatment which would could be associated with higher CO_2 fixation. This finding suggests that water quality may need to be accounted for when scheduling irrigation to meet turf requirements; however, the underlying mechanism causing this difference is unknown, suggesting a need for further research and investigation.

Summary and Conclusions

As golf course superintendants face changes in irrigation water allocations, it is important as researchers to explore ways to conserve water. Previous research indicated that some warm season grasses are able to persist while being irrigated at levels below their maximal water use rates; however, little is known about the extent to which they can persist while being irrigated with water of poor quality. Previous research has also indicated that applying a plant growth regulator such as trinexapac-ethyl to turfgrass could improve quality and drought response. Two 10-week greenhouse lysimeter studies were conducted to address the following objective. The objectives of were to 1) characterize growth and quality response of 'Tifway' bermudagrass (*Cynodon dactylon x C. traansvalensis* Burt Davy*)* to irrigation replacement of 1.0 and 0.3 of actual evapotranspiration (ET_a), 2) determine whether application of trinexapac-ethyl (TE) aids turf quality under water stress, and 3) determine whether minimal irrigation requirements are impacted by water quality (R.O., sodic potable, and saline).

In this greenhouse experiment, water source was not found to influence bermudagrass deficit irrigation response; however, higher daily ET_a was observed while irrigating with a sodic source. While this could be something to address, the mechanism for this is unknown and requires further evaluation. TE application did improve bermudagrass deficit irrigation response by improving overall quality and delaying leaf firing. While there was much higher salt accumulation within the saline irrigated bermudagrass lysimeters, salt accumulation failed to reach damaging levels.

Overall, these studies indicated that potential water savings for golf courses could lie in deficit irrigation practices supplemented with TE application regardless of irrigation water quality.

CHAPTER IV

CONCLUSION

Regardless of the water status throughout the state, turf managers will be required to meet customer demands even as populations continue to increase, drought conditions persist, and the supply of water available for irrigation continues to dwindle. Due to this there was an apparent need to further examine the findings of prior research to help guide turf managers during changes in irrigation water allocations. We did this through a series of field and greenhouse studies in College Station, Texas by investigating if the water conservation technique of Evaportranspiration (ET) based deficit irrigation is a viable option for golf course superintendants needing to meet a conservation goal.

In the field study, we evaluated if Tifway bermudagrass being irrigated three times weekly at levels below the turf coefficient of 0.6 x reference evapotranspiration (ETo) would be able to maintain adequate quality, persistence, recovery from divot and traffic stress, and also fall recovery once full irrigation volumes could be supplied. Our findings showed that Tifway bermudagrass plots, managed similarly to most Texas golf course fairways could maintain adequate growth and quality while being irrigated at levels as low as 0.3 x ETo. Even though divot and traffic recovery were slowed and a substantial increase in canopy temperatures were found at decreasing irrigation levels, we found turf quality to be acceptable in regards to membership and ownership demands. We also found, from our fall recovery evaluation that not irrigating during the summer months could cause cumulative effects since unnirrigated plots were not able to recover to acceptable levels during the fall of the second season.

We further expanded from our field study in two 10-week greenhouse studies to see if the minimal water requirements would be affected by different water sources, as well as determining if applying Trinexapac-ethyl (TE) could improve turf quality and drought response. Our findings showed that irrigation water quality will not significantly influence minimal irrigation requirements; however, turf that received sodic irrigation did exhibit considerably higher evapotranspiration (ET) rates relative to those receiving saline or RO irrigation. This could be something to address while irrigating with this water type, but this finding needs further investigation. We found TE to improve bermudagrass quality and delayed firing under the soil moisture stress from deficit irrigation.

The findings from this research provide timely and practical information that turf managers can employ to help meet water conservation goals by utilizing ET-based irrigation scheduling and/or low-quality water sources in the management of golf course turfgrass systems.

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