IMPROVING IRRIGATION EFFICIENCY IN SAND-CAPPED TURFGRASS SYSTEMS AND URBAN LAWNS

A Dissertation

by

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ABSTRACT

Given increased scrutiny over water use in urban green spaces, efficient management of water for turfgrass irrigation is imperative due to climate uncertainties and rapid urban population growth. For home lawns, water purveyors and municipalities commonly enforce landscape watering restrictions aimed at mitigating domestic water use in order to ensure adequate water supplies for growing populations and during times of drought. However, information is lacking concerning minimal irrigation frequency requirements needed to sustain aesthetically pleasing and functional warm-season turfgrass systems in southern climates. On golf courses and sports field turf areas, there has been an increasing trend of capping native soils with sand due in order to better cope with poor water quality. However, there is currently a lack of information on spatiotemporal variability of soil-moisture as well as irrigation best management practices for sand-capped systems. Therefore, a series of field studies were conducted in College Station, TX, to 1) evaluate turf response of commonly used warm-season turfgrass species subjected to five irrigation frequency regimes, 2) compare turf performance, soil moisture and salinity dynamics, and water use of four irrigation scheduling approaches in sand-capped systems, and 3) investigate factors contributing to spatiotemporal heterogeneity of soil water relations in sand-capped fairway systems. Our results demonstrate that warm-season turfgrasses can maintain acceptable visual quality while being irrigated at frequencies limited to once per week; however, species and variety selection are critical for maintaining aesthetically pleasing turf with implementation of more restrictive policies. In sand-capped systems, acceptable levels of turfgrass quality were maintained under all irrigation scheduling approaches including wireless soil moisture sensor-based, on-site reference evapotranspiration-based, Forecasted Reference Evapotranspiration-based, and visual wilt-based. Also, forecasted reference evapotranspiration appeared to be a reliable indicator of bermudagrass seasonal water needs and an accurate predictor of reference evapotranspiration. In our investigation of soil moisture variability within sand-capped fairways, considerable spatiotemporal variability was observed within two fairways evaluated following dry downs from rainfall and irrigation. Further, the factors contributing to variability in soil moisture did not translate between rainfall versus irrigation, days after dry down, or fairways. Overall, the findings from this research provide timely and practical information that municipalities, water purveyors, homeowners and turfgrass practitioners should be able to utilize for optimizing turfgrass ecosystem services while meeting landscape water conservation goals.

DEDICATION

To my family as we embark on a new and exciting journey.

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NOMENCLATURE

ANOVA	Analysis of Variance
CV	Coefficient of Variation
EC	Electrical Conductivity
ET	Evapotranspiration
ET_a	Actual Evapotranspiration
ET_o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FRET	Forecast Reference Evapotranspiration
GPS	Global Positioning System
HSD	Honestly Significance Difference
K_c	Crop Coefficient
LSD	Least Significant Difference
NDFD	National Digital Forecast Database
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PI	Precision Irrigation

PTM	Precision Turfgrass Management
SAWS	San Antonio Water System
VWC	Volumetric Water Content

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Water Allocation for Turfgrass Irrigation

Increased urban development driven by population growth has altered natural hydrologic cycles and has negatively impacted water resource availability (Lockaby et al., 2011; Marshall and Shortle, 2005; Wong et al., 2012). For long-term access, treatment, and delivery of water to be achieved, sustainable water management practices must be developed and enacted. Over the last decade urban regions within the Southern and Western regions of the United States have experienced rapid growth, containing 10 of the 15 fastest growing large U.S. cities (United States Census Bureau, 2020). Cause for concern is that many of these areas are water stressed, where water supplies are limited or unreliable (Fender, 2008). Even in the normally "water-abundant" Southeastern United States, water quantity in this region is becoming increasingly at risk due to climate change, land conversions, population growth, and sea level rise (Lockaby et al., 2011; Marion et al., 2012). Population growth in urban centers increases residential demand for water resources that is used for many purposes, including landscape irrigation and specifically turfgrass irrigation. According to Milesi et al. (2005), turfgrass areas covered approximately 40 to 50 million acres of land within the continental U.S. in the mid-2000s. As turfgrass areas are likely to increase in conjunction with urbanization, so will the use of water for turfgrass irrigation as rainfall in many of the areas in which turfgrass is grown is not sufficient for maintaining acceptable turfgrass quality and function (Gibeault et al., 1985; Emmons, 1995).

Of the approximately 40-50 million acres of turfgrass in the United States, home lawns account for about 66% of this total (Breuninger et al., 2013) and much of the water consumed in household water use is used towards maintaining landscape areas. Depending on geographic location, water used towards for outdoor purposes such as turfgrass irrigation has been found to comprise about 30-60% of domestic water uses (Fernald and Purdum, 1998; Hermitte and Mace 2012; Mayer et al., 1999). Turfgrasses water needs vary by species, geographic location, climactic conditions, time of year, and how they are maintained (Beard, 1989; Feldhake et al., 1983; Huang and Fry, 1999; Shearman 1985); however, water can be easily and is commonly applied in amounts greater than turfgrass requires for growth and function since it’s commonplace for homeowners to lack the knowledge and expertise for properly scheduling irrigation (Bremer et al., 2012). Best management practices exist for calculating turfgrass water needs and properly timing irrigation events; however, many homeowners are unaware of how to calculate the amount of water needed for maintaining their lawns and employ the “set and forget” irrigation scheduling strategy when they have access to in-ground irrigation connected to an automatic irrigation controller (Bremer et al., 2012; Serena et al., 2020). Combining current water status and elevated use of water for landscape irrigation, regulations, restrictions, and water conservation measures surrounding landscape irrigation (both required and suggested) have increased in recent years (Milman and Polsky, 2016; Texas Water Development Board, 2012). These which are aimed to meet long-term demands of municipal water limit the risk of water shortages in high population growth scenarios and during drought conditions by attempting to lower water use during times of low supply and high demand (Baumann et al., 1998; Sisser et al., 2016). Conservation measures include landscape conversions, promotion of best management practices, and ordinances for when irrigation can be applied aim to minimize water losses through over-application, or water waste (Devitt and Morris, 2008).

Landscape Water Regulation

The restriction commonly employed regulates the timing of irrigation application using municipal water supplies that limit application to certain days of the week and/or times of the day (Kenney et al., 2004). For instance, The Southwest Florida Water Management District employs year-round conservation measures in which lawn watering is limited to no more than twice per week (https://www.swfwmd.state.fl.us/business/epermitting/district-water-restrictions). The City of Santa Fe, New Mexico allows for a slightly increased watering schedule by limiting watering to three days a week but is restrictive for irrigation timing by not allowing outside watering from 10am to 6pm during months May-October (https://www.santafenm.gov/water_use_restrictions). In combination with either year-round or seasonal irrigation restrictions, some municipalities or water districts implement restrictions that increase based on the status of their water supply. The San Antonio Water System (SAWS) operates on a tiered or "stage" system in which restrictions are based on water level status of their primary water source, the Edwards aquifer (https://www.saws.org/conservation/drought-restrictions/). When water levels drop in the Edwards aquifer past predetermined levels, stage restrictions are enacted that limit landscape watering from as often as one day per week to once every other week. If a high-level drought is being experienced, no landscape irrigation is allowed until wells are recharged to a determined level. Along with other conservation measures, the SAWS approach to water conservation has resulted in significant water savings for the San Antonio area (SAWS, 2017).

Home-lawn best management practices include a multitude of factors; however, proper turfgrass species selection is a primary strategy for achieving perennial success of turfgrass systems and climate may be the primary factor influencing success of a particular species in a given area (Haravandi, et al., 2001). Of the two major turfgrass species categories of cool-season turfgrasses and warm-season turfgrasses, warm season turfgrass species are the primary turfgrass types utilized in the Southern United States, primarily due to their adaptation to warm temperatures (Emmons, 1995). They also exhibit increased suitability in areas prone to drought due to dehydration avoidance and increased root growth in comparison to cool season grass species (Beard, 1989). The water needs of warm-season turfgrass species have been researched in different climates, and in well-watered vs deficit scenarios (Beard, 1989; Feldhake et al., 1983; Fontanier et al., 2017; Fu et al., 2004; Kim and Beard, 1988; Hejl et al., 2016; Huang et al., 1997; Huang and Fry, 1999; Romero and Dukes, 2010; Wherley et al., 2014). However, many home owners associations, municipalities and water purveyors are interested in how frequently water must be applied to maintain aesthetically pleasing turf and it's difficult to answer this question given current literature. As such, the extent to which warm-season turf species are able to persist and/or maintain acceptable appearance under limited irrigation frequency or unirrigated conditions receiving only rainfall is largely unknown.

Data-driven Irrigation Scheduling for Sand-capped Golf Course Fairways

Capping Fairway Soil with Sand

As golf course turf managers strive to maintain satisfactory playing and growing conditions of their turfgrass, long-term irrigation with low-quality water sources leads to soil degradation and diminished agronomic health over time (Carrow and Duncan, 2012; Marcum, 2006). Fairways represent an average of 38% of the irrigated areas within United States golf courses (Gelernter et al., 2015) and could be prone to these diminished conditions when built atop native soil. Sand-capping fairway soil has become a common practice as it provides an improved growing medium for turfgrass by promoting better health, performance, and playability of turfgrass systems (White, 2013; Whitlark and Isom, 2020). Coupling this increased trend with current strains on water supplies, it's essential that efficient methods of irrigation management be developed for sand-capped fairway systems.

Weather-Based Programs

Evaporation and transpiration processes, collectively known as evapotranspiration (ET), along with drainage from large soil pores govern water use and loss in plant systems (Turgeon, 1998). Weighing lysimeters are used in research scenarios in calculating actual plant water use (ET_a) but are tedious in nature and difficult to apply for normal plant management (Barrett et al., 2003). Estimated daily water use, or reference ET (ET_o), is estimated when the weather variables that drive ET such as wind speed, temperature, solar radiation, and humidity are collected by weather stations and subjected to the Penman Monteith equation (ASCE-EWRI, 2005; Cai et al., 2007; Valipour, 2015). Reference ET (ET_o) applies to a hypothetical reference crop that is actively growing under non-limiting soil conditions and has the characteristics of a cool season grass grown at 0.12 m (Allen et al., 1994). Turfgrass actual ET (ET_a) compared to ET_o produces a crop coefficient (K_c where $K_c = ET_a/ ET_o$) and can be used to estimate plant water needs and therefore, irrigation amounts that can be used in making irrigation scheduling decisions (Allen et al., 1998). To produce appropriate turfgrass K_c values, numerous studies have evaluated turfgrass ET_a in lysimeter studies in order to elucidate turf ET_a relative to ET_o for a number of turfgrass species and in a number of climates (Atkins, 1991; Carrow, 1995; Devitt et al., 1992; Feldhake, 1983; Green et al., 1990; Kim and Beard, 1988; Kneebone and Pepper, 1982; Wherley, 2015). Hybrid bermudagrass is a warm-season grass species and is one of the most commonly utilized grass species for southern U.S. golf course fairways due to its ability to produce high-quality turf grown at low mowing heights in warm climates (Trenholm et al., 1998). While differences exist due to climate, the K_c value for warm-season grass species have been found to range from 0.6 to 0.8 during the summer month growth periods. As such, the year-round K_c value of 0.6 for warm-season grasses, as suggested by Meyer and Gibeault (1987), has been a widely accepted value for meeting consumptive irrigation requirements. Despite this efficient method of scheduling irrigation by providing data to meet seasonal irrigation demands of turfgrass, as of 2013 only 31% of golf courses within the U.S. reported the use of ET_o monitoring in making irrigation scheduling decisions (Gelernter et al., 2015). Since the utilization of ET_o in making irrigation scheduling decisions requires access to locally representative data (Allen et al., 1998) either by a near-by or on-site weather station, low-level adoption of ET based irrigation programs could be in part due to insufficient access to this data.

Turf managers access daily ET_o values via an on-site or nearby weather station which gathers and process necessary weather variables to estimate ET_o. If a facility lacks necessary resources to obtain an onsite weather station or is “out of range” of a publicly available weather station, adopting ET based irrigation scheduling is obviously hindered. A recently released experimental forecast reference ET (FRET) provided by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) provides ET_o data based on forecasted weather conditions (digital.weather.gov). Utilizing data supplied by the National Digital Forecast Database (NDFD), the data is open-access and is estimated for a 2.5-km grid everywhere in the contiguous United States and provides daily FRET values for the current day and up to 6 days in advance (Blankenau et al., 2020; Palmer et al., 2016). By providing ET data regardless of proximity to a weather station, NOAA FRET offers turfgrass managers another tool for making irrigation scheduling decisions and possibly makes the implementation of ET based irrigation scheduling a more widely accepted tool. While a recent study determined gridded weather data sets to be overestimating ET_o by 12 to 31% (Blankenau et al., 2020), there is currently no published research evaluating FRET as a reliable indicator of turfgrass irrigation needs by scheduling irrigation solely based on FRET values.

Soil Moisture Sensor Based Irrigation

Efficient irrigation scheduling involves applying supplying the turf system in the right volumes and in the correct intervals. Applying water in this way will decrease the likelihood of water being applied in amounts greater than what is needed and will avoid declines in turf quality and survivability. Applying water at the right times and in the right quantities relies on the basic understanding water storage, downward movement, and plant uptake of water in the soil. When the water status in the soil is high, nearly all pore space in the soil is filled with water and at this stage any water applied or received in excess is not useful for plant growth (Barrett et al., 2003). This reflects the near maximum amount of water a soil can hold and if additional water is added, through rainfall or irrigation, the water is wasted as pooling and runoff will occur. When soil water status is low, there is not enough water in the available pore space for plant uptake and growth (Barrett et al., 2003). The upper limits of soil water holding capacity is termed saturation, or satiation, while the lower end is the permanent wilting point (McCarty et al., 2016). Water in the soil is available to the plant for use when water status in the soil is between the permanent wilting point and field capacity (Barrett et al., 2003). Field capacity is reached when gravity has allowed for the downward movement of water below saturation and water is only held by capillary action in soil pores. Efficient irrigation management aimed at maintaining sufficient turfgrass quality and water conservation entails irrigating to maintain soil water status between field capacity and the permanent wilting point in the absence of rainfall. Attempting to maintain soil-water status between field capacity and the permanent wilting point can be done by actively monitoring soil moisture by using soil moisture sensors (SMS).

The monitoring of soil moisture levels is another common quantitative method for scheduling irrigation by measuring plant needs using soil moisture sensors (SMS) such as tensiometers or dielectric probes (Wade and Waltz, 2004). As evaporation and plant uptake occur, the moisture status of the soil decreases and if additional water is not supplied, plant uptake of water slows or ceases and plant quality declines (Emmons, 1995). SMS technology has improved over time allowing for increased accuracy and durability. As of 2013, the majority of golf courses that utilize SMS as a means for making irrigation scheduling decisions have been primarily employed using hand-held sensors (29% of U.S golf courses) as compared to in-ground SMS (4% of U.S. golf courses) (Gelernter et al., 2015). In-ground SMS have been primarily utilized in areas of the course of highest priority and with uniform soil characteristics, such as golf course greens. They are highly underutilized in larger areas of the course like golf course fairways possibly due to cost and the high degree of soil variability occurring in native soil systems. Since a higher degree of soil texture and moisture uniformity is to be expected in sand-capped systems relative to native soil, sand-capped systems could be a viable soil medium for the utilization of soil-moisture monitoring for irrigation scheduling. Many studies have compared time-based irrigation scheduling and SMS treatments where irrigation was allowed when soil water content reached a certain threshold. Results of decreased water use of 24 – 65% while avoiding diminished turf quality have been documented (Blonquist et al, 2006; Grabow et al., 2013; Haley and Dukes, 2012; Serena et al., 2020). However, research is lacking regarding the water savings potential and maintenance of turf quality in sand-capped systems comparing SMS to ET-based irrigation scheduling.

Given the increased trend of capping fairway soil with sand, research is needed to evaluate efficient means for scheduling irrigation within these systems. Research from such studies would provide much needed data to the golf course management community on the available data-driven approaches for irrigation scheduling, how they perform in sand-capped systems, and guidance for their application.

Spatiotemporal Variability in Sand-capped Fairway Systems

The emerging discipline of precision turfgrass management (PTM) encourages efficient application of management inputs through a targeted application approach that still maintains turfgrass quality and performance. Precision irrigation (PI), a sector of PTM, could offer a viable solution for sustainable water management of large and complex turfgrass areas, like golf course fairways. Technological advancements in handheld and wireless in-ground soil moisture sensors have led to increased assessment accuracy of soil moisture content for improved irrigation management in the turfgrass industry (Moeller, 2012; Serena et al., 2020). These devices could play a key role in PI, due to their ability to provide rapid, objective soil moisture data that can be used in conjunction with valve-in head sprinkler systems to develop site-specific irrigation strategies within and between fairways at a single golf course. However, fairways represent a median value of 28 acres of irrigated turf on the typical U.S. golf course (Gelernter et al., 2017); therefore, handheld devices could be an unreasonable approach to continually monitor soil moisture on a fine scale during growing months on large areas like golf course fairways. Stationary in-ground SMS are likely most practical by providing automated soil moisture data and storage remotely (Moeller, 2012); however, proper placement could be critical due to spatiotemporal variations in soil moisture.

For in-ground SMS to be properly implemented, a thorough knowledge of the spatiotemporal variability in regards to soil moisture is needed. Spatial variability of soil-water relations in golf course fairways was documented in Straw et al., 2020b as soil moisture variability was demonstrated to an extent on all 12 fairways sampled in the study. While the knowledge of variability and the extent to which it is occurring is powerful information, an understanding the factors contributing to variability is favorable in order to develop management plans. So far, research evaluating spatiotemporal variability in turf systems has been primarily conducted within native soil systems (Krum and Carrow, 2010; Straw et al., 2018; Straw et al., 2020a; Straw et al. 2020b). The increasing trend of capping fairway soil with sand could allow for a lesser degree of variability due to texture uniformity and control of sand depth during fairway construction. Conversely, it could also introduce other influences on soil moisture variability. Therefore, research assessing factors contributing to the spatiotemporal variability of soil moisture within these systems is warranted to progress the concept of precision irrigation on sand-capped fairways.

CHAPTER II

LONG-TERM PERFORMANCE OF WARM-SEASON TURFGRASS SPECIES UNDER MUNICIPAL IRRIGATION FREQUENCY RESTRICTIONS

Overview

Landscape irrigation frequency restrictions are commonly imposed by water purveyors and municipalities to curtail domestic water use and to ensure adequate water supplies for growing populations during times of drought. Currently, published data are lacking concerning irrigation frequency requirements necessary for sustaining acceptable levels of turfgrass quality of commonly used warm-season turfgrass species. The objective of this three-year field study was to determine comparative turfgrass quality of drought resistant cultivars of four warm-season lawn species in the south-central United States under irrigation frequency regimes of 0, 1, 2, 4, and 8 × monthly. Turfgrasses used in the study were based on previously reported drought resistance, and included ‘Riley’s Super Sport’ (Celebration®) bermudagrass (*Cynodon dactylon* (L.) Pers.), ‘Palisades’ zoysiagrass [*Zoysia japonica* Steud.], ‘Floratam’ St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), and ‘SeaStar’ seashore paspalum (*Paspalum vaginatum* Swartz). Results showed irrigation frequency of once per week was adequate to support acceptable turfgrass quality of all warm-season turfgrasses evaluated. However, with more restrictive irrigation frequencies, species selection became an important consideration. Under less than weekly irrigation frequency, St. Augustinegrass and seashore paspalum generally fell to below acceptable quality levels. Bermudagrass generally outperformed all other species under the most restrictive irrigation frequencies and also did not statistically differ from zoysiagrass. This information should be useful for policy makers as they attempt to design and implement irrigation frequency restrictions that achieve water conservation goals while preserving landscape health.

Introduction

Turfgrass landscapes provide numerous functional and aesthetic benefits in urban environments (Beard and Green, 1994); however, supplemental water, via irrigation, is often required when rainfall is not sufficient to sustain plant health (Emmons, 1995). Depending on geographic location, water used for outdoor purposes such as turfgrass irrigation has been found to comprise about 30-60% or higher of domestic water uses (Fernald and Purdum, 1998; Mayer et al. 1999; Hermitte and Mace, 2012). This surge in demand increases risk of water shortages, particularly when high population growth or exceptional drought conditions occur (Baumann et al., 1998; Sisser et al., 2016). To combat this demand, water purveyors and municipalities often enact landscape watering restrictions (St. Hilaire et al., 2008; Milman and Polsky, 2016).

Most commonly, municipal water restrictions are designed to limit landscape irrigation to specific days of the week and/or times of the day (Kenney et al., 2004; Dziegielewski and Kiefer, 2010). For instance, The Southwest Florida Water Management District employs year-round conservation measures in which lawn watering is limited to no more than twice per week (https://www.swfwmd.state.fl.us/business/epermitting/district-water-restrictions). In contrast, the City of Santa Fe, New Mexico limits watering to three days per week with no irrigation from 10 am to 6 pm from May to October (https://www.santafenm.gov/water_use_restrictions). In combination with either year-round or seasonal irrigation restrictions, some municipalities or water districts implement restrictions that vary based on the status of their water supply. For example, the San Antonio Water System (SAWS) operates on a tiered or “stage” system in which restrictions are based on water level status of their primary water source, the Edwards aquifer (https://www.saws.org/conservation/drought-restrictions/). Along with other conservation measures, the SAWS approach to water conservation has resulted in significant water savings for the San Antonio area (SAWS, 2017).

Municipalities often enact more stringent conservation strategies during severe water shortages caused by drought. For example, SAWS' stage 3 water restrictions allow for landscape watering only once every 14 days, while stage 4 restrictions may prohibit landscape irrigation entirely until wells are recharged. In 2007, the state of Georgia banned outdoor watering entirely because of severe drought (Campana et al., 2012). In 2011 as the state of Texas experienced its worst single-year drought on record, about 1,000 water systems in the state implemented watering restrictions and many areas within the state were instructed to completely cease outdoor watering (Schmidt, 2012; Thomas, 2012; Gholson, 2019).

While the mechanisms by which municipalities and water purveyors enact landscape irrigation restrictions vary, they often persist over consecutive years and take place in the presence of rainfall, even if received in sporadic or limited amounts. Furthermore, many homeowners associations, municipalities, and water purveyors have interest in knowing how infrequently water can be applied while maintaining aesthetically pleasing turf. It is difficult to answer this question, given that previous research has focused primarily on either survivability and recovery from prolonged drought periods (Steinke et al. 2010; Steinke et al. 2011) or performance under frequent irrigation at defined ET_o levels (Wherley et al., 2014; Hejl et al., 2016; Fontanier et al., 2017). As such, the extent to which warm-season turfgrass species are able to persist and/or maintain acceptable appearance under limited irrigation frequency or unirrigated conditions receiving only rainfall is largely unknown.

Therefore, the objective of this three-year field study was to determine comparative turfgrass quality of drought resistant cultivars representing four warm-season lawn species in the south-central United States under irrigation frequency regimes of 0, 1, 2, 4, and 8 × monthly.

Materials and Methods

Study Design and Treatment Layout

This study was conducted from 2016-2019 at the Texas A&M University Turfgrass Field Research Laboratory, College Station, Texas. The soil at the study site was characterized as a Boonville fine sandy loam (fine, montmorillonitic, thermic, Vertic Albaqualf). Chemical testing performed at the initiation of the study period indicated that all soil macro- and micro-nutrient concentrations in plots were sufficient. Drought-resistant cultivars of four widely used warm-season turfgrass species for the region were selected for use in the study. Turfgrasses 'Riley's Super Sport' (Celebration®) bermudagrass (*Cynodon dactylon* (L.) Pers.), 'Palisades' zoysiagrass [*Zoysia japonica* Steud.], 'Floratam' St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), and 'SeaStar' seashore paspalum (*Paspalum vaginatum* Swartz).

The study was arranged as a split-plot design with three replicate plots per treatment. Irrigation frequency (0, 1, 2, 4, or 8 × monthly), based on commonly imposed municipal irrigation restrictions in the region, was the whole-plot factor, while grass species (bermudagrass, zoysiagrass, St. Augustinegrass, or seashore paspalum) was the sub-plot factor. Irrigation frequency whole plots measured 6.1 m x 6.1 m in size, while species sub-plots measured 1.2 m x 1.2 m in size. Sub-plots were established from single 25 cm^2 plugs planted in July 2016 and allowed to establish for one year until a plot size of 1.2 m x 1.2 m was achieved. During the establishment period (July 2016 through June 2017), plots were irrigated 2-3 times weekly to encourage grow-in and to prevent wilt. To encourage rapid grow-in of plots from July through

October 2016 and May through June 2017 plots were fertilized monthly at a rate of 3.7 g m^{-2} using a 21–7–14 N–P–K fertilizer (American Plant Food Corp.) containing 64% of N as sulfur-coated urea and the remainder as ammoniacal N. During the remainder of 2017 through 2019, nitrogen was applied between May and October at 3.7 g m^{-2} every six weeks using the same previously mentioned fertilizer. All plots were mowed during the establishment and study period using a rotary mower at a 6.3 cm height of cut, representative of a typical lawn heights for the region, with clippings returned to plots. Pre-emergence herbicides were applied to plots during February and September of all years of the study using oxadiazon (Ronstar G, Bayer Environmental Sciences) at a rate of 2.25 kg ha^{-1} active ingredient. Henceforth for the purposes of this paper, the 2017, 2018, and 2019 seasons will be referred to as years 1, 2, and 3, respectively.

Irrigation Treatments

Irrigation frequency treatments were imposed from July through October of year 1, from late May through October of year 2, and from late May through August of year 3. No irrigation was applied during the slow growth/dormant season months of November through April. The 1 × monthly, 2 × monthly, and 4 × monthly frequency treatments received irrigation at a depth of 2.5 cm during each event. The 8 × monthly treatment was irrigated twice weekly to a depth of 1.25 cm resulting in 2.5 cm per week. This amount was calculated based upon the depth of water needed to replenish available water within a fine sandy loam soil with a 17.8 cm rootzone (USDA-NRCS, 1998). Whole plot irrigation was supplied via four in-ground rotor sprinklers (T5, The Toro Co., Windom, MN) located at the corners of each plot and were measured to have a precipitation rate of 3 cm h^{-1}. Each replicate whole plot was individually controlled by a valve and flow meter that was audited monthly to ensure accuracy of applied irrigation. All irrigation was applied between the hours of 10 pm and 8 am, and cycle soak methods were employed during all irrigation applications to prevent water runoff. The only water unirrigated plots received after the establishment period was from natural precipitation, which was measured on site and accounted for throughout the study period (Table 2.1). For the 4 × and 8 × monthly irrigation treatments, the irrigation schedule was adjusted to account for effective-rainfall received in the 72-hour period prior to the scheduled irrigation. For the 1 × and 2 × monthly treatments, irrigation events were delayed one week if rainfall ≥ 2.5 cm occurred during the week prior to the scheduled irrigation. Effective rainfall was calculated using a method developed by Texas A&M AgriLife Extension Service (2015) which assumes the first 2.5 cm of rainfall is 100% effective, rainfall of 2.5 to 5 cm is 67% effective, and rainfall > 5 cm is considered 0% effective. A summary of all rainfall and irrigation events during the measurement periods are provided in Table 2.2. Real-time weather data for the study were accessed through the Texas ET Network (texaset.tamu.edu), with data obtained from an onsite weather station (Campbell Scientific, Logan, Utah). Reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith equation (Allen et al. 1998).

Evaluation of Turfgrass Quality

Turfgrass quality data were collected on a biweekly schedule during the summer months of year 1 (July-August 2017), year 2 (May-August 2018), and year 3 (May-August 2019). Data were not collected until July of year 1 as plots had not yet reached full establishment. Plots were evaluated for turfgrass quality using a modified National Turfgrass Evaluation Program visual quality ranking system which uses a 1-9 scale for turfgrass quality (Morris and Shearman 1998), based on combined turfgrass attributes including color, density, and uniformity. For reference, a value of 1 indicated completely dead or dormant brown turf, a value of 5 represented minimal acceptable quality, and 9 indicated perfect green turf.

Data Analysis

At the conclusion of the project, all data were subjected to analysis of variance (ANOVA) procedures using the general linear procedures of SPSS (IBM, Armonk, NY). Where significant treatment x year interactions were detected, data were presented separately by year. Means were compared using Tukey's Honestly Significant Difference (HSD) test using a significance level of $P \leq 0.05$.

Results and Discussion

Environmental Conditions and Water Applied During Summer

Cumulative effective rainfall during the irrigation treatment period was 26.11 cm, 50.04 cm, and 19.81 cm for years 1, 2, and 3, respectively (Table 2.2). During the initial month of irrigation treatments (July 2017), seasonal evaporative demand coupled with below average monthly irrigation treatments (the two highest application frequencies) replenished only 48% and 45% of monthly ET_o (Table 2.3). This would have produced an estimated 20-25% irrigation deficit when comparing to consumptive water requirements for warm-season turfgrass, which have been reported to average 60% of ET_o (Wherley et al., 2015). Also during this time, the 1 × and 2 × monthly irrigation treatments received only 12% and 25% of monthly ET_o, respectively, which would have produced a 60-80% irrigation deficit (Table 2.3). However, these deficits were quickly replenished by above-average rainfall in late August of year 1, which resulted in each treatment receiving at least 148% of ET_o during the month (Table 2.3). During year 2, below average rainfall in August resulted in only 54% of ET_o being replaced by the most frequent irrigation schedule (Table 2.3). In contrast, unirrigated plots received only 7 and 24% of ET_o

during the months of July and August in year 3, respectively (Table 2.3), resulting in an estimated 88% and 60% irrigation deficit.

With the exception of the 4 × monthly and 8 × monthly irrigation treatments, total irrigation applied increased with increased frequency (Table 2.2). Irrigation applied and cumulative water received were similar to slightly greater in the 4 × compared to 8 × monthly irrigation frequency treatment, due to the timing of rainfall events and method of scheduling irrigation. Irrigation events were scheduled for Tuesday morning each week for the 4 × monthly treatment and Tuesday morning and Friday morning for the 8 × monthly treatment. Any rainfall received late-Tuesday morning through Thursday night was accounted for in the 8 × monthly treatment, which resulted in reduced irrigation volumes or bypassed irrigation events for the more frequent irrigation treatment.

Table 2.1. Daily mean reference evapotranspiration (ET_o) and precipitation amounts for the 2017 – 2019 study periods.

	Daily Mean ET_o (mm^{-1})			Monthly Total Precipitation (cm)		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
June	-	6.27	5.35	-	6.19	11.94
July	6.68	6.36	6.11	0.97	4.45	1.24
August	5.42	6.41	6.25	47.49	0.51	4.69

Table 2.2. Total number of rainfall and irrigation events with corresponding effective rainfall depth, irrigation volumes applied, and cumulative water received (effective rainfall + irrigation) for each irrigation frequency treatment during each trial year.

Year	Irrigation Frequency	Rain Events	Irrigation Events	Effective Rainfall (cm)	Irrigation Applied (cm)	Cumulative Water Received (cm)
1	Unirrigated	12	0	26.11	0.00	26.11
	1 × Monthly	12	4	26.11	10.16	36.27
	2 × Monthly	12	8	26.11	20.32	46.43
	4 × Monthly	12	14	26.11	35.36	61.47
	8 × Monthly	12	30	26.11	34.95	61.06
2	Unirrigated	45	0	50.04	0.00	50.04
	1 × Monthly	45	6	50.04	15.24	65.28
	2 × Monthly	45	11	50.04	27.94	77.98
	4 × Monthly	45	17	50.04	40.84	90.88
	8 × Monthly	45	34	50.04	38.13	88.17
3	Unirrigated	26	0	19.81	0.00	19.81
	1 × Monthly	26	3	19.81	7.62	27.43
	2 × Monthly	26	7	19.81	16.15	35.96
	4 × Monthly	26	13	19.81	28.70	48.51
	8 × Monthly	26	24	19.81	27.33	47.14

Table 2.3. Fraction of reference evapotranspiration received through effective rainfall and irrigation by irrigation frequency treatments for each year and month during the study period.

Year	Irrigation Frequency	June	July	August	September	October
1	Unirrigated	-	0.00	1.48	0.13	0.34
	1 × Monthly	-	0.12	1.48	0.31	0.34
	2 × Monthly	-	0.25	1.79	0.52	0.77
	4 × Monthly	-	0.48	1.95	1.04	0.98
	8 × Monthly	-	0.45	1.87	1.48	1.01
2	Unirrigated	0.30	0.23	0.03	1.45	2.70
	1 × Monthly	0.43	0.35	0.15	1.69	2.99
	2 × Monthly	0.57	0.48	0.28	1.93	3.27
	4 × Monthly	0.68	0.83	0.51	2.11	2.99
	8 × Monthly	0.70	0.74	0.54	1.95	2.98
3	Unirrigated	0.69	0.07	0.24	-	-
	1 × Monthly	0.85	0.20	0.37	-	-
	2 × Monthly	0.91	0.33	0.50	-	-
	4 × Monthly	1.07	0.71	0.72	-	-
	8 × Monthly	1.07	0.60	0.69	-	-

Effects of Irrigation Frequency on Mean Visual Turfgrass Quality

Analysis of variance showed a highly significant ($P < 0.001$) month by irrigation frequency interaction on turfgrass visual quality for each year of the study (Table 2.4). In year 1, despite a large water deficit in July, each irrigation treatment supported acceptable (≥ 5) turfgrass quality (when pooling across all species), likely due to residual soil water from the establishment period as well as the shorter duration of water deficit (Table 2.5). When pooling across all species during July of year 2, the unirrigated treatment resulted in unacceptable turf grass quality, and did not significantly differ from the 1 × or 2 × monthly treatments (Table 2.5). Irrigation limited to 1 × monthly supported acceptable turfgrass quality until August of year 2, at which time only the 4 × monthly and 8 × monthly treatments showed acceptable turfgrass quality (Table 2.5). By June of year 3, turfgrass quality within all irrigation frequency treatments except the unirrigated control had recovered to acceptable levels, due largely to 137 cm of rainfall received between September of year 2 and May of year 3 (Table 2.5). However, by July of year 3, the 2 × monthly and 1 × monthly frequency treatments had fallen to unacceptable quality levels (Table 2.5). These results suggest that when pooling across all species, weekly irrigation is generally required to support minimally acceptable turfgrass quality if applied over consecutive seasons.

In practice, most municipal water restrictions requiring less than 1 × weekly irrigation are only implemented periodically. How a more dynamic system of restrictions may influence turfgrass quality can only be speculated from these data. Water restrictions aim to reduce water use, but they are only as effective as the enforcement mechanism (Ozan and Alsharif, 2013). As lawns wilt or fire in response to drought stress during municipal water restriction periods, it is possible that on allowable watering days, homeowners may over-apply water (beyond soil field capacity) with the intention to aid in recovery or in hopes to maintain quality. As such, without proper enforcement mechanisms, water savings could be somewhat negated. Further research is needed to ascertain what amount of irrigation per event would allow for optimal turfgrass quality under longer irrigation intervals.

Table 2.4. Analysis of variance table for month, irrigation frequency, and species on visual quality during the three study years. Study main effect was significant for each parameter ($P \leq 0.05$)

	P-values		
	Year 1	Year 2	Year 3
Month (M)	ns	***	**
Irrigation Frequency (IF)	*	***	***
Species (S)	ns	***	***
M x IF	***	***	***
M x S	ns	***	ns
IF x S	ns	***	*
M x IF x S	ns	ns	ns

$^{NS, *, **, ***}$ Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively

Table 2.5. Average monthly visual quality for each year as affected by irrigation frequency. Data are pooled across species. Means with the same letter are not significantly different based on Tukey's HSD @ $P \leq 0.05$.

Year	Irrigation Frequency	June	July	August
1	Unirrigated	-	6.75ab	6.13b
	1 x Monthly	-	6.67ab	6.42b
	2 x Monthly	-	6.83a	6.25b
	4 x Monthly	-	6.58ab	7.08a
	8 x Monthly	-	6.25b	7.08a
	P-value		*	***
2	Unirrigated	5.42c	4.38b	1.88d
	1 x Monthly	5.58bc	5.04b	3.37c
	2 x Monthly	5.67bc	5.17b	4.58b
	4 x Monthly	6.17ab	6.38a	5.25ab
	8 x Monthly	6.63a	6.71a	6.08a
	P-value	***	***	***
3	Unirrigated	4.83a	4.67a	3.63c
	1 x Monthly	5.17a	4.53a	4.13bc
	2 x Monthly	5.17a	4.94a	4.67ab
	4 x Monthly	5.08a	5.00a	5.33a
	8 x Monthly	5.08a	4.81a	5.46a
	P-value	NS	NS	***

$^{NS, *, **, ***}$ Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively

Species Response to Irrigation Frequency

In years 2 and 3, there were highly significant irrigation frequency by species interactions for turfgrass quality (*P* < 0.001) (Table 2.4). When pooling across months during year 2, unirrigated (rainfall only) conditions led to unacceptable turfgrass quality in all species. When comparing among species in the absence of irrigation in year 2, turfgrass quality of seashore paspalum (3 out of 9) was significantly lower than that of zoysiagrass (4.2 out of 9), St. Augustinegrass (4.5 out of 9), and bermudagrass (4.7 out of 9) (Figure 2.1).

In year 3 of the study, bermudagrass was able to maintain acceptable quality under all irrigation frequency treatments and supported significantly higher turfgrass quality compared to St. Augustinegrass at all frequencies, although differences were not significant under 8 × monthly (Figure 2.1). Interestingly, zoysiagrass supported statistically similar turfgrass quality to bermudagrass under all irrigation frequencies and during all years of the study. However, zoysiagrass turfgrass quality fell to below-acceptable levels for the 1 × monthly and unirrigated treatments during both years 2 and 3.

The superior drought resistance and ability to maintain acceptable quality under infrequent irrigation observed in bermudagrass has been attributed to its strong drought avoidance attributes, which include deep rooting potential and somewhat lower evapotranspiration rates compared to other species (Carrow, 1995; Carrow, 1996). Although prior studies have characterized *Zoysia* spp. as having relatively shallow root systems, making them more sensitive to drying soil than bermudagrass (Carrow, 1996; Qian and Engelke, 1999), the cultivar used in the present study (Palisades) was previously shown to have relatively high root dry weight in comparison to 14 other zoysiagrass genotypes (Jespersen and Schwartz 2018). Palisades also showed stronger propensity for deep (25-50 cm) rooting compared to six other (predominantly finer-textured) zoysiagrasses in a 2-year Dallas, TX field study (Wherley et al., 2014).

St. Augustinegrass maintained similar turfgrass quality to bermudagrass and zoysiagrass in years 1 and 2. However, relatively high rainfall and wet soil conditions received during fall of year 2 contributed to high incidence of large patch disease (*Rhizoctonia solani)* in plots, which limited recovery from drought stress between years 2 and 3. Consequently, turfgrass quality of St. Augustinegrass in year 3 (which ranged from ~4 to 5 out of 9) was significantly lower than that of bermudagrass and zoysiagrass across all irrigation frequency treatments except 8 x monthly. It was also lower than that of seashore paspalum at all irrigation frequencies except for the unirrigated treatment (Figure 2.1).

In years 2 and 3, seashore paspalum was only able to achieve acceptable quality at the highest two (4 × and 8 × monthly) irrigation frequencies (Figure 2.1). In year 2, turfgrass quality of the unirrigated and 2 × monthly frequency treatments was significantly lower for seashore paspalum than for all other species. In year 3, turfgrass quality for the unirrigated treatment was significantly lower for seashore paspalum than for bermudagrass or zoysiagrass (Figure 2.1). While not yet widely used as a warm-season amenity lawn grass in most of the U.S., the response of seashore paspalum to the most stringent irrigation frequencies is consistent with the findings of Jespersen et al. (2019), who reported ‘Seastar’ seashore paspalum demonstrated the poorest drought response in a greenhouse study involving Celebration bermudagrass, two hybrid bermudagrasses, and two other seashore paspalum cultivars.

This study sought to determine minimal irrigation frequencies needed to support acceptable aesthetic quality of commonly used warm-season turfgrass species. As such, the data should not be misinterpreted as representative of irrigation amounts required for survival. A number of previous studies have reported on potential of warm-season grasses to enter dormancy survive, and recover from severe, longer-term drought periods (Steinke et al., 2010; Steinke et al., 2011; Hejl et al., 2016). Unfortunately, at the current time, most communities and/or home owners' associations do not tolerate the straw-colored appearance of dormant lawns, which remains a challenge for the long-term viability of turfgrass in the modern landscape.

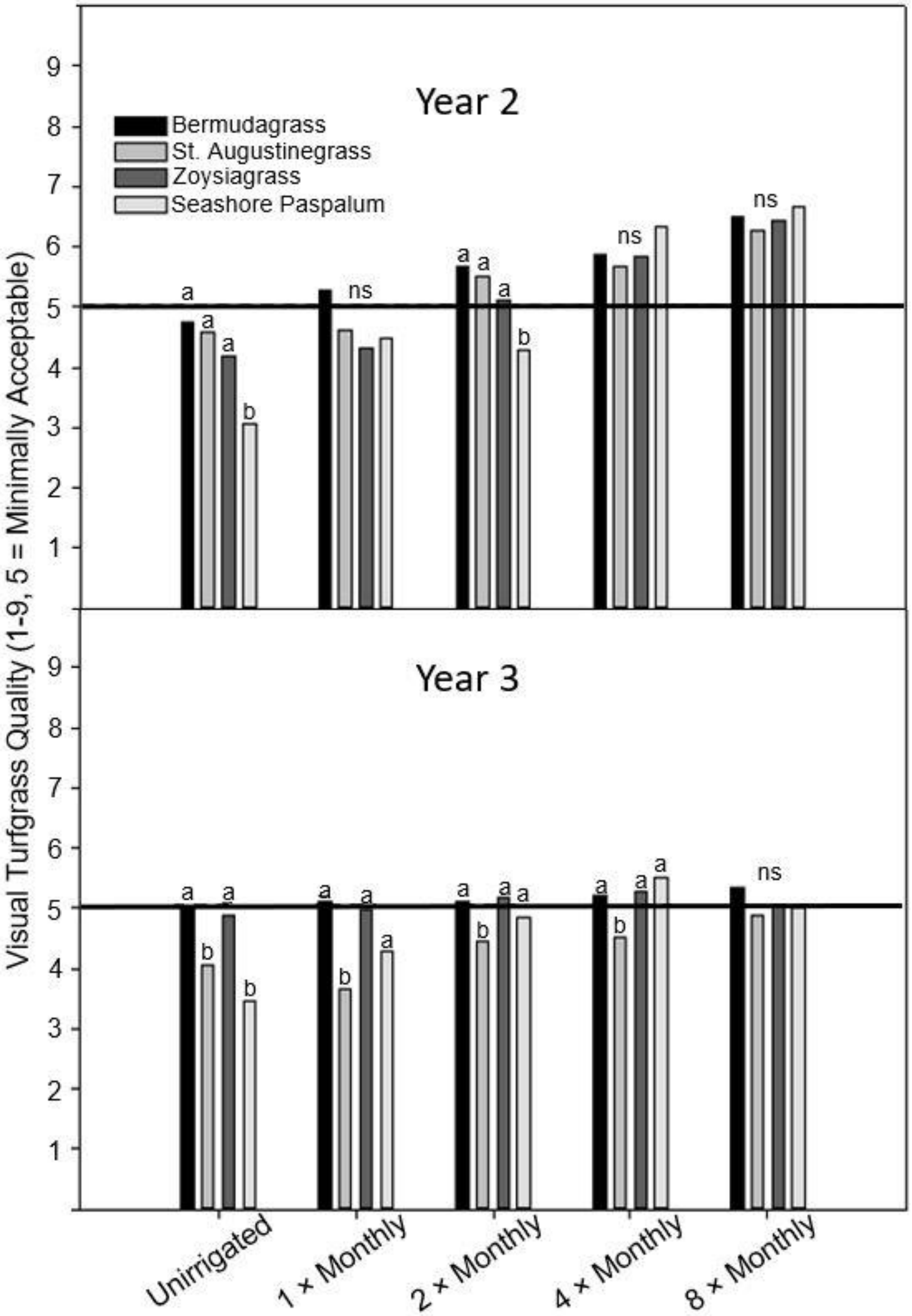

Figure 2.1. Average visual quality for each year as affected by species and irrigation frequency. Data are pooled across months. Means with the same letter are not significantly different based on Tukey's HSD @ $P \leq 0.05$ for each irrigation frequency. Solid line represents minimal acceptable quality.

Conclusions

Landscape watering restrictions are commonly enforced as water purveyors and municipalities seek to mitigate discretionary domestic water use to ensure adequate water supplies for growing populations and during times of drought. Application of such policies has rarely considered irrigation frequency requirements needed to support acceptable appearance among turfgrass species. Our results from this 3-year field study indicate that, on average, the warm-season turfgrass species used were able to maintain acceptable visual quality while being irrigated at frequencies limited to once per week in this central Texas climate. Among the four species included, bermudagrass (cultivar Celebration) maintained acceptable visual quality across the broadest set of irrigation frequencies. Zoysiagrass (cultivar Palisades) performed similarly to bermudagrass at most irrigation frequencies, suggesting that selection of drought resistant cultivars within a given species is an important consideration when selecting drought-adapted landscape grasses. This information should be useful for policy makers as they attempt to design and implement irrigation frequency restrictions that achieve water conservation goals while preserving landscape health.

CHAPTER III

EVALUATION OF IRRIGATION SCHEDULING APPROACHES WITHIN SAND-CAPPED TURFGRASS SYSTEMS

Overview

In an effort to improve performance of turfgrass irrigated with poor quality water, the trend of sand-capping is increasing. Given current strains on water supplies, it's essential to evaluate efficient methods of irrigation scheduling approaches in these systems. The objectives of this 2 year field study were to evaluate turfgrass performance, temporal and spatial soil moisture and salinity dynamics, and comparative water use associated with four irrigation scheduling approaches including: 1) wireless soil moisture sensor (SMS), 2) on-site reference evapotranspiration (ET_o), 3) National Oceanic and Atmospheric Administration (NOAA) Forecasted Reference Evapotranspiration (FRET) and 4) a visual wilt-based. Results of the study demonstrated all irrigation scheduling approaches produced similar levels of acceptable turfgrass quality and percent green cover. Forecasted Reference Evapotranspiration was considered a good predictor of on-site ET_o, (R^2= 0.97). Under wilt-based irrigation, the volumetric water content at which wilt occurred was highest mid-summer, but declined during early and late summer months, suggesting that different thresholds may need to be used at different times of the year in SMS-based irrigation scheduling. Finally, the use of a 22% leaching fraction within the SMS-based treatment failed to decrease sand-cap electrical conductivity below that of other treatments, suggesting that greater water savings could have been realized in the SMS-based treatment with minimal impact on root zone salinity. The results provide important information to aid irrigation scheduling of sand-capped turf systems and should also help foster greater adoption of data-driven irrigation scheduling.

Introduction

As turfgrass managers strive to maintain satisfactory conditions for turfgrass growth, irrigation with low-quality water sources can lead to soil degradation and diminished turfgrass health over time (Carrow and Duncan, 2012; Marcum, 2006). Golf course fairways, sports fields, and lawns are prone to these diminished conditions when grown on fine-textured native soil and irrigated with water high in sodium or salts (Dyer et al., 2020). Sand-capping the existing native soil has become a common practice to deal with poor water quality or excessive rainfall, since it provides an improved, well-draining growing medium for turfgrass leading to improved performance and playability (White, 2013; Whitlark and Isom, 2020). Limited published data are available concerning irrigation of sand-capped systems. Dyer et al. (2020) found no differences in percent green cover between 1 vs. 2 day-per-week irrigation frequency regimes on sand-capped 'Tifway' hybrid bermudagrass [*Cynodon dactylon* L. (Pers.) × *C. transvaalensis* Burtt-Davy]. Given the increased trend of sand-capping and current strains on water supplies, it is essential that efficient methods of irrigation management be developed for these systems.

Since rainfall is insufficient to sustain functionality and aesthetic appeal of turfgrass in many regions, supplemental irrigation is often necessary (Emmons, 1995). In making irrigation scheduling decisions, quantitative or qualitative methods are employed (Davis and Dukes, 2010). Irrigation scheduling on golf courses is normally decided based on a number of factors; however, the overwhelming percentage of U.S. golf courses make irrigation scheduling decisions based on visual observation of the turfgrass (96% in 2013 and 94% in 2013), while data-driven scheduling practices have been much less utilized (Gelernter et al, 2015). Basing irrigation decisions on turf observations may be an effective means of achieving desired turfgrass conditions, but it could create challenges when courses are required to budget water needs as a result of increasing water regulations (Gelernter et al., 2015).

Scheduling irrigation based on quantitative methods aims to estimate plant-water needs by monitoring soil moisture levels or estimating evapotranspiration (ET) losses (Wade and Waltz, 2004). Evapotranspiration is comprised of the two mechanisms for which water is lost in plant systems: soil evaporation and plant transpiration (Allen et al., 1998). Weather variables such as wind speed, temperature, solar radiation, and humidity are factors that drive ET. Weather stations that measure these variables and input them to the Penman-Monteith equation are able to calculate daily reference ET (ASCE-EWRI, 2005 Valipour, 2015). Reference ET (ET_o) applies to a hypothetical reference crop that is actively growing under non-limiting soil moisture conditions and has the characteristics of a cool-season turfgrass grown at 0.12 m (Allen et al., 1994). Actual turfgrass ET (ET_a) compared to ET_o produces a crop coefficient (K_c, where $K_c = ET_a/ET_o$) that can be used to estimate plant water needs, and therefore, irrigation amounts to assist with making irrigation scheduling decisions (Allen et al., 1998).

To produce appropriate turfgrass K_c values, numerous studies across a range of species and climates have used lysimeters to measure ET_a in concurrently with ET_o (Atkins, 1991; Carrow, 1995; Devitt et al., 1992; Feldhake, 1983; Green et al., 1990; Kim and Beard, 1988; Kneebone and Pepper, 1991; Wherley et al., 2015). A year-round K_c value of 0.6 was suggested by Meyer and Gibeault (1987), and has become a widely accepted value for irrigating warm-season turfgrasses. However, reported K_c values for hybrid bermudagrass range from 0.52 to 0.89, with an overall average of 0.76 during the summer growing months (Colmer and Barton, 2017), which may be attributed to factors such as fertility, mowing height, or differences in climatic conditions under which studies were conducted.

Despite its proven efficiency, as of 2013 only 31% of golf courses within the U.S. reported using ET as a basis for irrigation scheduling decisions (Gelernter et al., 2015). Since the utilization of ET_o in making irrigation scheduling decisions requires access to locally representative data (Allen et al., 1998), either by a nearby or on-site weather station, low-level adoption of ET-based irrigation programs could be in part due to insufficient access to locally representative ET_o data. A recently released experimental forecast reference ET (FRET) provided by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) provides ET_o data based on forecasted weather conditions (digital.weather.gov). The NOAA FRET data are reported by the National Digital Forecast Database (NDFD) and are open-access and estimated on a 2.5-km grid basis across the contiguous United States. The FRET values are available for the current day, as well as up to 6 days in advance (Blankenau et al., 2020; Palmer et al., 2016). By providing ET data regardless of proximity to a weather station, NOAA FRET offers turfgrass managers another tool for guiding irrigation scheduling and may aid in adoption of ET-based irrigation scheduling for golf courses. While a recent study determined gridded weather data sets to be overestimating ET_o by 12 to 31% (Blankenau et al., 2020), there is currently a lack of published research evaluating the reliability of FRET for predicting ET_o, particularly as it relates to scheduling turfgrass irrigation needs.

The monitoring of soil moisture levels through use of soil moisture sensors (SMS) such as tensiometers or dielectric probes, is another common quantitative method for scheduling irrigation (Wade and Waltz, 2004). Soil moisture sensing technology has improved over time allowing for increased accuracy and durability. As of 2013, the majority of golf courses that utilize SMS as a means for making irrigation scheduling decisions have been primarily employed using hand-held sensors (29% of U.S golf courses), compared to in-ground SMS (4% of U.S.

golf courses) (Gelernter et al., 2015). In-ground SMS have been primarily utilized in high priority areas of golf courses and those with uniform soil characteristics, such putting greens, but have been underutilized in larger areas of golf courses such as fairways, possibly due to cost and extent of soil moisture variability occurring in native soil systems (Straw et al., 2020b). Given the potential for greater uniformity of soil texture and moisture within sand-capped systems compared to native soil, sand-capped systems could offer a large-scale opportunity for utilization of SMS-based irrigation scheduling. Numerous studies have compared calendar-based and SMS-based irrigation scheduling approaches, with reported water savings of up to 24 to 65% (Blonquist et al, 2006; Grabow et al., 2013; Haley and Dukes, 2012; Serena et al., 2020). However, at this time, research is lacking regarding potential water savings from SMS or ET-based irrigation scheduling in sand-capped turf systems.

Given the increased trend of sand-capping golf course fairways and sports fields, research is needed to evaluate irrigation scheduling approaches within these systems. Therefore, the objectives of this 2 year field study were to evaluate turfgrass performance, temporal and spatial soil moisture and salinity dynamics, and comparative water use associated with four irrigation scheduling approaches including 1) wireless SMS, 2) on-site ET_o, 3) NOAA FRET and 4) visual wilt-based.

Materials and Methods

Research Location and Sand-Cap Facility Construction

This experiment was conducted from 10 June 2019 through 31 October 2020 at the Texas A&M University Turfgrass Field Laboratory, College Station, Texas (30.6014° N, 96.3144° W). A 0.9 ha sand-capped fairway research facility was constructed for the project during July 2018. The sand-cap layer was placed at a depth of 17.8 cm atop native Boonville fine sandy loam topsoil, hereafter referred to as ‘subsoil’ (fine, montmorillonitic, thermic, Vertic Albaqualf). Capping sand was a locally-sourced, medium-coarse textured ‘concrete’ sand with 80% of particles <2 mm, 73% of particles <1 mm, 56% of particles <0.5 mm, bulk density of 1.76 g cm^3, total porosity of 33.8%, and a coefficient of uniformity of 3.2. Subsoil testing (0-10 cm depth) at the onset of the study showed a pH of 8.5 and high levels of all essential macro and micronutrients except for phosphorus (45 ppm) and potassium (109 ppm), which were considered to be at moderate-high levels. The elevated pH was due to the local irrigation water used at the site, which had pH of 8.4, electrical conductivity of 1.0 dS m^{-1}, 234 ppm Na, 509 ppm bicarbonates, and SAR of 33.7. The subsoil beneath sand-capped plots was laser graded to a final 1% slope draining away from the centerline between the two rows of treatment plots within the facility into adjacent alleys.

On 15 August 2018, ‘Latitude 36’ hybrid bermudagrass was planted at a rate of 83 m^3 h^{-1} of bagged sprigs. From August 2018 through April 2019, frequent irrigation, fertilization, and mowing were used to promote successful establishment. Plots established rapidly, and had achieved full coverage by late fall 2018.

Study Area Cultural Management

Beginning April 2019, plots were mowed two to three times weekly during the growing season at a height of 1.3 cm using a triplex reel mower with clippings returned. Fertilizer was applied at a rate of 3.7 g N m^{-2} every 3 to 4 weeks between May and September during both growing seasons using a 21-7-14 N-P-K fertilizer (American Plant Food Corp.) containing 64% of N as sulfur-coated urea and the remainder as ammoniacal N. To avoid hydrophobicity within the sand-cap, Aquatrols ® Revolution ® (Paulsboro, NJ) wetting agent was applied monthly from April 2019 through October 2020 at a rate of 1.9 mL m^{-2}. Pre-emergence herbicides were applied to plots during February and September of all years of the study using oxadiazon (Ronstar G, Bayer Environmental Sciences) at a rate of 2.25 kg ha^{-1} active ingredient. Irrigation was applied at a 3 mm depth immediately following fertilizer, wetting agent, and herbicide applications.

Irrigation Scheduling Approaches

Four irrigation scheduling approaches were evaluated including 1) wireless SMS, 2) on-site ET_o, 3) NOAA forecasted ET_o, and 4) visual wilt-based. A single Toro TurfGuard® Wireless SMS was installed in the center of all treatment plots to monitor VWC and electrical conductivity (EC) within the upper portion of the sand-cap (7.6 cm below surface) and upper portion of the underlying subsoil (20.3 cm below surface). Within the visual wilt-based plots, a second sensor was installed 30 cm from the first to also monitor VWC within the lower portion of the sand-cap (15.2 cm below surface) and deeper subsoil (27.9 cm below surface). While soil VWC was monitored within all treatments, the wireless SMS treatment plots were the only treatments where irrigation was applied based on soil VWC status. The wireless SMS were programmed to record soil VWC and EC (dS m^{-1}) on 5-minute intervals throughout the study.

For wireless SMS treatment plots, irrigation was applied to allow for 75% allowable depletion, or when measured VWC at the 7.6 cm depth fell below 25% of estimated plant available water (calculated to be 7% VWC). Through field calibration following rainfall and subsequent dry downs during May of Year 1, saturation (28% ± 3 VWC), field capacity (17% ± 1 VWC), and permanent wilting point (4% ± 2 VWC) were determined for the 7.6 cm sensor depth within each replicate wireless SMS plot. During these calibrations, minimal VWC fluctuation was observed at the subsoil (20 cm) sensor depth, so irrigation was scheduled based on changes in measured soil moisture at the 7.6 cm sensor depth. This information combined with total porosity (34%) data obtained through initial testing of the capping sand was used to estimate plant available water for the sand-cap layer. Soil VWC of wireless SMS plots was monitored daily throughout the study, with irrigation scheduled once the allowable depletion threshold (≤7% VWC) was reached for a given plot. Thus, with few exceptions, plots were usually irrigated prior to visible onset of wilt. Irrigation return amounts for this treatment were 2.4 cm per event, which was intended to provide a 22% leaching fraction. Irrigation events were split into two applications (1.2 cm each), applied three hours apart.

For the on-site ET_o treatment, plots were irrigated twice weekly based on the previous 3 days (Monday through Wednesday) or 4 days (Thursday through Sunday) on-site cumulative ET_o multiplied by the warm-season turfgrass K_c (0.6). Real-time weather data for the study were accessed through the Texas ET Network (texaset.tamu.edu), with data obtained from an onsite weather station (Campbell Scientific, Logan, Utah). Reference evapotranspiration was calculated using the FAO Penman-Monteith equation (Allen et al., 1998).

The NOAA forecasted ET_o treatment plots were irrigated twice weekly based on split applications of total weekly FRET values multiplied by the warm-season turfgrass K_c (0.6). Data were accessed through the National Weather Service NOAA website (digital.weather.gov). For both ET_o treatments, effective rainfall was accounted for in calculating irrigation requirements. Effective rainfall was calculated using a method designed by the Texas A&M AgriLife Extension Service (2015) that assumes the first 25 mm of rainfall in an event to be 100% effective, subsequent rainfall <25 to 50mm to be 67% effective, and rainfall >50mm to be 0% effective.

For the visual wilt-based approach treatment, plots were visually evaluated for wilt every afternoon between 1200 and 1500 hours. When individual plots expressed ≥50% wilt on an area basis, irrigation was scheduled for the next morning in the amount of 2.4 cm of water. This was the calculated amount of water needed to return soil VWC from wilt point back to field capacity, as determined through the aforementioned porosity and field calibration measurements. As with SMS-based treatment plots, irrigation events were split into two applications, applied three hours apart.

All irrigation treatment plots measured 6.1 m x 6.1 m, and were irrigated using in-ground rotor sprinklers (T5, The Toro Co., Windom, MN) positioned at the corners of each plot. Irrigation audits were conducted on each plot bi-monthly to ensure accuracy of irrigation volumes applied. Irrigation precipitation rates averaged 38 mm h^{-1} with mean lower quartile distribution uniformity of 0.67.

Regression Analysis of FRET vs. ET_o

At the conclusion of the study, linear regression analysis was performed to determine the relationship between NOAA FRET and ET_o. For these analyses, all daily FRET and ET_o values (cm per day) from both 2019 to 2010 seasons were included for determining the accuracy at which FRET predicted actual on-site ET_o data. Also, since the FRET data accessed on Monday mornings represented daily forecasted ET_o values for the upcoming Monday through Sunday, comparisons were then made to determine the accuracy of daily FRET when accessed utilizing various lead times ranging from 0 (day of prediction) to 6-days in advance, relative to the actual day's on-site ET_o. Linear regression analysis was performed using SPSS (IBM, Armonk, NY), with R^2 and significance levels of regression equations presented.

Turfgrass Performance Evaluations

Turf performance was evaluated during the study period through visual quality ratings and digital image analysis (DIA) for percent green cover in plots. Plots were evaluated for turfgrass quality using a modified National Turfgrass Evaluation Program visual quality ranking system of assigning values according to a 1-9 scale (Morris and Shearman, 1998), and are based on combined characteristics of color, density, and uniformity of the turfgrass. For reference, a value of 1 indicated completely dead or dormant brown turfgrass, a value of 5 represented minimal acceptable quality, and 9 indicated green, dense, and uniform turfgrass.

Digital images of plots were also taken on a bi-weekly basis using a Nikon Coolpix 7100 digital camera (Nikon, Tokyo, Japan) mounted on a 0.6 m^2 square light-box equipped with four compact fluorescent bulbs that was randomly positioned within each plot. Camera settings were as follows: image type (JPEG Image), dimensions (1280 × 960 pixels), color (sRGB), no flash, focal length (6 mm), F-stop (F 2.8), exposure time (1/30 sec), ISO 200, white balance K6670. Images were analyzed for percent green cover using Turf Analyzer software (Green Research Services, LLC, Fayetteville, AR) (Karcher et al., 2017).

Determination of Seasonal Water Use

Seasonal water use for each treatment was determined through a Recordall® Mechanical Water Meter installed at the valve of each plot (Badger Meter, Milwaukee, Wisconsin). Water meter readings (gallons) from the start of each season (early June) in both years was subtracted from end of season (late October) values in order to obtain total gallons used. Total gallons applied were then converted to depth (cm) of irrigation applied to each plot.

Sand-Cap Volumetric Water Content at Wilt

To determine whether the soil moisture threshold at which wilt occurred changed throughout the growing season, the mean soil VWC for the afternoon hours (1200 to 1500 hrs) was determined each time ≥50% visual wilt was observed within visual wilt-based plots. These values were obtained for each of the two wireless SMS sensor depths (7.6 cm, 15.2 cm) positioned within the 17.8 cm deep sand-cap from June through October during both years of the study.

Irrigation Scheduling Approach Effects on Root Zone Salinity

Root zone soil salinity was simultaneously measured along with VWC at all wireless SMS sensor depths throughout the study. Mean monthly electrical conductivity data for the 7.6 cm (middle sand-cap) and 20.3 cm (upper subsoil) depths were then evaluated to compare effects of the various irrigation approaches on root zone salt accumulation.

Root Development

In November of both years, a tractor-mounted hydraulic soil sampling probe was used to remove soil samples (5-cm diameter x 35 cm deep) from two random locations within each plot. Sand-cap and subsoil fractions were separated in order to determine root dry weights for each fraction. The samples were washed and sieved to separate roots from soil, then oven dried at 65 °C for 72 h and weighed for determination of the mass of dry roots.

Analysis of Data

At the conclusion of the project, all data were subjected to analysis of variance (ANOVA) procedures using the general linear procedures of SPSS (IBM, Armonk, NY). Month and Year were both considered a fixed effect in the model. Means were compared using Fisher's protected least significant difference (LSD) test using a significance level of $P \leq 0.05$.

Results

Total precipitation during the study period was considerably lower than normal, when comparing actual to historical amounts. When comparing the 5-month June through October periods for both seasons, rainfall was higher in the first season (27.5 and 21.3 cm for 2019 and 2020, respectively) (Figure 3.1). However, rainfall patterns differed between the 2019 and 2020 seasons. The majority of rainfall in 2019 was received early (June) and late (October) in the season, whereas much greater rainfall was received mid-season (July and August) during 2020. Evaporative demand at the site was similar for both seasons (79.5 and 78.6 cm for June through October of 2019 and 2020, respectively).

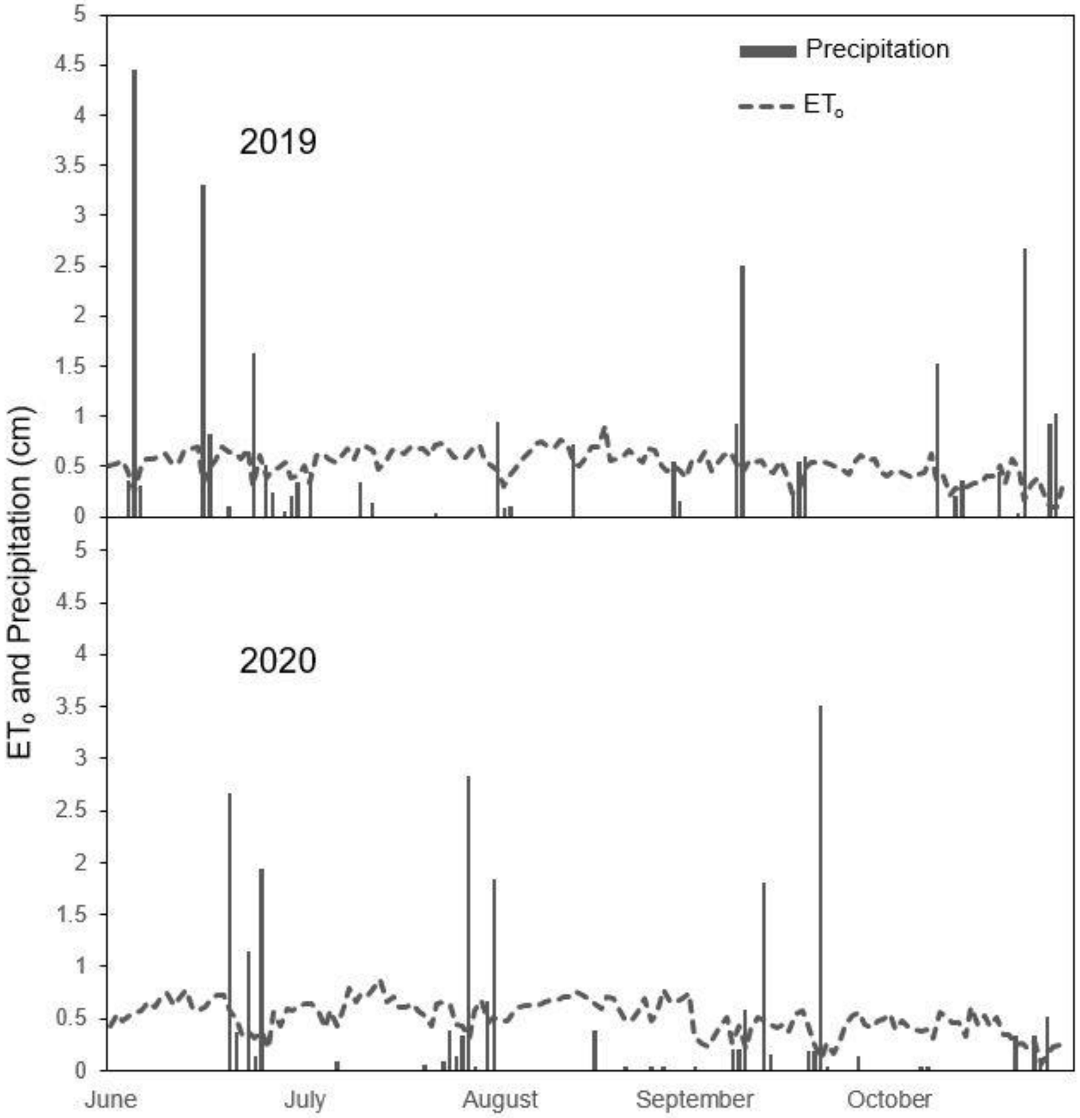

Figure 3.1. Reference evapotranspiration (ET_o) and precipitation amounts (cm) for the 2019 (upper) and 2020 (lower) seasons.

Irrigation Scheduling Approach Effects on Turfgrass Visual Quality and Green Cover

All irrigation scheduling approaches supported above-acceptable visual quality (≥5) throughout both seasons, and ANOVA showed no significant effects or interactions of irrigation on turf quality (Table 3.1). There was a significant Year × Month interaction for turfgrass visual quality. When pooling across irrigation scheduling approaches, mean monthly visual quality ranged from 6.5 to 7.7 (Table 3.2). In 2019, treatments began the season at visual quality levels >6, and although a slight decline was observed in July, all treatments maintained visual quality of >7 from August through October (Table 3.2). Plots began the 2020 season at visual quality levels >7 for June followed by another slight decline in July, with levels of ≥7 maintained from August through October (Table 3.2).

Digital image analyses of percent green cover were in agreement with the observed visual quality trends, with no significant differences observed among treatments (Tables 3.1 and 3.2). Similar to turf quality, there was a significant Year × Month interaction for percent green cover, so monthly data have been presented separately by year. When pooling across treatments in 2019, percent green cover ranged from 79 to 90%, with significant mid-summer declines observed during July and August (Table 3.2). In 2020, percent green cover averages remained at consistent and statistically similar (87 to 90%) across the season. Similar to turf quality, all irrigation scheduling approaches provided similar percent green cover levels, and adequate amounts of water to support consistently high levels of green cover across both seasons.

Table 3.1. Analysis of variance for year, month, and irrigation scheduling approach on turf and soil parameters during the 2-year irrigation study.

	P-values									
	Visual Turf Quality	Percent Green Cover	Water Use	Sand-Cap Wilt Threshold		Electrical Conductivity		Root Dry Weight		
				7.6 cm	15.2 cm	7.6	20.3 cm	Sand	Subsoil	Total
Year (Y)	ns	ns	ns	ns	ns	ns	***	**	ns	ns
Month (M)	***	***		*	ns	ns	*			
Irrigation (I)	ns	ns	*			ns	**	ns	ns	ns
Y x M	***	***		ns	ns	ns	ns			
Y x I	ns	ns	ns			ns	ns			
M x I	ns	ns				ns	ns			
Y x I x M	ns	ns				ns	ns			

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

Table 3.2. Average turfgrass visual quality and percent green cover pooled across irrigation scheduling approach for each month during the 2019 and 2020 seasons.

		Visual Turfgrass Quality	Green Cover (%)
2019	June	6.8	90.2
	July	6.5	84.2
	August	7.2	79.2
	September	7.3	90.2
	October	7.4	88.9
	LSD	0.5	4.5
2020	June	7.7	89.0
	July	6.9	90.2
	August	7.2	88.2
	September	7.1	86.5
	October	7.0	90.9
	LSD	0.4	7.4

Seasonal Water Use Based on Irrigation Scheduling Approach

Water use was determined by subtracting start-of-season (early June) from end-of-season (late October) water meter readings for each treatment plot. Annual water use totals have been pooled across years, as ANOVA showed no significant effect of year on total water use (Table 3.1). Total water use for the weather-based treatments was 37 and 38 cm for the on-site ET_o and FRET based treatments, respectively (Figure 3.2). Since effective rainfall was accounted for in these treatments, the fraction of ET_o received through irrigation was 47% and 48% for the on-site ET_o and FRET-based treatments, respectively (Figure 3.2). Total water use for the Wireless SMS-based and visual-wilt-based treatments was 48 and 44 cm, respectively (Figure 3.2). The wireless SMS irrigation treatment resulted in significantly higher (30% higher) water use compared to onsite ET_o, but there were no statistical differences in water use noted among any other irrigation approaches (Figure 3.2).

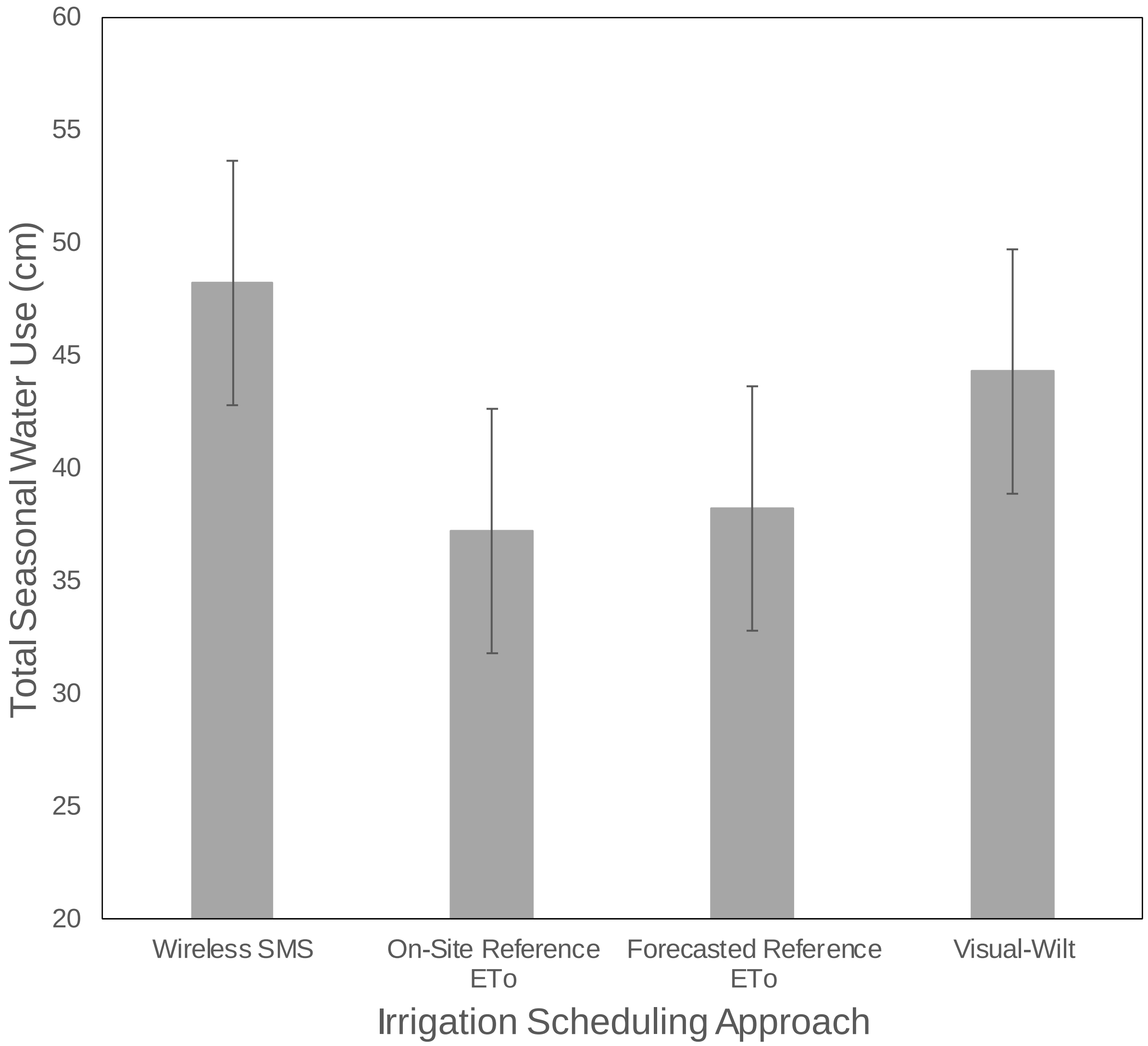

Figure 3.2. Effect of irrigation scheduling approach on total seasonal water use. Data are pooled across 2019 and 2020 seasons. Bars denote Fisher's LSD at $P \leq 0.05$.

Relationship between FRET and ET_o

Regression analysis of NOAA FRET vs. actual on-site ET_o showed FRET to be a good predictor of on-site ET_o ($R^2 = 0.97$) (Figure 3.3). Interestingly, although FRET over-estimated water requirements when ET_o was less than 0.5 cm per day, it appeared to under-estimate water requirements during days of higher evaporative demand, when daily ET_o exceeded 0.5 cm. Also, when comparing FRET vs. actual ET_o based on different lead times ranging from 0 (day of) to 6 days in advance, there did not appear to be greater accuracy gained through use of shorter lead times, with R^2 ranging from 0.59 to 0.79 (Table 3.3).

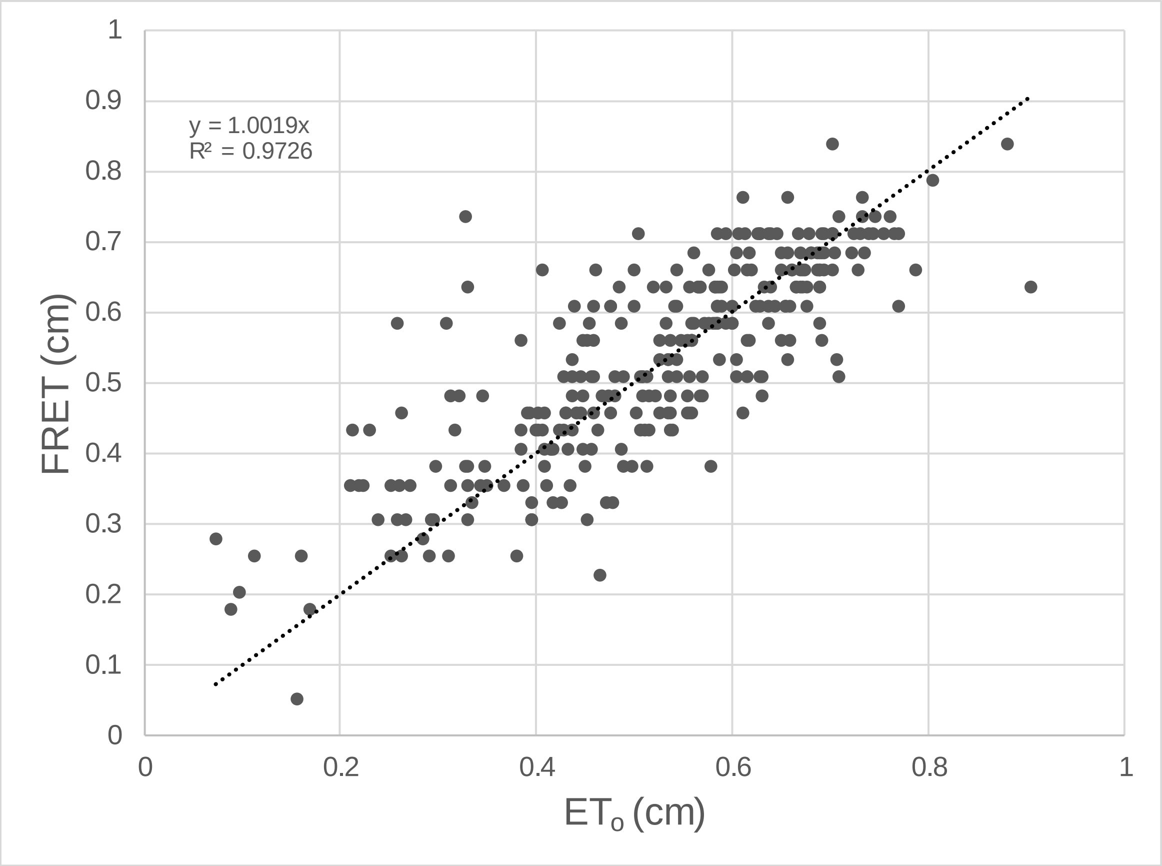

Figure 3.3. Regression analysis of daily FRET and actual on-site ET_o values for the 2019 and 2020 seasons.

Table 3.3. Calculated R^2 for linear regression models comparing FRET to on-site ET_o when FRET data were accessed at 0 (same day) up to 6-days in advance.

Lead Time (Days)	R^2	Significance
0	0.69	***
1	0.66	***
2	0.63	***
3	0.59	***
4	0.79	***
5	0.65	***
6	0.59	***

*** Significant at $P \leq 0.001$

Soil Volumetric Water Content at Wilt Threshold

The ANOVA showed a significant effect of month, but no effect or interaction of year, on the soil VWC threshold at which wilt occurred (Table 3.1). Based on measured VWC at the 7.6 cm depth, wilt occurred at a lower VWC (1.8 to 2.2%) early and late in the season (June and October), compared with mid-summer months (4.1 to 4.7% during July-September) (Figure 3.4).

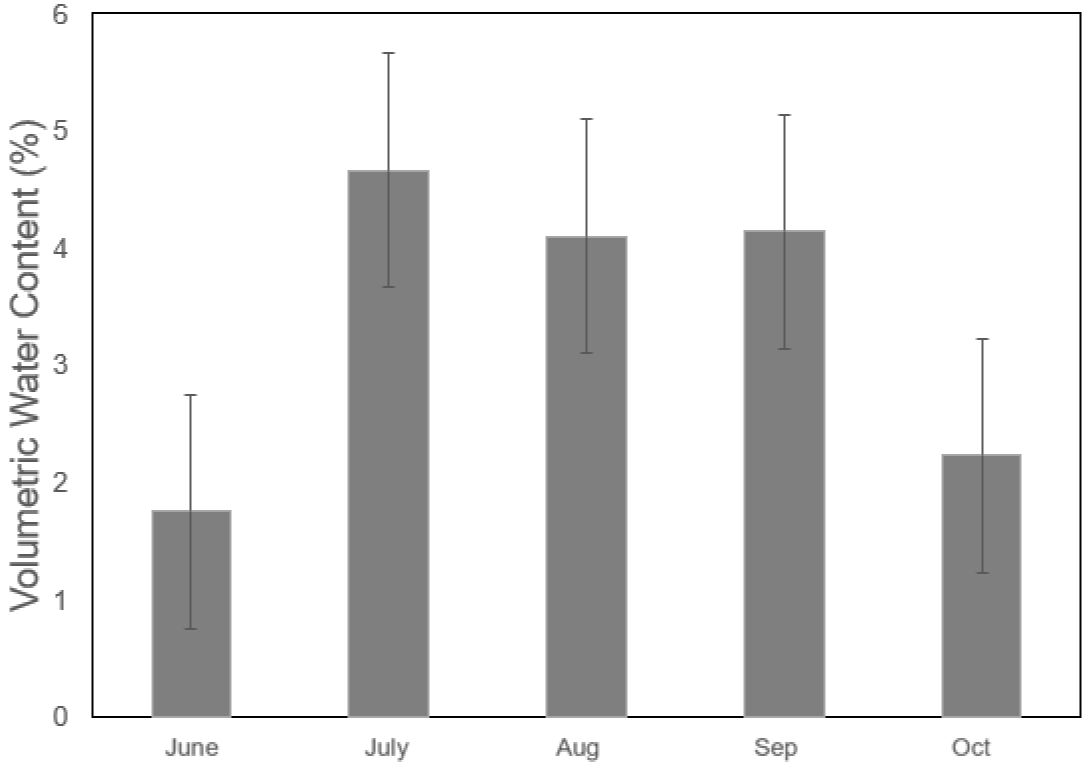

Figure 3.4. Soil volumetric water content (7.6 cm depth) at which wilt was observed in the visual-wilt based plots. Data are pooled across the 2019 and 2020 seasons. Error bars denote Fisher's LSD at $P \leq 0.05$.

Irrigation Scheduling Effects on Root Zone Salinity

Soil salinity remained low (< 0.5 dS m^{-1}) within the sand-cap but was considerably elevated within the upper subsoil throughout the study. Based on analysis of sand-cap (7.6 cm depth) electrical conductivity values, ANOVA showed no differences due to year, month, or irrigation scheduling approach (Table 3.1). There were, however, significant differences observed within the upper subsoil (20 cm depth) due to year, month, and irrigation scheduling approach (Table 3.1). In 2019, the visual-wilt-based treatment maintained lower EC (1.3 dS m^{-1}) within the upper subsoil depth as compared to the FRET-based treatment (1.9 dS m^{-1}). In 2020, significantly higher subsoil EC was observed in August (2.43 dS m^{-1}) compared to June (1.9 dS m^{-1}).

Impacts on Root Development

Roots were observed to be fully extended through the 17.8 cm sand-cap and into sub-soil of all treatments when root sampling was initiated in November 2019. The ANOVA showed no detectable differences of irrigation scheduling approach on root dry weights within the sand or sub-soil portion of the rootzone in 2019 (Table 3.1). There was a year main effect for root dry weight within the sand-cap. As such, 80% greater root dry weights were observed within the sand-cap at the end of 2020 compared to 2019 (Figure 3.5). There were no observed rooting differences either due to irrigation treatment or year within the subsoil.

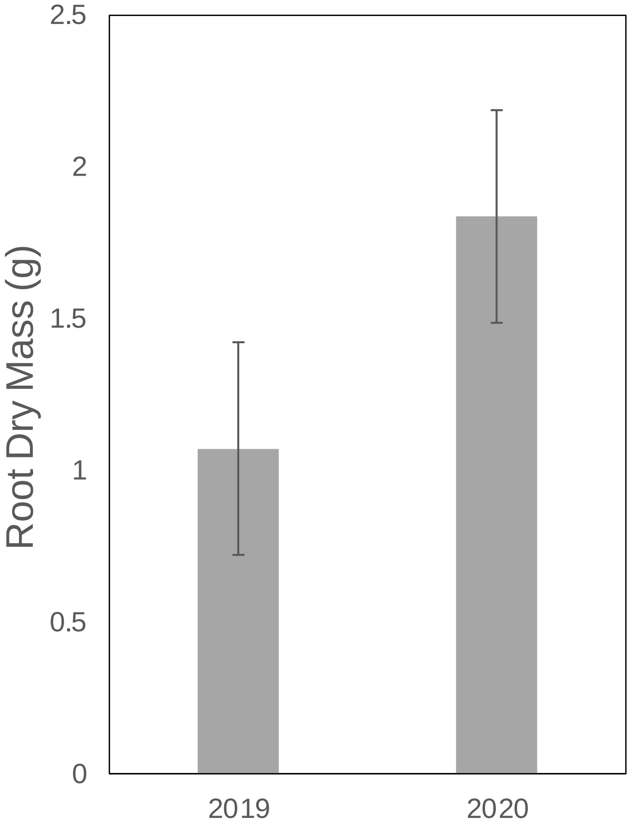

Figure 3.5. Main effect of year on root dry mass within the sand-cap layer. Error bars denote Fisher's LSD at $P \leq 0.05$.

Discussion

Irrigation Scheduling Approach Effects on Turf Visual Quality and Green Cover

Our results, which demonstrated that bermudagrass maintained acceptable quality and high levels of green cover while receiving irrigation at the K_c of 0.6 x ET_o, are consistent with those of Hejl et al. (2016), who showed Tifway bermudagrass grown atop native fine sandy loam could maintained acceptable visual quality and > 80% green cover while being irrigated at the K_c level of 0.6 x ET_o in Texas. While there has been limited published research on irrigation requirements of sand-capped systems, one study evaluating bermudagrass response to 1x vs. 2x weekly irrigation at 0.6 K_c x historical ET_o, showed decline in mid-summer green cover (65%) occurred with deeper (20 cm) sand-cap placements (Dyer et al., 2020). In our study, a similar sand and slightly shallower (17.8 cm) capping depth was used. It is important to note that the authors reported hydrophobicity was observed primarily in the deeper sand-caps (20 cm) as compared to the shallower (5 and 10 cm), which contributed to loss of green cover in their study. In the current study, hydrophobic conditions were never evident, likely due to monthly wetting agent applications to plots. When comparing the effects of irrigation treatments on maintenance of visual quality in our study, all treatments supported acceptable quality, with no differences between weather-based and SMS-based approaches. These observations are consistent with those of Serena et al. (2020), who reported adequate bermudagrass summer turf performance was achieved through use of ET-based, calendar-based, and SMS-based scheduling approaches in New Mexico.

Evaluation of FRET-based Irrigation Scheduling

FRET appeared to be a reliable indicator of bermudagrass seasonal water needs as turfgrass quality and percent green cover were maintained at acceptable levels, and total water volumes used were similar when comparing to on-site ET_o based scheduling. Interestingly, FRET slightly over-estimated ET when evaporative demand was low, but under-estimated actual ET when evaporative demand was high. We are unaware of any previous studies indicating this trend. During the study period of June through October of both 2019 and 2020, 88% of the daily FRET values were within +/- 0.13 cm of daily values predicted by on-site ET (data not shown). These data agree with those of Osborne et al. (2013), who reported 80% of daily FRET values were within +/- 0.13 cm of ET_o measurements obtained through a California weather station.

Seasonal Water Use Based on Irrigation Scheduling Approach

Previous research has shown K_c values to fluctuate throughout the year, ranging from ~0.3 in early spring to ~0.8 during summer months under well-watered conditions (Wherley et al., 2015). For the weather-based treatments in this study, the industry-accepted seasonal average K_c value of 0.6 x ET_o was used for scheduling irrigation volumes. It is possible that the observed trend toward lower overall water use in the on-site ET_o and FRET based treatments (relative to visual wilt or SMS-based) without declines in turfgrass quality could be due to bermudagrass' ability to maintain visual quality while receiving less than optimal (or deficit) levels of irrigation (Hejl et al., 2016). Higher water use for the SMS-based treatment, as compared to the onsite ET_o treatment, was most likely driven by the use of a 22% leaching fraction. Also, this leaching fraction did not appear to reduce EC below that of the other irrigation scheduling approaches for the 7.6 cm depth (Table 3.1). As such, it is possible that greater water savings could have been realized with the SMS-based treatment while avoiding increased soil EC, had lower irrigation return amounts been used. Determination of appropriate irrigation return volumes for minimizing salt accumulation while conserving water under SMS-based irrigation is an area of future research that is needed.

The benefits of actively monitoring soil moisture in respect to stress thresholds following rainfall was highlighted in September 2020, as precipitation was received on a near weekly basis (Figure 3.1). As a result, irrigation was completely by-passed in SMS-based treatments for the entire month. This finding is consistent with prior studies showing higher water savings potential during wet-weather conditions when scheduling irrigation based on SMS (Cardenas-Laihacar et al., 2008).

Soil Volumetric Water Content at Wilt Threshold

The higher wilt threshold observed during mid-summer months is likely attributed to higher radiant energy load and evaporative demand in comparison to early and late season months of June and October. During the higher evaporative demand months of July and August, it is probable that higher mid-day evaporative demand contributes to loss of cell turgor and onset of wilt at higher VWC compared to June and October. We are unaware of any previous studies that have reported similar findings in regards to seasonal effects on soil moisture thresholds for wilt. These observations should be validated in future studies, but suggest that soil moisture thresholds may need to be modified throughout the year, both for water conservation as well as for promoting better plant root development.

Root Development

The ability of hybrid bermudagrass to maintain acceptable visual quality under all treatments (including visual wilt-based) in this study highlights the strong genetic rooting potential of this species as well as the water storage potential of the subsoil within these systems. Even as the sand-cap dried down to below 5% VWC, adequate moisture was always present within the subsoil, where VWC rarely dropped below 30% (data not shown). Root collections conducted at the end of each season indicated roots were fully extended into the subsoil, demonstrating the turfgrass was able to access moisture at these depths.

Irrigation scheduling caused no detectable difference in root development, which is consistent with Serena et al. (2020), who noted that rooting morphology was not impacted by irrigation scheduling approaches similar to those evaluated in this study. However, their work was conducted in a non-sand-capped system and it is difficult to determine if differences would have occurred had shallower capping depths were evaluated, given that Dyer et al. (2020) reported an inverse relationship between capping depth and extent of subsoil root development.

Conclusions

The trend of sand-capping native soil turfgrass systems is increasing, especially in situations where poor water quality is used. In evaluating approaches to irrigation scheduling within sand-capped systems, our results from this 2-year field study demonstrated that season-long turfgrass quality could be maintained in sand-capped systems utilizing on-site ET_o (K_c = 0.6), FRET (K_c = 0.6), SMS, and visual-wilt-based approaches. The use of FRET appears to offer a reliable prediction of bermudagrass water needs during the growing season. The results of this study also demonstrated that the volumetric water content at which wilt occurs changes throughout the season, indicating that different wilt thresholds may need to be used when utilizing SMS-based irrigation scheduling. The inclusion of a leaching fraction lead to increased water use with the SMS-based approach compared to on-site ET_o without significantly decreasing EC. As such, increased water savings could have been realized in the SMS-based treatments if irrigation return amounts were decreased while simultaneously managing soil EC. Collectively, the findings contribute to our understanding of irrigation scheduling strategies for sand-capped turf systems and should aid turf managers in maintaining high quality turf while meeting water conservation goals.

CHAPTER IV

FACTORS LEADING TO SPATIOTEMORAL VARIABILITY OF SOIL MOISTURE AND TURFGRASS QUALITY WITHIN SAND-CAPPED GOLF COURSE FAIRWAYS

Overview

Precision irrigation utilizing soil moisture data and valve-in head sprinkler systems may be a viable solution for sustainable water management on complex turfgrass areas. There is currently no research investigating the factors that influence soil moisture and turfgrass quality variability within sand-capped golf course fairways to aid in precision irrigation-related management decisions. Therefore, the objective of this study was to measure several turfgrass and soil characteristics from two sand-capped fairways during a dry down from rainfall and irrigation to determine their relationship and contribution to soil moisture and turfgrass quality variability. Considerable spatiotemporal variability was observed within the two fairways during the dry down periods from rainfall and irrigation. Factors that were found to have a significant influence on soil moisture and turfgrass quality were sand capping depth, elevation, and thatch depth, but these relationships were not consistent between rainfall versus irrigation events, days after dry down, or even the specific fairways. Also, the direction of many of the relationships were opposite from what was expected. These findings highlight the complexity of soil moisture and turfgrass quality variability on sand-capped golf course fairways. To incorporate soil moisture sensor technologies into large-scale precision irrigation practices, mapping soil moisture with an understanding of contributing factors is a necessary preliminary step. Although there are several current practical limitations, the information presented in this study provides a strong foundation for future research.

Introduction

Turfgrass quality can diminish over time when grown atop fine-textured soils irrigated with poor quality water (Marcum, 2006). In an effort to promote improved quality and playability of golf course fairways in these situations, the process of sand-capping (i.e. the addition of a sand layer above existing native soil) is becoming common during renovation and construction (White, 2013). Sand-capping improves water infiltration and provides easier management of salts and sodium in the root zone; however, improper sand-capping procedures at construction can lead to challenges in maintaining turfgrass performance (Dyer et al., 2020). Given this increasing trend and that moisture dynamics are influenced by sand-cap characteristics, research towards improving water management in these systems is needed.

The emerging discipline of precision turfgrass management encourages efficient management input applications by using a site-specific, targeted approach, while still maintaining turfgrass quality and playability (Carrow et al., 2010). Precision irrigation is a subdiscipline that could offer a viable solution for sustainable water management of large and complex turfgrass areas like golf course fairways. Technological advancements in handheld and stationary in-ground soil moisture sensors (SMS) could play a key role in precision irrigation, due to their ability to provide rapid, objective soil moisture data. These data could then be used in conjunction with valve-in head sprinkler systems to develop site-specific irrigation programs within and between fairways at a single golf course. Intense data collection across fairways with handheld devices is not practical in day-to-day maintenance, so in-ground SMS may be most useful because soil moisture data is collected automatically and stored in digital form for easy access (Moeller, 2012). However, proper placement location of sensors could be critical if soil moisture variability is extreme.

Global Positioning System (GPS)-equipped SMS for use on golf courses are commercially available and becoming widely used. They are primarily handheld and used for monitoring soil moisture status of putting greens, so their GPS and mapping features are rarely utilized, especially on fairways (Straw et al., 2019). Previous studies have demonstrated that extreme soil moisture variability can exist within and between native soil fairways (Krum et al., 2010; Straw et al., 2019), indicating an opportunity for precision irrigation. However, at this time, information of this type is lacking for sand-capped fairways. The addition of a sand layer atop native soil would seemingly reduce soil texture variability and improve soil moisture uniformity for simpler in-ground SMS placement decisions. Conversely, it could also introduce other influences on soil moisture variability. Therefore, research assessing factors contributing to the spatiotemporal variability of soil moisture within these systems is warranted to progress the concept of precision irrigation on sand-capped fairways. The purpose of this study was to measure and map several turfgrass and soil characteristics on two sand-capped golf course fairways. The relationship and contributions of these factors to soil moisture and turfgrass quality variability were subsequently investigated.

Materials and Methods

Fairway Descriptions

Research was conducted at The Golf Club at Texas A&M in College Station, TX. The golf course opened in 1951 and was renovated in 2013 due to degradation of fairway soils from use of poor quality irrigation water. In the renovation, fairways were capped with sand to a target depth of 13 cm and then sprigged with ‘Riley’s Super Sport’ (Celebration®) bermudagrass (*Cynodon dactylon* (L.) Pers.). A locally sourced, medium-coarse textured “concrete” sand was used in constructing the sand-caps. Testing showed the sand had 79% by mass of particles <2 mm, 42% of particles <0.5 mm, a bulk density of 1.85 g cm^{-3}, a total volumetric porosity of 30%, and a saturated hydraulic conductivity of 34 cm h^{-1}. Cores of the sand that were 7.5 cm tall retained 28, 26, 24,16, and 12% volumetric water content when their tops were at 0, -10, -20, -30, and -40 cm matric water potential, respectively. The native soil profile underlying sand-capped layer of the sampled fairways was reworked on original construction and subsequently eroded over the 60 years before renovation. The profile consists of fine sandy loam of variable depth overtop very slowly permeable clay (Boonville and Zack Series). Fairways 4 and 16 were selected for the study based on observed differences in performance by the golf course superintendent during periods of low rainfall and high temperatures. Fairway 4 was noted as having ‘consistent performance,’ while fairway 16 was considered to have ‘inconsistent performance.’

Data Collection

A Geo 7X GPS receiver (Trimble; Sunnyvale, Ca) with TerraSync mapping software (version 5.86) was utilized to georeference fairway boundaries. GPS Pathfinder Office (version 5.85) was then used to convert the boundary layers to a shapefile. A 6.1 m^2 sampling grid was generated for each fairway in ArcMap 10.4 with the “Create Fishnet” tool and clipped with the boundary layers. This procedure generated 124 and 128 sampling locations within fairway 4 and 16, respectively, that were used for all future data collections.

Sand-capping depth (i.e. depth to subgrade interface; cm) was measured 25 September 2018 and thatch depth (cm) was measured 15 December 2020, each with a ruler by extracting a soil core with a 5 cm diameter probe. Elevation (mean sea level; m) point data were collected 6 April 2021 using a Tornado antenna on a 2 m surveying pole that was connected to the GPS receiver (SECO; Redding, Ca). Soil volumetric water content (VWC; %) and normalized difference vegetation index (NDVI, a spectral reflectance measure of turfgrass quality) were collected during a dry down 3 and 5 days after rainfall on 4 and 6 August 2020, respectively. A cumulative total of 2.5 cm of rainfall was received 31 July to 1 August 2020 prior to the first data collection, and no additional rainfall or irrigation was applied before the second data collection. Volumetric water content and NDVI were also collected during a dry down 1 and 5 days after irrigation on 8 and 13 October 2020, respectively. Irrigation was applied in the amount of 0.8 cm on two consecutive days prior to the first data collection, and no additional rainfall or irrigation occurred before the second data collection. Soil volumetric water content data were collected with a FieldScout TDR 350 soil moisture meter (Spectrum Technologies, Aurora, IL) within the upper 0 to 7.6 cm depth of soil and NDVI data were collected with a RapidSCAN CS-45 handheld crop sensor (Holland Scientific, Lincoln, NE).

Data Analysis

Descriptive statistics were calculated in ArcMap and used to identify central tendencies, simple measures of variability, and dispersion of all measured variables. Correlation coefficients were calculated using the ‘modified.ttest’ function in the ‘SpatialPack’ package of RStudio (RStudio Team (2020). RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/.) to assess the strength and direction of relationships between variables. Interpolation of all point data was done in ArcMap using ordinary kriging to create spatial maps of the variables. Elevation data were used to create digital elevation models and for developing slope and aspect maps. Degree slope data were extracted from slope maps to sampling points using the “Sample” tool in ArcMap, and then used in correlation coefficient calculations. All map legends represent the range (i.e. lowest and highest values) of a respective variable.

Results and Discussion

Fairway 4

As noted previously, Fairway 4 was said to have consistent performance. Descriptive statistics of VWC, NDVI, capping depth, thatch depth, elevation, and slope for Fairway 4 are presented in Table 4.1. Mean VWC decreased 5.9% from day 3 to 5 following the rain event, while mean NDVI increased 0.01. Mean VWC decreased 9.3% from day 1 to day 5 following the irrigation events, while mean NDVI decreased 0.03. The average capping depth was 15 cm, which was well above the targeted 13 cm depth during renovation. Thatch depth for Fairway 4 averaged 2.7 cm, more than double the 1.3 cm threshold at which agronomic problems often occur (Emmons, 1995).

Volumetric water content had a significant positive relationship with capping depth on both days following rainfall [r=0.38 (P<0.001) and r=0.51 (P<0.001) 3 and 5 days after, respectively] (Table 4.2). It also had a significant positive relationship with VWC following irrigation [r=0.26 (P<0.05) and r=0.33 (P<0.05) 1 and 5 days after, respectively] (Table 4.3). As reported in Dyer et al. 2020, increased sand-capping depth resulted in decreased VWC, so the direction of the significant correlations between capping depth and VWC reported here were counterintuitive. Significant negative relationships were observed between NDVI and capping depth on both days following rainfall [r=-0.30 (P<0.05) and r=-0.27 (P<0.05) 3 and 5 days after, respectively] (Table 4.2). Surprisingly, elevation had a significant positive relationship with VWC [r=0.41(P<0.05)] 3 days after rainfall (Table 4.2), as higher VWC at lower elevations would be expected.

The VWC coefficient of variation (CV) was noticeably influenced during the dry downs, since over time it increased 10% and 19% after rainfall and irrigation, respectively (Table 4.1).

The CV for NDVI was influenced during the dry downs to a lesser degree (-0.6% and +3.0 after rainfall and irrigation, respectively). The significant relationships between capping depth and VWC, as well as capping depth-NDVI, led to comparable spatial distributions (e.g. a trend of increased VWC and decreased NDVI in areas of increased capping depth) (Figure 4.1). These findings suggest that capping depth plays a major role in the spatiotemporal variability of soil moisture and turfgrass quality of this fairway. The significant, positive relationship between elevation and VWC also led to comparable spatial distributions between those variables, but only 3 days after rainfall (Figure 4.1).

Table 4.1. Descriptive statistics of volumetric water content (VWC) after rainfall and irrigation, normalized difference vegetation index (NDVI) after rainfall and irrigation, capping depth, thatch depth, elevation, and slope on Fairway 4.

	Days after	Min	Max	Range	Mean	SD	CV (%)
				——%——			
VWC (rainfall)	3	14.7	57.8	43.1	37.3	9.2	24.5
VWC (rainfall)	5	7.8	51.6	43.8	31.4	10.9	34.8
				——%——			
VWC (irrigation)	1	15.1	55.8	40.7	39.6	9.9	25.2
VWC (Irrigation)	5	4.5	52.8	48.3	30.3	13.3	43.9
NDVI (rainfall)	3	0.44	0.76	0.32	0.68	0.05	7.8
NDVI (rainfall)	5	0.46	0.77	0.31	0.69	0.05	7.2
NDVI (irrigation)	1	0.53	0.74	0.22	0.66	0.05	7.9
NDVI (irrigation)	5	0.31	0.76	0.45	0.63	0.06	10.9
				——cm——			
Capping depth	-	1.3	24.7	23.5	15.1	4.6	30.5
				——cm——			
Thatch depth	-	0.5	5.0	4.5	2.7	1.0	38.9
				——m——			
Elevation	-	95.8	98.1	2.3	97.1	0.4	0.4
				——degree——			
Slope	-	0.1	4.2	4.1	2.0	0.7	35.5

Table 4.2. Correlation coefficient matrix showing the relationship between volumetric water content (VWC), normalized difference vegetation index (NDVI), capping depth, thatch depth, elevation, and slope 3 days and 5 days (in parenthesis) after rainfall on Fairway 4.

	VWC	NDVI	Capping depth	Thatch depth	Elevation	Slope
VWC	1	-0.11 (-0.24)	0.38*** (0.51***)	-0.22 (-0.33)	0.41* (0.35)	-0.08 (0.05)
NDVI		1	-0.30* (-0.27*)	0.24 (0.15)	-0.11 (-0.06)	-0.06 (-0.09)
Capping depth			1	-0.12	0.18	0.14
Thatch depth				1	-0.29	0.04
Elevation					1	-0.15
Slope						1

ns, **, *** not significant, significant at $P \leq 0.05$, 0.01, 0.001, respectively.

Table 4.3. Correlation coefficient matrix showing the relationship between volumetric water content (VWC), normalized difference vegetation index (NDVI), capping depth, thatch depth, elevation, and slope 1 days and 5 days (in parenthesis) after irrigation on Fairway 4.

	VWC	NDVI	Capping depth	Thatch depth	Elevation	Slope
VWC	1	0.06 (-0.04)	0.26* (0.33*)	0.14 (0.02)	0.14 (0.21)	0.19 (0.10)
NDVI		1	-0.23 (-0.19)	0.45 (0.31)	-0.23 (-0.17)	0.00 (-0.05)
Capping depth			1	-0.12	0.18	0.14
Thatch depth				1	-0.29	0.04
Elevation					1	-0.15
Slope						1

ns, **, *** not significant, significant at $P \leq 0.05$, 0.01, 0.001, respectively.

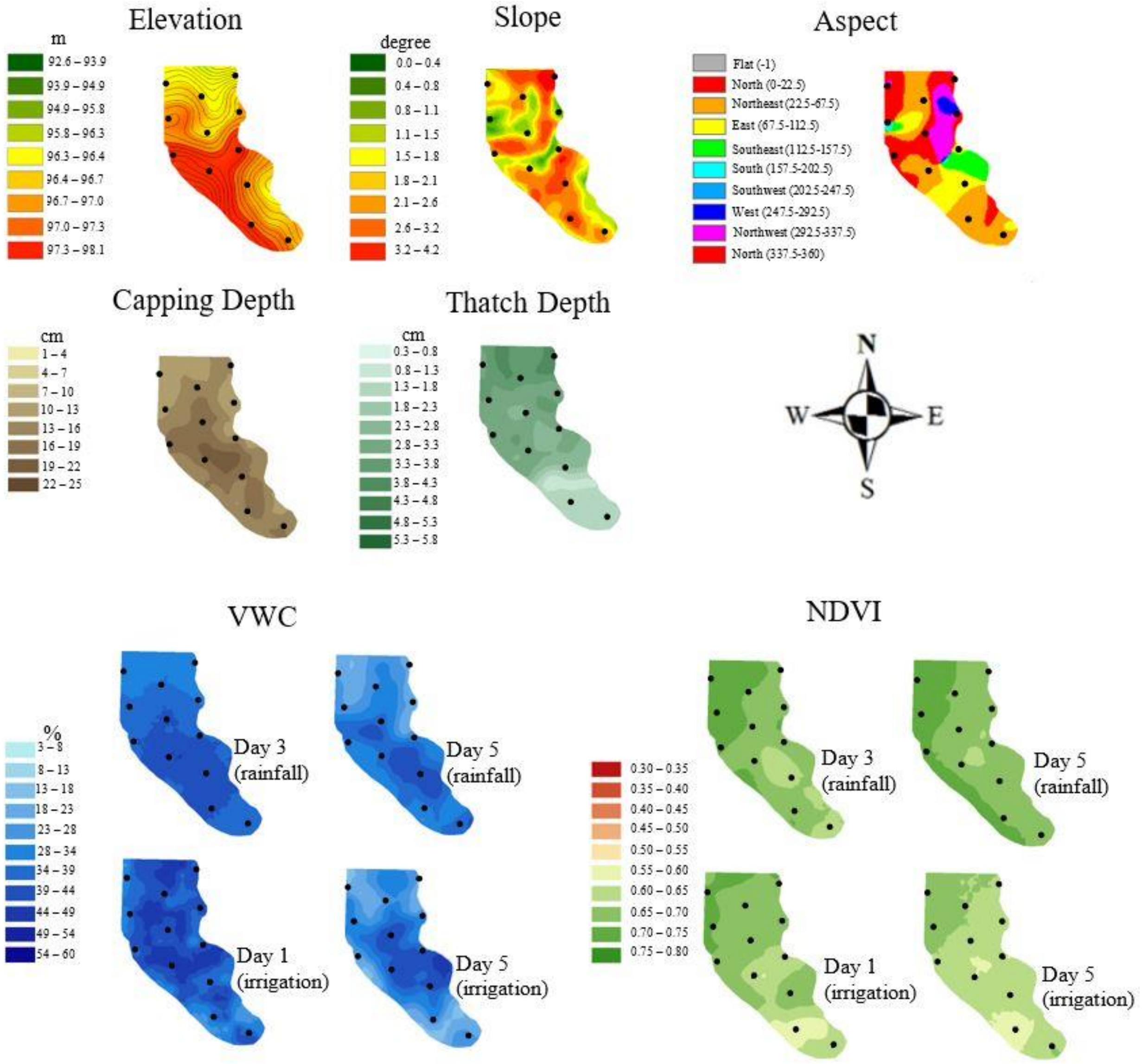

Figure 4.1. Spatial maps of elevation (from mean sea level), slope, aspect, capping depth, thatch depth, volumetric water content (VWC) after rainfall and irrigation, and normalized difference vegetation index (NDVI) after rainfall and irrigation on Fairway 4. Black dots represent the locations of sprinkler irrigation heads.

Fairway 16

As noted previously, Fairway 16 was said to have inconsistent performance. Descriptive statistics of VWC, NDVI, capping depth, thatch depth, elevation, and slope are presented in Table 4.4. Mean VWC decreased 10.3% from day 3 to day 5 after rainfall, while mean NDVI decreased 0.05. Mean VWC decreased 13.3% from day 1 to day 5 after the irrigation events, while mean NDVI decreased by 0.03. The average capping depth was 9.7 cm, which was well below the targeted 12.7 cm depth during renovation. Thatch depth averaged 3.1 cm, more than double the 1.3 cm threshold at which problems have been commonly noted to occur.

No significant relationships were observed between measured variables following the rainfall event (Table 4.5). Thatch depth had a significant, negative relationship with NDVI [r=-0.17 ($P<0.01$)] 1 day after irrigation (Table 4.6). Furthermore, VWC had a significant, positive relationship with NDVI [r=0.33 ($P<0.05$)] and capping depth [r=0.20 ($P<0.05$)], as well as a significant, negative relationship with thatch depth [r=-0.20 ($P<0.01$)], 5 days after irrigation (Table 4.6).

The VWC CV was noticeably influenced by the dry downs, since over time it increased 18% and 22% after rainfall and irrigation, respectively (Table 4.4). The CV for NDVI was influenced during the dry downs to a lesser degree (+0.6% and +2.2 after rainfall and irrigation, respectively). The lack of significant relationships between variables on this fairway led to no strong visual similarities of spatial distributions in the maps (Figure 4.2). Some comparisons can be made within maps of those variables with significant relationships; however, large-scale similarities are not evident, possibly due to the relationships being overall weak. Thatch accumulation does appear to have an increased role in influencing spatial variability of VWC and NDVI in Fairway 16, compared to Fairway 4, whereas capping depth was not as influential.

Table 4.4. Descriptive statistics of volumetric water content (VWC) after rainfall and irrigation, normalized difference vegetation index (NDVI) after rainfall and irrigation, capping depth, thatch depth, elevation and slope on Fairway 16.

	Days after	**Min**	**Max**	**Range**	**Mean**	**SD**	**CV (%)**
				%			
VWC (rainfall)	3	17.0	49.1	32.1	29.3	6.6	22.4
VWC (rainfall)	5	7.5	46.6	39.1	19.0	7.7	40.2
				%			
VWC (irrigation)	1	8.3	51.4	43.1	32.7	9.3	28.4
VWC (Irrigation)	5	3.6	51.6	48.0	19.4	9.8	50.4
NDVI (rainfall)	3	0.56	0.79	0.24	0.69	0.04	6.8
NDVI (rainfall)	5	0.53	0.74	0.21	0.64	0.04	7.4
NDVI (irrigation)	1	0.46	0.74	0.27	0.63	0.04	7.8
NDVI (irrigation)	5	0.35	0.75	0.40	0.60	0.06	10.0
				cm			
Capping depth	-	0.00	21.6	21.6	9.7	4.1	41.6
				cm			
Thatch depth	-	0.5	5.0	4.5	3.1	0.8	25.5
				m			
Elevation	-	92.5	97.5	5.0	94.8	1.4	1.48
				degree			
Slope	-	0.6	4.0	3.4	2.0	0.7	36.3

Table 4.5. Correlation coefficient matrix showing the relationship between volumetric water content (VWC), normalized difference vegetation index (NDVI), capping depth, thatch depth, elevation, and slope 3 days and 5 days (in parenthesis) after rainfall on Fairway 16.

	VWC	**NDVI**	**Capping depth**	**Thatch depth**	**Elevation**	**Slope**
VWC	1	0.07 (0.06)	0.13 (0.01)	-0.11 (0.04)	0.04 (0.04)	-0.06 (-0.20)
NDVI		1	-0.07 (-0.05)	-0.02 (0.07)	0.32 (0.25)	0.12 (0.07)
Capping depth			1	0.00	0.13	0.00
Thatch depth				1	-0.03	0.03
Elevation					1	0.42
Slope						1

ns, **, *** not significant, significant at *P* ≤ 0.05, 0.01, 0.001, respectively.

Table 4.6. Correlation coefficient matrix showing the relationship between volumetric water content (VWC), normalized difference vegetation index (NDVI), capping depth, thatch depth, elevation, and slope 1 days and 5 days (in parenthesis) after irrigation on Fairway 16.

	VWC	**NDVI**	**Capping depth**	**Thatch depth**	**Elevation**	**Slope**
VWC	1	0.19 (0.33*)	0.09 (0.20*)	-0.09 (-0.20**)	0.13 (0.15)	0.11 (0.10)
NDVI		1	0.06 (0.06)	-0.17** (-0.00)	0.47 (0.29)	0.09 (0.04)
Capping depth			1	0.00	0.13	0.00
Thatch depth				1	-0.03	0.03
Elevation					1	0.42
Slope						1

ns, **, *** not significant, significant at *P* ≤ 0.05, 0.01, 0.001, respectively.

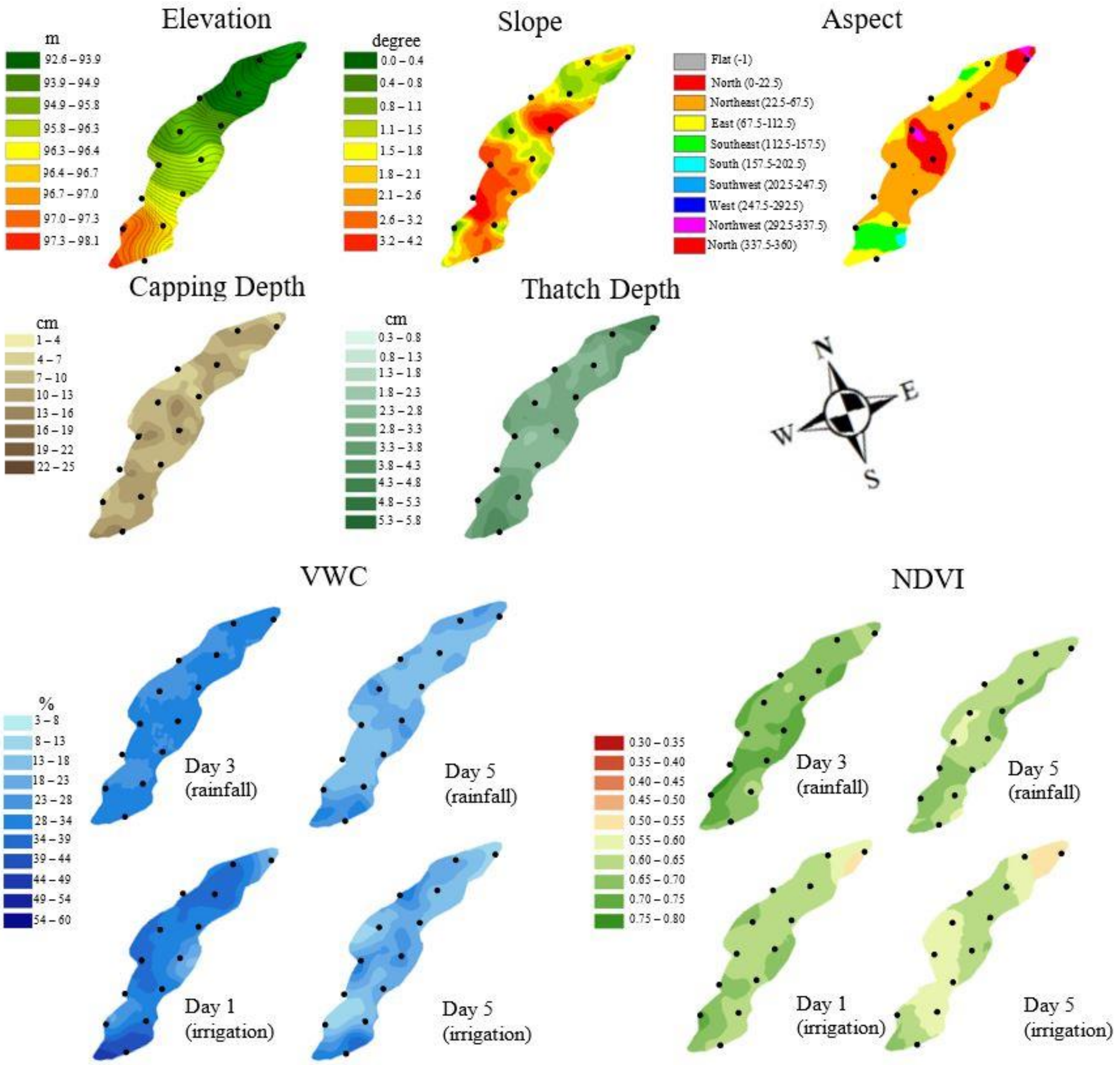

Figure 4.2. Spatial maps of elevation (from mean sea level), slope, aspect, capping depth, thatch depth, volumetric water content (VWC) after rainfall and irrigation, and normalized difference vegetation index (NDVI) after rainfall and irrigation on Fairway 16. Black dots represent the locations of sprinkler irrigation heads.

Conclusions

This study demonstrated that considerable spatiotemporal variability of soil moisture and turfgrass quality can be present within and between just two sand-capped fairways on the same golf course. When extrapolated to an entire course, the variability is likely to be even more extreme. The complexity of these systems is further highlighted by the fact that contributing factors to soil moisture and turfgrass quality did not directly translate between rainfall versus irrigation events, days after dry down, or even fairways. Complexity is also highlighted by the direction of many of the significant relationships between factors. Future research related to this topic should consider additional factors, such as irrigation distribution uniformity, surface hydrophobicity, soil compaction, organic matter accumulation, soil texture, or subsoil influences, as these could also be contributing to variability. Additionally, this was the first study to consider topographical factors on golf course fairways (elevation, slope, and aspect), and although they had a minimal role here, they could be a major factor at courses more substantial elevations and slopes.

For SMS technologies to be a viable part of precision irrigation on sand-capped fairways, mapping soil moisture with an understanding of the contributing factors is a necessary preliminary step. This information could then be used to identify proper placement of in-ground SMS for creating soil moisture or turfgrass quality thresholds to trigger a site-specific irrigation event. A practical and rapid method of mapping soil moisture during a variety of scenarios is currently a major limitation to adoption of a precision irrigation approach in the turfgrass industry.

CHAPTER V

CONCLUSION

As turf managers aim to maintain quality of their turfgrass systems, the efficient use of water for irrigation is essential due to population growth and climate uncertainties. Due to this there was an apparent need to expand on current literature by providing turf managers with improved practices in regards to increased use of landscape watering restrictions and the increased trend of capping fairway soils with sand. We accomplished this through a series of field studies in College Station, Texas by 1) evaluating the response of commonly used warm-season turfgrass species to limited irrigation frequencies, 2) comparing data-driven irrigation scheduling techniques in sand-capped systems, and 3) investigating factors contributing to spatiotemporal variability of soil moisture and turfgrass quality within sand-capped golf course fairways.

In regards to landscape watering restrictions, our results indicated that the average warm-season turfgrass species can maintain acceptable visual quality while being irrigated at frequencies limited to once per week in a central Texas climate. However, species and variety selection is important for more restrictive policies as ‘Celebration’ bermudagrass maintained acceptable visual quality in the presence of more limited frequencies, with ‘Palisades’ zoysiagrass performing similar.

The research demonstrated several data-driven irrigation scheduling approaches were viable for maintenance of bermudagrass grown on a sand-capped rootzone. Our results also indicated that access to reference evapotranspiration (ET_o) data representative of local conditions could be expanded due to forecasted reference evapotranspiration (FRET). Also, the VWC at which wilt occurred appeared to increase during peak summer compared to early and late season months, indicating that different wilt thresholds need to be used when utilizing SMS-based irrigation scheduling. This study provided needed information to guide improved irrigation scheduling decisions and guide further research regarding in-ground SMS irrigation scheduling in sand-capped systems.

Finally, we found considerable spatiotemporal variability for soil moisture and turfgrass quality present within just two sand-capped fairway systems. Also, results highlighted the complexity of these systems as the factors found to have contributed to variability did not translate between sampling events or even fairways. While other factors could be contributing to variability, this study provided a strong foundation for further research regarding variability within sand-capped fairway systems so that soil moisture sensor technology could be better implemented.

The findings from this research provide timely and practical information that turf managers can employ to help meet water conservation goals while also maintaining turfgrass quality. It also guides further research regarding improved irrigation management within sand-capped systems.

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