ABSTRACT

PINNIX, GARLAND DREWRY. Defining Water Use and Assessing Viability of Evapotranspiration Technology for North Carolina Turfgrasses. (Under the direction of Dr. Grady L. Miller).

The accurate measurement of turfgrass evapotranspiration (ET) is required to develop irrigation recommendations for turfgrass managers and others who manage turfgrasses in the landscape. Analyses of historical meteorological data and field research was conducted to update irrigation recommendations for standard and recently introduced turfgrasses managed in North Carolina. Furthermore, the surface renewal technique was deployed to assess the precision of continuous turfgrass ET measurements compared to standard methodology in the southeastern United States.

Field research was designed to derive crop coefficients (K_c) for tall fescue (*Festuca arundinacea* Schreb.) and hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy]; two popular turfgrass species managed in North Carolina. Direct measurements of actual turfgrass evapotranspiration (ET_a) were made through the weighing of lysimeters from May through October. Turfgrass crop coefficients were computed by the quotient of ET_a and reference turfgrass evapotranspiration (ET_o). Tall fescue and hybrid bermudagrass K_c ranged from 0.69 to 0.85 and 0.44 to 0.59, respectively. Turfgrass crop coefficients developed from this research can assist turfgrass managers locally in North Carolina and throughout the transition zone in scheduling irrigation based upon historical or current turfgrass ET_o measurements.

Analyses of historical meteorological data at eleven locations across North Carolina revealed varying turfgrass irrigation recommendations are needed throughout the state. The difference in crop evapotranspiration and effective rainfall considering variation in soil type, rooting depth, and type of grass were used to estimate net irrigation requirements for each

location. Mean effective rainfall from May - October was consistently ~50% of total rainfall at all locations with the exception of Wilmington. Net irrigation requirements varied from 124 mm in Boone to 305 mm in Fayetteville. These results were used to update current irrigation recommendations across North Carolina.

In addition to accurate irrigation regimes, an increasingly popular water conservation practice is the establishment of turfgrasses with lower water use rates. Field research was conducted to compare water use characteristics of 'TifTuf' a recently released bermudagrass cultivar with reported drought tolerance with a commonly planted tall fescue/bluegrass mix in North Carolina. Cumulative bermudagrass ET_a was 44% less than tall fescue when established in the spring. When established during summer, cumulative bermudagrass ET_a was similar to tall fescue (3% less). Both grasses provided acceptable turf quality (TQ $\geq$ 6), when planted during the spring. However, tall fescue TQ was rated unacceptable following summer establishment. TifTuf bermudagrass provided acceptable quality in the landscape with significantly lower water requirements compared to Triple Threat tall fescue.

Continuous, long-term ET measurement is desirable to best manage irrigation over time. Actual evapotranspiration measured from a surface renewal (SR) system was compared to turfgrass ET_a measured by eddy covariance (EC) and micro-Bowen ratio (MBR) techniques over 'El Toro' zoysiagrass (*Zoysia japonica* Steud.). Surface renewal estimates of zoysiagrass actual evapotranspiration (ET_a) were well correlated with EC ($R^2 = 0.99$) and MBR ($R^2 = 0.73$) ET_a during both years of the study. As a result, differences in cumulative SR ET_a compared to EC (< 2 mm) and MBR (< 8 mm) methods were minimal during two-month campaigns each year. Overall, SR appeared to be an acceptable method to estimate zoysiagrass ET_a in the southeastern

United States, therefore providing an economical alternative to other flux measurement techniques.

Results from this research provide updated information pertaining to irrigation management in North Carolina that are also applicale to other areas throughout the transition zone. Turfgrass managers can implement water conservation strategies through responsible applications of irrigation as the result of better understanding the water demands of popular turfgrass species.

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Defining Water Use and Assessing Viability of Evapotranspiration Technology for North Carolina Turfgrasses

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DEDICATION

This work is dedicated to all of those whose influence has directed me to where I am today.

BIOGRAPHY

Garland Drewry Pinnix was raised in Severn, North Carolina, where his family continues to reside today. While part of his family operates a peanut processing facility, his father was head golf professional at a nearby country club during childhood. As a result, Drew developed an interest in both agriculture and golf. Growing up, he participated in many sports in addition to other outdoor activities such as hunting and fishing. Due to his passion for being outdoors, agriculture, and the game of golf, Drew naturally became interested in pursuing a career in turfgrass management. Upon graduation from Northeast Academy in 2007, Drew moved to Raleigh, NC to pursue a B.S. degree in Turfgrass Science from North Carolina State University.

During his undergraduate career, Drew participated in internships at various golf courses across the United States in preparation for a career in the golf course industry. However, after completing an internship between his junior and senior year, Drew realized he preferred an alternative career in the turfgrass industry. After obtaining his B.S. degree in 2011, Drew began a Master of Science degree under the direction of Dr. Grady Miller investigating management of turfgrass colorants and athletic field paint. In 2014, Drew successfully completed his M.S. degree and was granted the opportunity to continue his education working towards a Ph.D. degree researching turfgrass water use. Soon after beginning his doctorate degree, Drew was offered the position of Research Technician within Dr. Grady Miller's research program while continuing his graduate research. This afforded Drew many opportunities and experiences to develop as a researcher.

To date, Drew has authored or co-authored eight peer-reviewed publications, three extension publications, 11 popular trade articles, and 25 scientific abstracts. During his time at NCSU, he has given 18 extension presentations at various industry events in North Carolina. He has also taught three lab sections of turfgrass management courses, in addition to 9 guest lectures in various courses within the Crop and Soil Sciences department. Awards received during his graduate career include the North Carolina Sports Turf Managers Association Scholarship, 2nd place in the Crop Science Society of American Turfgrass Science graduate student oral competition, College of Agriculture and Life Sciences Leadership Learning Institute, Dr. James Watson SAFE Graduate Student Scholarship, and Turfgrass Council of North Carolina Eagle's Award.

Upon completion of his degree, Drew intends to continue an active career in the turfgrass industry.

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To my parents, Paige and Eddie, your unwavering support has propelled me throughout my life. It is impossible to put my gratitude into words and I hope this work makes you proud. To my brother, Harrison, you have continually sacrificed much for my benefit and for that I am grateful. I have many personal friends who deserve acknowledgement. There are too many to list, but you all have played an instrumental role in my life and therefore, this work. Thank you to all.

I have had the privilege of working with many intellectual minds at NC State. At the top of that list is Scott Brinton, who has taught me much through his guidance and tireless work ethic. Raymond McCauley, you have played an instrumental role in this work. You have taught me much and I know you will find success throughout your career. I would also like to thank Matthew Jeffries for invaluable advice throughout my graduate career. You have been a dear friend and I am happy for your continued success. I am thankful to you all and look forward to continued friendship.

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LITERATURE REVIEW

Turfgrasses provide many ecological and environmental benefits to landscapes of all types. Turfgrasses also contribute to social interactions and positive mental health through the maintenance of safe and durable recreational areas (Beard and Green, 1994; Stier et al., 2013). Research has documented sediment loss from a non-vegetated surface to be nearly four times the amount loss from a managed turfgrass site (Gross et al., 1991). The impact of turfgrasses in terms of heat dissipation was documented by Dousset and Gourmelon (2003) who measured a 23% decrease in air temperature within the outskirts of Los Angeles compared to the downtown area due to actively transpiring vegetation. Turfgrasses also contribute to the reduction of atmospheric pollutants, such as carbon dioxide. Su et al. (2007) reported tall fescue (*Festuca arundinacea* Schreb.) and Kentucky bluegrass (*Poa pratensis* L.) used 2,000 g m^{-2} of carbon dioxide over a 14-h photoperiod. However, these results were reduced by 50% when exposed to heat and subsequent drought stress demonstrating the importance of adequate water availability in order for turfgrasses to maintain functionality in the environment. As a result, managing water applied via irrigation is a primary component of turfgrass management to ensure the many benefits of turfgrasses are realized.

Turfgrass Adaptation

Turfgrasses are sub-divided into two categories (cool- or warm-season) based upon their adaptation to climatic conditions. Air temperature, sunlight, rainfall, and other abiotic factors greatly affect the adaptability of turfgrasses across various environments and also impact water use rates. The influence of these factors help define the three primary regions of turfgrass adaptation in the United States: the northern-cool region, the southern-warm region, and the transition zone. The northern-cool and southern-warm regions are also subdivided into arid and humid regions (Emmons, 2000; Fry and Huang, 2004; Turgeon, 2008). The cool-season grasses are best adapted to the northern-cool region while the warm-season grasses are most adapted to the southern-warm region. The area between these two regions is the transition zone, defined as the 300-700 mile north to south area where the use of cool- and warm-season grasses overlap (Dunn and Diesburg, 2004).

As part of the transition zone, turfgrass managers in North Carolina often manage both cool- and warm-season grasses. Environmental conditions vary greatly across North Carolina. Conditions near the coast where air temperatures are warmer and soils are coarse, warm-season grasses predominate. Further west into the mountain region, soils are fine textured and air temperatures are cooler, creating favorable conditions for cool-season grasses. The most recent comprehensive survey conducted in North Carolina indicated that 63% of single-family dwellings maintained a cool-season turfgrass, while 37% maintained warm-season turfgrass (NCDA, 1999). Tall fescue (*Festuca arundinacea* Schreb.) is overwhelmingly the most common lawn grass in North Carolina as it comprises 58% of North Carolina lawns. The remaining five percent of cool-season lawns are occupied by Kentucky bluegrass (*Poa pratensis* L.) and fine fescue (*Festuca rubra* L.). The improved drought and heat tolerance among the cool-season grasses in addition to maintaining year-round green color makes tall fescue an attractive choice for homeowners in the transition zone (Miller et al., 2016). The most popular warm-season turfgrass species among North Carolina homeowners are centipedegrass [(*Eremochloa ophiuroides* (Munro.) Hack.] and bermudagrass (*Cynodon sp.*). Centipedegrass comprises nearly 67% of home lawns across North Carolina where warm-season grasses are managed. This is primarily due to its minimal maintenance requirements. Bermudagrass is a widely used warm-season grass that ranks second among North Carolina warm-season lawn grasses. The superior drought tolerance, ability to establish quickly, withstand wear, and recover quickly from injury encourages the use of bermudagrass. Other warm-season species managed in North Carolina include zoysiagrass (*Zoysia sp.*) and St. Augustinegrass [*Stenotaphrum secundatum* (Waltz.) Kuntz.] which only account for 4 and 2%, respectively, of the managed warm-season home lawns.

Physiological Role of Water in Turfgrass

Water is required for many metabolic processes in the turfgrass plant. However, only 1-3% of water absorbed by turfgrasses is dedicated to these processes (Fry and Huang, 2004). Rather, the majority of water that enters the turfgrass plant is dedicated to transpiration. Water enters the plant via root absorption through the apoplast, cellular pathway, or a combination of the two (Taiz and Zeiger, 2010). The rate at which plant stomata release water vapor into the atmosphere drives water movement from the roots into the above ground tissue through the xylem (Kopp and Jiang, 2013). The negative hydrostatic pressure resulting from water vapor release into the atmosphere pulls water from the xylem into the mesophyll where it evaporates in the leaf air spaces and exits through the stomata. During this process, energy is released, thus cooling the turfgrass.

The rate of turfgrass transpiration is regulated by the internal leaf diffusion resistance, boundary layer resistance, and vapor pressure gradient between the air and leaf (Fry and Huang, 2004). The distribution of mesophyll cells, cuticle thickness, and stomatal regulation all influence the internal leaf diffusion resistance. Turfgrass stomata are of particular interest as they regulate the exchange of water vapor and gases between the leaf and atmosphere. Specifically, 90 – 95% of water loss from the leaf occurs as the result of water vapor exiting through the stomata (Fry and Huang, 2004). The opening and closing of turfgrass stomata are regulated by the flux of potassium ions (Salisbury and Ross, 1992). An influx of potassium ions into guard cells that surround turfgrass stoma cause the stoma to open, thus lowering the osmotic potential and allowing water to move into the cell. Conversely, stoma close when potassium exits guard cells increasing the osmotic potential with less water retained within the leaf. Stomatal characteristics are unique to turfgrass species and cultivars. Therefore, transpiration rates and subsequent water use differ among turfgrasses.

Water vapor diffusion from the leaf into the atmosphere is also affected by the resistance of the boundary layer, or layer of unstirred air above the turfgrass canopy (Taiz and Zeiger, 2010). Rate of transpiration is regulated by the thickness of the boundary layer which largely depends on wind speed. When wind is negligible, the boundary layer resistance is intensified, reducing the rate of water vapor diffusion. However, as wind speed increases, the air above the turfgrass canopy is disturbed, reducing the resistance of the boundary layer and increasing transpiration. Characteristics of the turfgrass canopy can also influence the boundary layer resistance. Such characteristics include mowing height and turfgrass density, in addition to certain morphological traits (trichomes) (Taiz and Zeiger, 2010).

The vapor pressure gradient between the leaf and the atmosphere is perhaps the most important factor in determining turfgrass transpiration. This is mostly affected by the relative humidity of the atmosphere since the relative humidity inside the leaf remains at 100% majority of the time (Fry and Huang, 2004). Therefore, the vapor pressure gradient is increased on days when the atmospheric relative humidity is low, thus increasing turfgrass transpiration. During times of high atmospheric relative humidity, turfgrass transpiration is low as the vapor pressure gradient is reduced.

Physiological processes such as photosynthesis, respiration, hormone synthesis, and nutrient uptake are all affected when water is limiting (Huang and Gao, 1999). Photosynthesis is of special concern due to its importance to overall plant health. As water becomes limited, the water potential of cells will lower which is consequential to the machinery involved in turfgrass photosynthesis (Kopp and Jiang, 2013). The supply of carbon dioxide, a primary ingredient of plant photosynthesis, is reduced during times when water is limiting as the result of stomatal closure, which is a defense mechanism by the plant to conserve water. To prevent detrimental effects of drought on turfgrass growth and functionality, supplemental water must be supplied through irrigation.

Turfgrass Water Use

Turfgrass water use is termed evapotranspiration (ET) as it considers water loss through plant transpiration and evaporation from the soil surface. Evaporation is typically considered to be negligible as managed turfgrass sites consists of completely vegetated surfaces (Beard, 1973; Huang, 2006). However, recent research has observed considerable water loss due to evaporative demands during darkness (Rosas-Anderson et al., 2018). Measured ET rates under non-limiting soil moisture conditions are routinely used to define water use requirements for turfgrasses. Cool-season turfgrasses typically require increased water demands compared to warm-season turfgrasses (Huang, 2008). Furthermore, water use can vary significantly across and within single turfgrass species (Beard, 1989).

Previous research has found that tall fescue ET rates range from 3.0 – 9.7 mm d^{-1} in arid and greenhouse environments (Kopec et al., 1988; Bowman and Macaulay, 1991). During field studies conducted in Griffin, GA, tall fescue ET rates were much lower ranging from 2.7 – 6.1 mm d^{-1} (Carrow, 1995; Carrow 1996). Aronson et al. (1987) measured water use rates of

Kentucky bluegrass, fine fescue, and perennial ryegrass (*Lolium perenne* L.) during a field study in Rhode Island. In consecutive years from July – September mean ET rates were 3.44, 3.38, and 3.40 mm d^{-1} for Kentucky bluegrass, fine fescue, and perennial ryegrass, respectively. The range in daily turfgrass ET, however, was between 2.6 – 7.6 mm d^{-1}. A study that investigated bentgrass (*Agrostis sp.*) water use in New Jersey indicated average daily ET rates ranged from 6.3 mm d^{-1} in July to 2.1 mm d^{-1} in October (DaCosta and Huang, 2006).

Studies quantifying bermudagrass ET found use rates are generally lower and fluctuate less (Kim and Beard, 1988; Carrow, 1995; Wherley et al., 2015; Amgain et al., 2018). Specifically, bermudagrass ET ranged from 2 – 6 mm d^{-1} in studies conducted in Texas, Georgia, Florida, and Oklahoma. Reduced bermudagrass ET rates are measured during winter months in the southern US as bermudagrasses typically do not reach full dormancy. During summer months when irrigation is more likely, ET rates typically ranged from 4 – 6 mm d^{-1}. Carrow (1995) found daily centipedegrass ET (3.80 mm d^{-1}) to be higher compared to all other evaluated warm-season grasses evaluated. Other research has measured centipedegrass ET to range from 4.7 – 8.5 mm d^{-1} (Beard, 1985; Kim and Beard, 1988). Zoysiagrass water use is routinely considered to be greater compared to other warm-season turfgrass species (Beard, 1985; Kim and Beard, 1988; Green et al., 1991; Carrow, 1995). Specifically, zoysiagrass ET rates have been measured to range from 2.7 – 9.9 mm d^{-1}. Reported St. Augustinegrass ET rates (3.28 – 7.8 mm d^{-1}) are similar to those for centipedegrass (Atkins et al., 1991).

Due to the popularity of tall fescue and bermudagrass as managed turfgrasses in North Carolina, differences in measured water use among the two turfgrass species are of particular interest. Differences in tall fescue and bermudagrass ET have been noted during studies that included both grass species (Biran et al., 1981; Kneebone and Pepper, 1982; Qian et al., 1996).

During these studies, tall fescue ET rates were measured to be on average 35 – 41% greater than bermudagrass. Furthermore, Carrow (1995) found tall fescue ET rates to be 15% greater than bermudagrass during a two-year study in Griffin, GA. As noted, the most recent published work comparing the two species simultaneously was in 1996. In the time since this study there have been many releases of new tall fescue and bermudagrass cultivars.

Public Concerns Regarding Water Use through Landscape Irrigation

Many municipalities and water purveyors around the world are beginning to closely monitor the supply of potable water. Landscape irrigation is often subjected to heightened scrutiny in urban areas where managed turfgrass is often considered a non-essential component of the landscape. It has been reported that the majority of the 16 million ha of turfgrass in the United States is irrigated to some extent, which is three times the area of any other crop (Milesi et al., 2005). Mayer et al. (1999) reported outdoor water use to range from 22-67% of the total household water consumed throughout the US and Canada. Results from a study conducted in Florida indicated that 64% of household water use was dedicated to irrigation (Haley et al., 2007). Overwatering is often due to the lack of seasonal adjustments to irrigation run times, which can lead to 30-40% more water applied than what is required by the plant (Trenholm et al., 2001; Adhikari et al., 2006). Bremer et al. (2012) reported a greater percentage of homeowners who water two – three times weekly have automatic irrigation systems compared to those who irrigate manually. Consequently, homeowners with automatic systems maintained consistent irrigation runtimes regardless of environmental conditions or visual appearance. All homeowners who irrigated, regardless of method, claimed to recognize turfgrass water demands. However, at least 65% of surveyed individuals across each group did not know how much water was applied while irrigating.

In order to combat use of potable water resources towards landscape irrigation, some local governments have enacted ordinances and restrictions for outdoor watering (Devitt and Morris, 2008; St. Hilaire et al., 2008; Nautiyal et al., 2015). This is normally achieved by restricting outdoor water use on certain days, tiered rate structures, or eliminating outdoor watering altogether. Failure to abide by such legislation can result in monetary fines. Although well intended, imposed water restrictions do not always translate to a decrease in water use. Ozan and Alsharif (2013) reported water usage increased after a once per week irrigation restriction was imposed in Tampa, FL compared to allowing outdoor watering two days per week. The authors attributed this increase to fines that were unable to affect public change and the lack of personnel to enforce laws. These observations suggest that additional education and information may be more beneficial to homeowners with irrigation systems in order to most efficiently match irrigation applications with turfgrass water demands.

In addition to watering restrictions, some have offered incentives to install plants that are considered ‘water-wise’ (TOC, 2008). This can be troublesome as less is known about water requirements of many ornamental plants often established in place of turfgrasses in the landscape (Devitt and Morris, 2008). For years, turfgrass researchers have devoted much time and resources into determining water requirements of popular grasses used in the landscape. Prior to the decision of substituting turfgrasses with other ornamental plants, governing bodies must be informed of water use characteristics and other environmental impacts. In Cary, NC, incentives have been offered for substitution of a cool-season grass for a warm-season grass. This can be problematic in many lawns as the warm-season turfgrass may not be adapted to localized stresses such as shade. Although many use characteristics must be considered when selecting a turfgrass for use in the transition zone, it is imperative to consider water use potential of available turfgrasses as water conservation efforts continue. Furthermore, increasing the knowledge of homeowners and turfgrass irrigation managers in terms of current turfgrass water demands is critical to advancing the conservation of potable water reserves through efficient irrigation applications.

Turfgrass Water Use Measurement Techniques

Matching applied irrigation rates with plant water use is a critical component of turfgrass management. Technologies that can be paired with landscape irrigation controllers to monitor plant water needs has recently been a popular topic among turfgrass researchers (Cardenas-Lailhacar and Dukes, 2012; Haley and Dukes, 2012; Grabow et al., 2013; Vick et al., 2017). Such technology include irrigation controllers that determine irrigation runtimes based on soil-moisture and ET observations. Many of these technologies are now affordable and have been proven to increase landscape irrigation efficiency. However, the use of historical meteorological data to estimate reference evapotranspiration (ET_o) remains a primary function of irrigation management (Wherley et al., 2015). Empirical models such as the Penman-Monteith equation have historically been used to estimate ET_o (Monteith, 1965). Other examples of empirical models include the Thornthwaite (1948), Blaney-Criddle (1962), Doorenbos and Pruitt (1977), and Hargreaves-Samani (1985) methods. Since the derivation of the original Penman-Monteith equation, there have been several alterations allowing for use across various environments (Allen et al., 1998; Allen et al., 2005). Following estimation, ET_o requires adjustment by appropriate crop coefficients (K_c) to derive an estimate of actual evapotranspiration (ET_a) which is then used to schedule irrigation. Distinct environmental conditions across the United States influence water use among turfgrass species and subsequent K_c. Careful consideration should be given when selecting turfgrass K_c as they vary among species, geographic location, and level of turfgrass management (Meyer and Gibeault, 1986; Devitt et al., 1992; Carrow, 1995; Jia et al., 2007; Wherley et al., 2015). Previous turfgrass K_c research has primarily taken place in the southern United States. A comprehensive review of published crop coefficients by Romero and Dukes (2016) details K_c for a variety of turfgrass species during various times of the year in the southern United States. Most research agrees that K_c fluctuates throughout the year given seasonal changes in environmental conditions. However, the degree in which they change geographically and among turfgrass species is variable. Devitt et al. (1992) found bermudagrass managed on a golf course resulted in K_c ranging from 0.74 – 0.89 from May through October in Nevada. In Florida, bermudagrass K_c fluctuated from 0.17 in February to 0.99 in July during a three year study (Wherley et al., 2015). Another study in Florida identified bahiagrass (*Paspalum notatum* Flüggé) K_c varied from 0.35 – 0.90 (Jia et al., 2007).

While empirical models provide an economical approach to estimate ET, methods that directly measure ET are desirable. The use of field lysimetry has historically been considered the standard for directly measuring ET by computing the difference in mass of a closed system between weighing events over a known period of time (Allen et al., 1989; Fry et al., 1997; López-Urrea et al., 2006; Trajkovic, 2010, Peterson et al., 2017). This provides a reliable measurement of ET, however, lysimeters are usually not considered an option for continuous, long-term ET measurement due to costs of infrastructure, long-term maintenance, and subsequent labor requirements. The use of lysimeters require certain conditions to be met (Allen et al., 2011). Perhaps the most important is the surrounding vegetation must be representative of that within the bounds of the lysimeter. This condition is critical in order to extrapolate water use from the lysimeter to expansive areas. This is typically not an issue at most managed turfgrass sites as the goal of turf management is to achieve a uniform turf surface. Included in the maintenance of the surrounding area, soil moisture must also be maintained at similar levels to ensure consistent balance of available energy.

Evapotranspiration can also be obtained through micrometeorological techniques that measure energy flux components of the surface energy balance. Energy components that comprise the surface energy balance include net radiation (R_n), latent heat flux (LE), sensible heat flux (H), soil heat flux (G), physical energy storage (S_t), biochemical energy storage (P), and advected energy (A_d). However, due to minimal contributions to the overall energy balance, certain terms are neglected to offer a more simplistic expression. A simplified expression of the surface energy balance was presented by Brutsaert (1982) which eliminated the S_t, P, and A_d terms:

$$R_n = G + H + LE$$

The measurement of significant energy balance terms presents some challenges. Notably, the measurement of H and LE require advanced instrumentation and data processing due to boundary-layer turbulence that dominates both components while measurements of R_n and G are relatively easy to obtain (Monteith and Unsworth, 1990). Due to the sophistication of required instrumentation, the cost to directly measure LE can be exorbitant. To combat cost limitations, calculating LE as the residual of the surface energy balance following measurements of R_n, G, and H is the most economical approach (Shapland et al., 2012):

$$LE = R_n - G - H$$

Once LE has been calculated, it is then divided by the latent heat of vaporization (L) to derive ET.

Net radiation is commonly measured by net radiometers which measure the net difference in energy input to two blackened surfaces. One surface is directed up, facing the sun while the other is facing the ground. This allows for the capture of incoming and outgoing energy. Soil heat flux is measured by soil heat flux plates. These plates are made of material whose thermal conductivity is similar to soil. Thermocouples and moisture sensors are also needed in tandem to account for stored energy within the soil volume between the soil heat flux plate and the soil surface.

There are multiple micrometeorological techniques that can be used to measure sensible heat flux density. Perhaps the most popular, the eddy covariance (EC) technique measures *H* by quantifying the covariance of the vertical wind speed with sonic temperature (Swinbank, 1951). These measurements are commonly collected by way of a sonic anemometer. The advanced knowledge of turbulent theory and biophysics coupled with the challenge of post-processing large amounts of data from EC can be daunting for many agricultural researchers (Allen et al., 2011). However, improvements to instrumentation and post processing data software have allowed for its expanded use.

The Bowen (1926) ratio method measures vapor pressure and air temperature gradients near the evaporating surface in order to arrive at *H* and is considered a standard technique in partitioning energy at earth's surface (Tanner, 1960; Sinclair et al., 1975). The Bowen ratio method is popular due to practicality and the simple measurements of water vapor and air temperature at two heights near the evaporating surface. Like most other micrometeorological techniques, sufficient fetch of a uniform surface is required to establish equilibrium of the boundary layer (Allen et al. 2011). Recently, Micro-Bowen ratio (MBR) systems have been deployed as a scaled-down version of a Bowen ratio system designed to measure a small footprint (Holland et al., 2013). Initially, the MBR system was deployed to measure evaporation near bare surfaces (Ashktorab et al., 1989). Research has since evaluated MBR and its ability to quantify evaporation under canopies such as corn and vineyards (Zeggaf et al., 2008; Holland et al., 2013). Most recently, MBR derived ET measurements agreed well with lysimeter and eddy covariance measurements of ET in vineyard interrows planted with a cool-season turfgrass (Holland et al., 2013).

The use of fine-wire thermocouples to quantify sensible heat flux density by measuring high frequency temperature fluctuations in coherent air parcels above the crop surface is known as the surface renewal (SR) method. Much research has taken place in California evaluating this technique for ET measurement over various vegetation (Paw U et al., 1995; Synder et al., 1996). A comprehensive explanation of flux measurement theory and current SR methodology is provided by Shapland et al. (2013). Compared to other micrometeorological technique, the required instrumentation are relatively inexpensive. Furthermore, sampling procedures are simple compared to other techniques. However, data computations are complex much like EC systems. Performance testing of ET estimation by the SR method has been investigated over a variety of cropping systems including rangeland grass, orchards, vineyards, rice, tomato, and tall fescue turfgrass (Castellví and Snyder, 2008; Castellví and Snyder, 2009; Castellví and Snyder, 2010; Castellví et al., 2012; Rosa et al., 2013; Suvočarev et al., 2013). The aforementioned trials have demonstrated that the SR method can produce accurate measurements of ET comparable to standard measurement techniques. In addition to minimal investment in instrumentation, advantages of the SR include the ability to collect data on sloped terrain, lack of needed axis correction that is required by EC systems, and as a result, reduced fetch requirements (Snyder et al., 2008; Castellví, 2012).

As water conservation efforts continue to evolve, research is needed to update water use characteristics of new turfgrass species. Specifically, there is need for comparison of modern cultivars of popular turfgrasses managed in North Carolina in order to assess water conservation and monetary benefits that stem from reduced irrigation inputs. Research is also needed to update current irrigation recommendations for both cool- and warm-season turfgrass across various environments locally in North Carolina. Furthermore, there has been little research investigating the use of micrometeorological techniques in measuring ET over managed turfgrass sites in the transition zone. As a result, additional research is required to assess the viability of novel micrometeorological techniques to continuously measure ET that can assist in the conservation of potable water resources.

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CHAPTER 1: CROP COEFFICIENTS FOR TALL FESCUE AND HYBRID BERMUDAGRASS IN THE TRANSITION ZONE

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Abstract

Accurate turfgrass crop coefficients are critical when scheduling irrigation based upon reference evapotranspiration (ET_o). Currently, locally derived turfgrass crop coefficients are lacking in the transition zone. The objective of this field study was to derive crop coefficients (K_c) for 'Triple Threat' tall fescue (*Festuca arundinacea* Schreb.) and 'Tifway' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] managed in the transition zone. Direct measurements of actual evapotranspiration (ET_a) were made through the weighing of lysimeters planted with tall fescue and hybrid bermudagrass. Data were collected from May through October during 2017 and 2018 from non-stressed turfgrass. Turfgrass crop coefficients were computed by the quotient of ET_a and ET_o, which was calculated from the ASCE-Standardized reference evapotranspiration equation using meteorological data collected from an on-site weather station. Tall fescue and hybrid bermudagrass K_c varied by month ($P <$ 0.0001). Means for tall fescue and hybrid bermudagrass K_c ranged from 0.69 to 0.85 (± 0.16 SD) and 0.44 to 0.59 (± 0.10 SD), respectively. Tall fescue K_c exceeded hybrid bermudagrass every month as the result of higher ET_a. The use of locally derived turfgrass crop coefficients can assist turfgrass managers in the transition zone to better meet turfgrass water demands.

Matching applied irrigation rates with plant water use is a critical component of turfgrass management. Recently, research has focused on technologies that can be paired with landscape irrigation controllers to monitor plant water needs (Cardenas-Lailhacar and Dukes, 2012; Haley and Dukes, 2012; Grabow et al., 2013; Vick et al., 2017). Many of these technologies are now affordable and have been proven to increase landscape irrigation efficiency. However, the use of historical meteorological data to estimate reference evapotranspiration (ET_o) remains a primary function of irrigation management (Wherley et al., 2015). Empirical models such as the Penman-Monteith equation have historically been used to estimate ET_o (Monteith, 1965). Since the derivation of the original Penman-Monteith equation, there have been several alterations allowing for use across various environments (Allen et al., 1998; Allen et al., 2005). Reference evapotranspiration requires adjustment by appropriate crop coefficients (K_c) to derive an estimate of actual evapotranspiration (ET_a) that can be used to schedule irrigation. Distinct environmental conditions across the United States influence water use among turfgrass species and subsequent K_c. Careful consideration should be given when selecting turfgrass K_c values as they vary among species, geographic location, and level of turfgrass management (Meyer and Gibeault, 1986; DeVitt et al., 1992; Carrow, 1995; Jia et al., 2007; Wherley et al., 2015).

Previous turfgrass K_c research has primarily taken place in the southern United States. A comprehensive review of published crop coefficients by Romero and Dukes (2016) details K_c for a variety of turfgrass species during various times of the year in the southern United States. Most research agrees that K_c fluctuates throughout the year given seasonal changes in environmental conditions. However, the degree in which they change geographically and among turfgrass species is variable. Devitt et al. (1992) found bermudagrass managed on a golf course resulted in K_c ranging from 0.74 – 0.89 from May through October in Nevada. In Florida, bermudagrass K_c

fluctuated from 0.17 in February to 0.99 in July during a three year study (Wherley et al., 2015). Another study in Florida identified bahiagrass (*Paspalum notatum* Flüggé) K_c varied from 0.35 – 0.90 (Jia et al., 2007). The vast ranges found among turfgrasses managed in Florida can be attributed to continued growth (although limited) of warm-season grasses during the winter in areas throughout the southern United States.

The transition zone is a unique area of the United States where the use of cool- and warm-season grasses overlap. The southern edge of the transition zone is routinely defined near the southern boarders of North Carolina, Tennessee, Arkansas, and Kansas (Dunn and Diesburg, 2004). Information regarding turfgrass K_c in the transition zone is lacking and would aid in developing scientific irrigation regimes based upon historical weather data. Locally in North Carolina, commonly used cool- and warm-season grasses include tall fescue and bermudagrass (Miller et al. 2016). Carrow (1995) measured ET_a for both species in a study conducted in Griffin, GA (32.2468° N, 84.2641° W). This has been the closest study, geographically, to Raleigh, NC (35.7796° N, 78.6382° W) to report water use and subsequent K_c. However, their results should be used with caution as the K_c values were developed under water-limiting conditions as a function of the study.

Determining accurate K_c values for popular turfgrasses managed in the transition zone may assist turfgrass managers in meeting plant water demands when irrigating. The objective of this field study was to derive crop coefficients (K_c) for tall fescue and hybrid bermudagrass for use in the southern transition zone.

Lysimeter Maintenance and Measurement

Turfgrass water use measurements were collected from May through October during 2017 and 2018 at the Lake Wheeler Turfgrass Field Laboratory in Raleigh, NC. Field lysimeters were constructed from 10 in diameter Schedule 40 polyvinyl chloride (PVC) pipe cut to 13 in lengths. Steel rods were inserted through the wall of the PVC pipe to support a 0.25 in PVC foam board bottom plate recessed 1 in from the bottom of the PVC pipe, resulting in an effective lysimeter depth of 12 inches and 942 in^3 volume. Four 11/16 in holes were threaded into the bottom PVC foam board to allow for drainage during the establishment period. Lysimeter bottom plates were lined with geotextile fabric to prevent media loss through drainage holes during establishment. During active measurement, holes were plugged to prevent water loss to drainage. Experimental lysimeters were filled with calcined clay soil amendment (Profile Porous Ceramic Greens Grade, Buffalo Grove, IL) and established with washed 'Triple Threat' tall fescue (*Festuca arundinacea* Schreb.) and 'Tifway' hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt-Davy] sod measuring 79 in^2 with four replications. Each year, lysimeters were established mid-March to allow for an establishment period of six weeks prior to initiating water use measurements. Following establishment, lysimeters were inserted into in-ground plastic sleeves to prevent native soil adherence to lysimeter outer walls. In-ground holes were also lined with rock below lysimeters to allow for drainage of excess water. Complete instructions detailing lysimeter construction can be found in a published manuscript by Wherley et al. (2009).

Lysimeters were maintained at 4 and 2 in mowing heights for tall fescue and hybrid bermudagrass, respectively, using a Honda HRX217HZA walk-behind mower (Honda Power Equipment, Alpharetta, GA) with clippings returned. Monthly fertility was applied to all lysimeters at a nitrogen rate of 1.0 lb 1000 ft^{-2} depending on species and month. Tall fescue lysimeters received 1.0 lb N rates during May, September, and October while hybrid bermudagrass received 1.0 lb N rates during June, July, and August. A sulfur coated urea fertilizer (Reed & Perrine Sales, Tennent, NJ) containing micronutrients and an analysis of 25% N - 5% P_2O_5 – 10% K_2O was used for all fertilizer applications. Preventative fungicide applications were made every 21 days from June through September to control brown patch (*Rhizoctonia solani*) and gray leaf spot (*Pyricularia grisea*) in tall fescue with axozystrobin at 0.4 oz 1000 ft^{-2}. All management practices were selected based upon recommendations detailed in Carolina Lawns (Miller et al., 2016).

Measurements of actual evapotranspiration (ET_a) were made every 2 to 3 days between 0600 and 0800 hours during both years of the study for a total of 226 weighing periods. Lysimeters were housed underneath a portable rainout shelter (Four Season Tools, Kansas City, MO) covered with a clear plastic to prevent rainfall interference allowing for continuous measurement from May-October. An S-Beam load cell (CAS S-Beam, NTEP CoC 96-073A1, East Rutherford, NJ) powered by a digital indicator (Salter Brecknell 200 SL, Salter Brecknell Weighing Products, Fairmont, MN) mounted to a tripod hoist (Cabela's Inc, Springfield, MO) was used to quantify turfgrass water use during weigh events. Prior to data collection, lysimeters were saturated and allowed to drain for a period of 24 hours to establish field capacity. The corresponding mass for field capacity was recorded for each lysimeter. The difference in mass between weigh events was the result of turfgrass ET_a with water replenished to field capacity to maintain well-watered, non-stressed conditions throughout the study. Reference evapotranspiration (ET_o) was determined by the ASCE-EWRI Standardized reference evapotranspiration equation for short grass canopies (Allen et al., 2005):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_o is short grass reference crop evapotranspiration (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux density at the soil surface (MJ m^{-2} day^{-1}), T is mean air temperature

(°C), u_2 is wind speed (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$), and γ is the psychometric constant (kPa $°C^{-1}$). Meteorological data required for ET_o calculation were collected at 30 min intervals by an on-site HOBO Micro Weather Station Data Logger (Onset Corporation, Bourne, MA). Turfgrass crop coefficients (K_c) were then derived by dividing ET_a by ET_o. In addition to turfgrass water use measurements, turfgrass quality ratings were made every two weeks during the course of the study according to guidelines established by the National Turfgrass Evaluation Program (NTEP) using a 1-9 scale (1 = brown, low-quality turf, 9 = green, high-quality) (Morris and Shearman,1998). Turf quality ratings of 6 were considered minimally acceptable.

Statistical Analysis

All statistical analyses were performed using Statistical Analysis System (version 9.4, 2013; SAS Institute Inc., Cary, NC). Data from ET_a measurements, derived K_c values, and turfgrass quality ratings were found to be independent and normally distributed. These data were subjected to ANOVA to determine treatment effects using the PROC GLM procedure. Significant interactions were identified and subjected to Fisher's Protected LSD test at the 0.05 probability level. Data are presented for significant species and month interactions.

Meteorological Data

Meteorological data collected throughout the study can be found in Table 1. Minimum air temperature ranged from 35.8 to 63.1°F during the two year study. In May and October, nightly air temperatures were reduced closer to 40°F. However, minimum air temperature was ~10° warmer in May 2018 compared to 2017. Maximum air temperature fluctuated less compared to minimum air temperature. Maximum air temperature remained below 90°F over the course of an entire month only once (October, 2017). Averaged relative humidity remained consistent throughout. Relative humidity in September 2018 was highest (80.1%) due to excess moisture as the result of two tropical weather events. As expected, incoming solar radiation was greatest during summer months and was reduced during May, September, and October.

Measured Turfgrass Water Use

Monthly averaged daily ET_o ranged from 0.15 inches during October 2017 to 0.35 inches in June 2018. In 2018, the evaporative demand during June, August, and September increased by 9, 13, and 10%, respectively compared to 2017 (Fig 1). Higher air temperature during June and September in addition to increased solar radiation during August were likely reasons for higher ET_o (Table 1). During May and July 2018, ET_o rates were lower (3 and 6%, respectively) compared to 2017.

Averaged tall fescue water use ranged from 0.11 - 0.30 inches day^{-1} during the two year study. Tall fescue ET_a was greatest in June 2018 and lowest during October 2017 which is consistent with measured ET_o (Fig 1). Under non-limiting soil moisture, Beard (1994) reported water use of cool-season grasses to range from 0.12 – 0.31 in day^{-1}. Additional studies have reported higher ET_a for turf-type tall fescue ranging from 0.18 – 0.38 in day^{-1} (Bowman and Macaulay, 1991; Kopec et al., 1988). Averages for hybrid bermudagrass ET_a peaked and bottomed-out during the same months as tall fescue ranging from 0.07 – 0.22 inches day^{-1}. Hybrid bermudagrass water use was similar to ET_a rates reported in previous studies (Amgain, 2018; Beard 1994; Carrow, 1995; Kim and Beard, 1988; Wherley et al., 2015). On average, tall fescue water use was 46% higher than hybrid bermudagrass. Research conducted in more arid climates have also found differences in tall fescue and hybrid bermudagrass water use comparable to those reported in this study (Biran et al., 1981; Kneebone and Pepper, 1992; Qian et al., 1996).

Derived Turfgrass Crop Coefficients

Previous research has shown that turfgrass K_c fluctuates over short time periods. As a result, values are typically averaged by month (Carrow, 1995). Derived K_c values were variable across months during 2017 and 2018 (Table 2). In 2017, hybrid bermudagrass K_c fluctuated from 0.35 in May to 0.61 in September (Table 3). Hybrid bermudagrass K_c was lower during spring (May – 0.35) and fall (October – 0.46) months compared to summer. During the summer, hybrid bermudagrass K_c increased, ranging from 0.53 – 0.61. The opposite was found of tall fescue during 2017. The lowest K_c was derived during July (0.71), whereas the highest was in September (0.89). In 2018, hybrid bermudagrass K_c values were 55 and 19% higher during May and June, respectively, compared to 2017. The range in hybrid bermudagrass K_c was reduced in 2018 (0.50 – 0.63) compared to 2017 (0.35 – 0.61) as the result of the lower K_c in May. The lower May hybrid bermudagrass K_c in 2017 can be attributed to a cool, wet spring that delayed green-up throughout the piedmont region of North Carolina. The range of K_c was increased for tall fescue during 2018. Values ranged from 0.64 in May and August to 1.00 in October. The greatest differences in K_c from 2017 - 2018 were a 31% reduction in September and a 35% increase in October. In September 2018, central North Carolina experienced prolonged periods of clouds and rain which reduced tall fescue K_c compared to September 2017 which brought a month of dry, hot weather. Conversely, warm temperatures in early October 2018 produced ideal tall fescue growing conditions increasing K_c compared to other months. Air temperature influences ET_a, as water loss through evapotranspiration cools the plant (Fry and Huang, 2004). As a result, ET_o and subsequent K_c are also affected by changes in air temperature. The effects of maximum and minimum air temperatures on turfgrass ET_a throughout the study can be found in Fig 2.

Bermudagrass and Tall fescue Quality

In addition to water use measurements, turfgrass quality ratings were collected. Analysis of variance indicated significance for the turfgrass × month interaction ($P = 0.0005$). Lysimeters were maintained to prevent stress, therefore, it was not surprising turf quality of both grasses were rated above the minimally acceptable value of 6 during all rating dates (Fig 3). Hybrid bermudagrass quality was rated higher than tall fescue during each month with the exception of May. Hybrid bermudagrass quality remained static throughout evaluations as monthly averaged quality ratings were rarely below 8. Tall fescue quality ratings varied more than hybrid bermudagrass with values ranging from 6.6 in October to 8.1 in May. Growth patterns of the two turfgrass species provide explanation for differences in turf quality since the majority of data collection occurred during summer favoring hybrid bermudagrass growth (Christians, 2004).

Use of Updated Turfgrass Crop Coefficients

A study conducted in Griffin, GA provided data on turfgrass water use and crop coefficients for hybrid bermudagrass, common bermudagrass [*C. dactylon* (L.) Pers.], zoysiagrass (*Zoysia japonica* Steud.), common centipedegrass [*Eremochloa ophiuroides* (Munro.) Hack.], St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze], and tall fescue (Carrow, 1995). Monthly K_c for hybrid bermudagrass and tall fescue varied more during the Griffin, GA study compared to values derived during this two-year study. Griffin, GA is located in the southern, warm region of the United States rather than the transition zone which likely caused higher K_c values. The use of field lysimetry during this study resulted in reduced K_c variability compared to the Griffin, GA study which used TDR (time domain reflectometry) probes. Lysimeters have historically been considered the standard for measuring evapotranspiration compared to alternative methodology (Allen et al., 1989; Fry et al., 1997; López-Urrea et al., 2006; Trajkovic, 2010). More recently, two studies have reported water use of warm-season grasses in Florida. Jia et al. (2009) developed K_c for bahiagrass using ET_a measured via eddy covariance. Results recommend crop coefficients of 0.80 and 0.90 during March and April, which may overestimate hybrid bermudagrass water demand further north in the transition zone. Wherley et al. (2015) developed hybrid bermudagrass K_c values ranging from 0.56 to 0.99 from May through October over three years. It is apparent from comparing results from these two Florida-based studies with our data that environmental conditions can influence turfgrass K_c. Values derived from these studies would result in over-irrigation if applied in the transition zone. Furthermore, significant water savings were realized when using K_c presented in this research compared to those found by Carrow (1995) and Wherley et al. (2015) when applied to Tifway hybrid bermudagrass in the transition zone. Specifically, considering an average Raleigh, NC (7,700 ft^2) lawn and historical ET_o from May through October, irrigation would be reduced by 23 and 53%, compared to using K_c values reported by Carrow (1995) and Wherley et al. (2015), respectively.

Information regarding use of turfgrass crop coefficients in the transition zone is lacking. This is particularly true for dominant turfgrass species such as bermudagrass and tall fescue. The results of this study provide turfgrass managers and homeowners in the transition zone data that can be used to schedule irrigation based on current or historical weather data. Turfgrass K_c derived during this study fluctuated throughout the year similar to results reported in other regions of the United States. Values were also lower compared to previous work conducted in the southern United States. Similar to recent studies, our results agree that suggested standard K_c

values of 0.6 and 0.8 for cool- and warm-season grasses, respectively, are not always appropriate to maximize irrigation efficiency. Therefore, the use of locally derived K_c can increase water conservation through efficient landscape irrigation, while maintaining turfgrass functionality.

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Table 1. Meteorological data collected from May through October 2017 and 2018. Data are averages unless otherwise noted.

Year	Month	Temp (min)	Temp (max)	Relative Humidity	Solar Radiation	Wind Speed	Dew Point
		°F	°F	%	w/m^2	mph	°F
2017	May	44.5	91.1	74.1	244.8	3.0	59.7
	June	55.4	91.3	75.7	265.0	2.0	65.9
	July	59.2	98.7	75.9	269.3	2.1	71.1
	Aug	59.4	95.5	77.4	215.1	1.8	69.0
	Sep	52.9	92.8	77.7	192.4	1.8	63.8
	Oct	38.0	87.3	79.6	158.2	1.6	56.5
2018	May	52.7	93.5	75.9	232.6	1.9	67.6
	June	63.1	97.1	69.6	269.2	1.8	69.1
	July	59.8	97.0	72.2	256.4	1.6	69.7
	Aug	58.4	95.0	76.8	241.5	1.5	71.2
	Sep	62.4	95.1	80.1	189.6	0.9	70.7
	Oct	35.8	92.5	77.2	149.9	1.3	60.4

Table 2. Analysis of variance for the fixed effects of year (Y), grass (G), month (M), and subsequent interactions on derived turfgrass crop coefficients (Kc) at the NC State University Lake Wheeler Turfgrass Field Laboratory in Raleigh, NC.

Source of Variation	df	*F*-value	*p*-value
Year, Y†	1	1.55	0.2131
Grass, G‡	1	964.94	<0.0001
Month, M§	5	29.37	<0.0001
Y × G	1	6.20	0.0130
Y × M	5	34.78	<0.0001
G × M	5	19.12	<0.0001
Y × G × M	5	23.96	<0.0001

† Year, Y; 2017 and 2018
‡ Grass, G; ‘Triple Threat’ tall fescue and ‘Tifway’ hybrid bermudagrass
§ Month, M; May-October

Table 3. Derived hybrid bermudagrass and tall fescue crop coefficients averaged by month during 2017 and 2018.

	May	June	July	Aug	Sep	Oct
2017	Turfgrass Crop Coefficient (K_c)					
Hybrid Bermudagrass	0.35 (0.12‡)	0.53 (0.05)	0.60 (0.07)	0.54 (0.09)	0.61 (0.06)	0.46 (0.06)
Tall Fescue	0.78 (0.20)	0.80 (0.15)	0.71 (0.13)	0.72 (0.11)	0.89 (0.12)	0.74 (0.15)
LSD†	0.08	0.05	0.04	0.04	0.05	0.07
2018						
Hybrid Bermudagrass	0.54 (0.10)	0.63 (0.08)	0.53 (0.04)	0.52 (0.05)	0.50 (0.06)	0.55 (0.10)
Tall Fescue	0.64 (0.13)	0.86 (0.23)	0.74 (0.07)	0.64 (0.12)	0.68 (0.13)	1.00 (0.23)
LSD	0.06	0.04	0.02	0.04	0.07	0.10
2017-18 avg.						
Hybrid Bermudagrass	0.44	0.59	0.57	0.53	0.57	0.51
Tall Fescue	0.71	0.83	0.72	0.69	0.83	0.85

† LSD = least significant difference according to Fisher's Protected LSD (*P*=0.05)
‡ Values within parentheses denote one standard deviation from the mean.

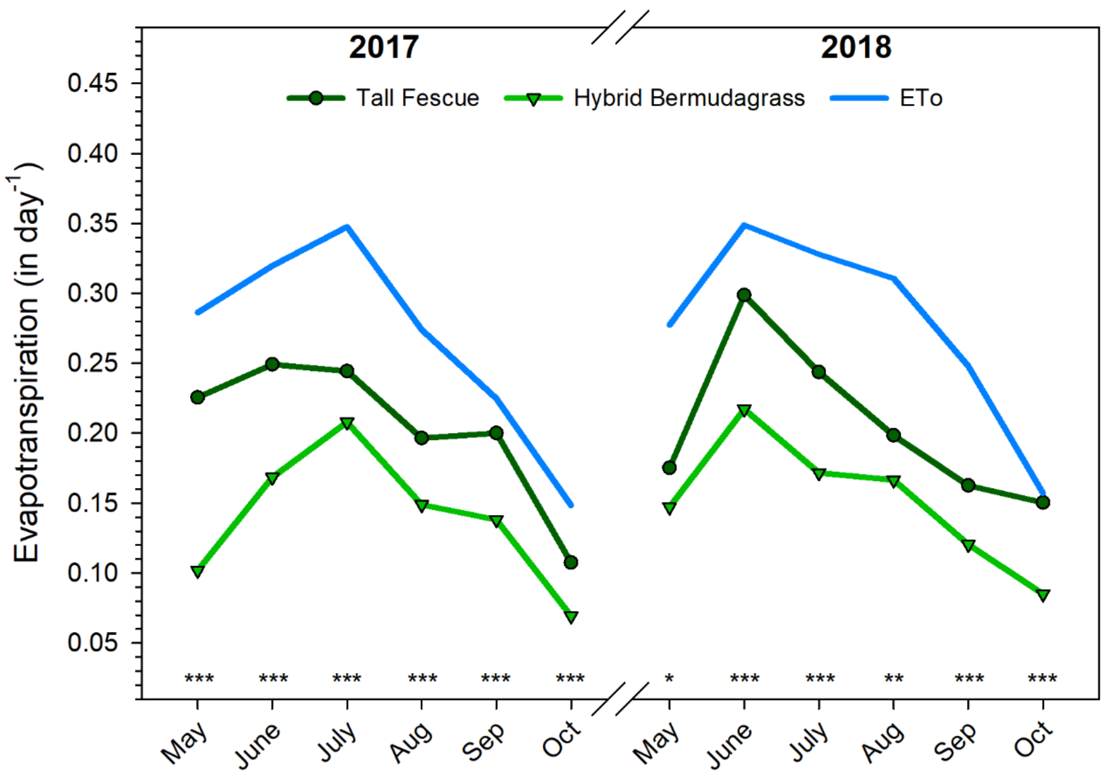

Figure 1. Reference evapotranspiration (ET_o) as well as tall fescue and bermudagrass actual evapotranspiration (ET_a) during 2017 and 2018. *, **, and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively.

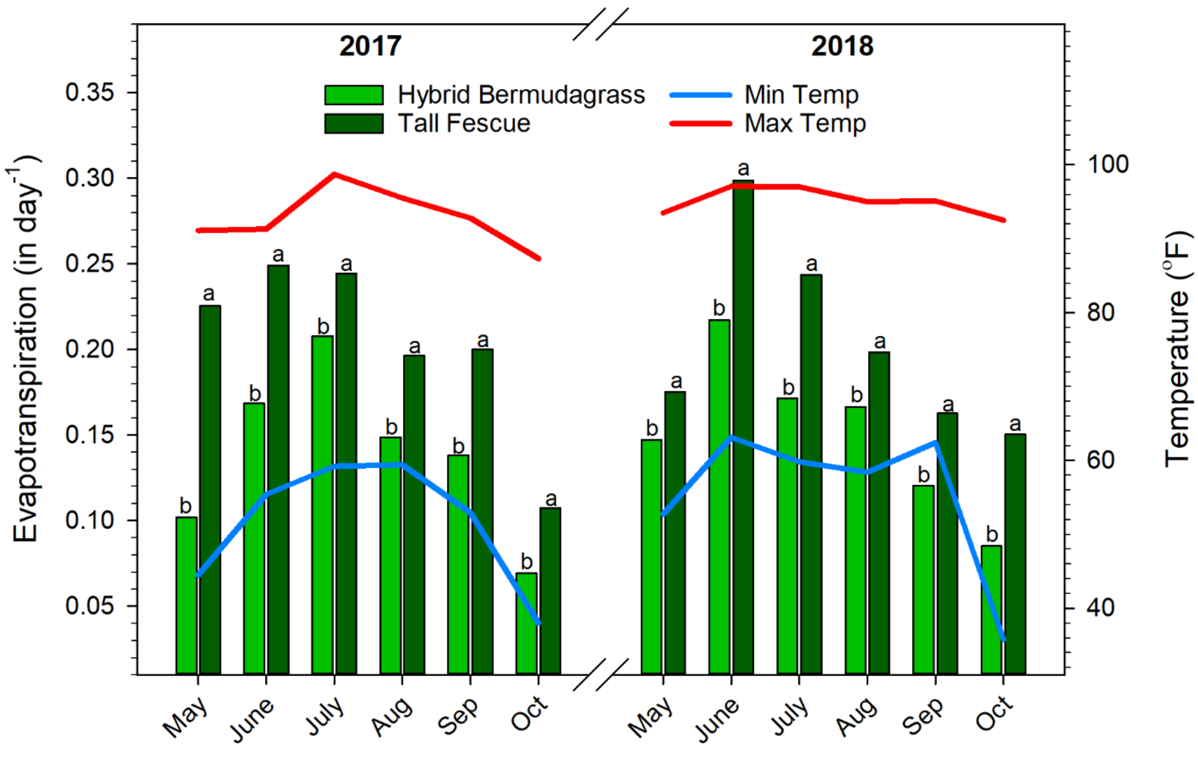

Figure 2. Bermudagrass and tall fescue actual evapotranspiration (ET_a) as it relates to minimum and maximum air temperatures during 2017 and 2018. Bars with different letters indicate significant differences in turfgrass actual evapotranspiration (ET_a) within month based on Fisher's Protected LSD test (*P*=0.05).

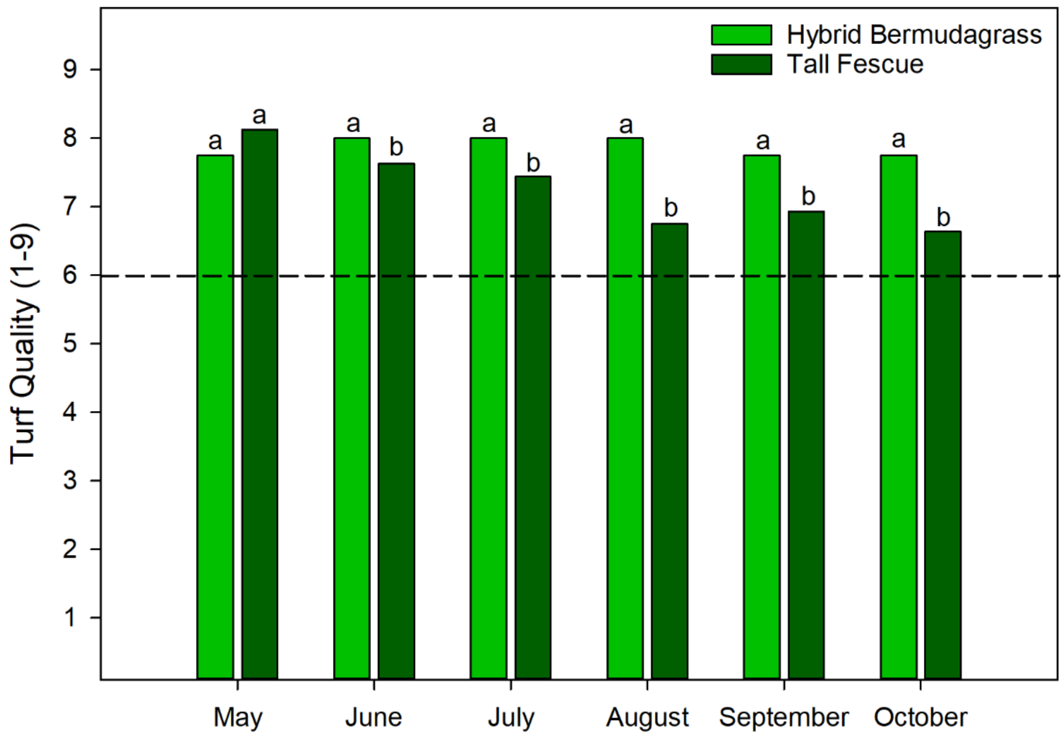

Figure 3. Bermudagrass and tall fescue turfgrass quality ratings averaged over month during 2017 and 2018. Bars with different letters indicate significant differences in turfgrass quality within month based on Fisher's Protected LSD test (*P*=0.05). Horizontal line denotes minimally acceptable turf quality.

CHAPTER 2: TURFGRASS IRRIGATION REQUIREMENTS IN NORTH CAROLINA

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Abstract

The use of meteorological data to estimate historical reference evapotranspiration (ET_{os}) is an economical approach when scheduling turfgrass irrigation. The objective of this study was to utilize historical weather data at various locations across North Carolina to develop turfgrass irrigation recommendations for homeowners and turfgrass managers. Net irrigation requirements were estimated for eleven locations across North Carolina for both cool- and warm-season turfgrasses from May through October. Meteorological data including maximum and minimum air temperature, maximum and minimum relative humidity, wind speed, and rainfall were collected and quality checked prior to their use. Solar radiation was estimated by the Hargreaves-Samani equation and adjusted according to calibration procedures. Historical meteorological data at each location were used with the ASCE-EWRI standardized reference evapotranspiration equation to derive daily turfgrass evapotranspiration rates. The difference in monthly turfgrass evapotranspiration and effective rainfall considering variation in soil type, rooting depth, and turfgrass species was used to estimate net irrigation requirements for each location. Average annual ET_{os} ranged from 1,023 mm in Boone to 1,362 mm in Fayetteville. Mean effective rainfall from May - October was consistently near 50% of total rainfall at all locations with the exception of Wilmington. However, net irrigation requirements varied substantially from 124 mm in Boone to 305 mm in Fayetteville. Results from this study can be used to increase landscape irrigation efficiency through proper irrigation scheduling that matches turfgrass water requirements for distinct environments across North Carolina.

Introduction

Landscapes serve a vital role in the environment, especially within urban, residential, and commercial properties. Landscapes add aesthetic value, decrease runoff, remove environmental pollutants, and provide a cooling effect (Devitt and Morris, 2008). Like all landscape vegetation, turfgrasses require water for growth and survival. Without adequate water, turfgrasses are unable to survive and lose functionality within the environment (Huang, 2008). To maintain healthy turfgrass during drought stress, supplemental irrigation (to meet turfgrass water requirements not provided by rainfall) is required. It has been reported that landscape irrigation accounts for 58% of potable water in the United States (Mayer et al., 1999). It was also reported that 22-67% of total household water use is directed towards outdoor watering. Overwatering is often due to the lack of seasonal adjustments to irrigation run times, which can lead to 30-40% more water applied than what is required by the plant (Trenholm et al., 2001; Adhikari et al., 2006).

Water conservation is an issue that municipalities and governing bodies will continue to face in the foreseeable future due to increasing population and reoccurring droughts. Over the next fifty to seventy-five years, population in urban areas throughout the world are expected to double (Jury and Vaux, 2005). Locally in North Carolina, the population increased by 18.5% from 2000 to 2010, to a total of 9.5 million people. This growth rate doubled the national average and ranked sixth nationally among the fastest growing states (US Census Bureau, 2010). An increasing population coupled with recent droughts, highlights the importance of water conservation in North Carolina.

Droughts in the early 2000s and 2007 were among the most extreme droughts on record in North Carolina. From 1998-2002, precipitation deficits were the largest documented since weather data collection was initiated (Weaver, 2005). In 1998, communities throughout North

Carolina were stricken with drought conditions and by 2002 a number of these communities had restricted outdoor watering year round or during summer drought episodes (Osmond and Hardy, 2004). More recently, the Town of Cary, NC implemented a ban on landscape watering during the fall of 2007 which extended into 2008 due to drought conditions (Nautiyal et al., 2014). In order to manage critical water reserves, responsible and accurate application of water must be achieved during landscape irrigation.

Environmental and climatic conditions vary greatly across North Carolina. On the coast, where coarse-textured soils dominate and air temperatures are warmer, warm-season grasses predominate. Further west into the mountain region, soils are fine textured and air temperatures are lower, creating favorable conditions for cool-season grasses. The varying climate across the state results in different turfgrass water demands. Peacock and Bruneau (2006) reported an average annual reference evapotranspiration rate of 1,156 mm for Wilmington (coast), 22% higher than Asheville (mountains). Variations in evaporative demand across the state substantiate the need for localized irrigation recommendations for distinct environments in North Carolina.

With consumptive water use expected to increase as the result of a growing population, it is important to provide information to North Carolina residents concerning turfgrass irrigation requirements. This information will better inform residents and landscape personnel on how to efficiently provide supplemental irrigation to maintain turfgrass functionality. Net irrigation requirement estimates will take into account climatic variations between locations for cool- and warm-season grasses. The objective of this research was to use historical weather data for eleven locations across the state of North Carolina to estimate net irrigation requirements for cool- and warm-season grasses. The application of these estimates will increase the efficiency of landscape irrigation resulting in greater conservation of water.

Materials and Methods

Weather Data Screening and Calibrations

Historical meteorological data were analyzed for eleven locations across North Carolina (Fig 1). Daily weather data were gathered over a thirty year period (January 1, 1984-December 31, 2013) for Wilmington, Raleigh, Greensboro, Charlotte, and Asheville locations. Daily weather data periods for the remaining locations were dependent on data availability: Hickory-16 years (January 1, 1998-December 31, 2013); Elizabeth City and Fayetteville-15 years (January 1, 1999-December 31, 2013); Boone, Kinston, and Lewiston-12 years (January 1, 2002-December 31, 2013). Meteorological data were acquired from weather stations installed over clipped grass following considerations outlined in the ASCE Standardized reference evapotranspiration equation manual (Allen et al., 2005). Similar sites were used to collect historical meteorological data by Romero and Dukes (2013) when defining turfgrass irrigation requirements for various locations across Florida. Data for this analysis were gathered from the North Carolina Climate Retrieval and Observations Network of the Southeast (CRONOS, 2014) and the National Climatic Data Center, NCDC (USDC, 2014) databases. Weather parameters obtained for each location included daily maximum and minimum air temperature, average daily wind speed (adjusted to 2 m), daily maximum and minimum relative humidity, and daily total precipitation.

Daily average solar radiation (R_s) was estimated at each location by the Hargreaves and Samani (1985) equation:

$$R_s = K_r(T_{max} - T_{min})^{0.5} R_a \tag{1}$$

where K_r = empirical coefficient; T_{max} = mean daily maximum air temperature (°C); T_{min} = mean daily minimum temperature (°C); and R_a = extraterrestrial radiation (MJ m^{-2} day^{-1}). Previous research (Dinon et al., 2011) in North Carolina determined locally derived K_r did not improve R_s

estimates compared to statewide use of $K_r = 0.18$ as suggested by Hemperly (2007). Therefore, $K_r = 0.18$ was used to estimate R_s at all locations. Following R_s estimation, values were calibrated against the clear sky envelope at each location according to guidelines set by Allen et al. (2005). Calibration factors are developed by computing multipliers that bound upper R_s estimates to R_{so} on clear sky days. Multipliers are computed every sixty days to account for seasonal variation throughout the year. All historical weather data (measured and estimated) were screened for quality in accordance to guidelines set by Allen et al. (2005)

Missing daily weather parameters were estimated by taking the average of the preceding and following day, while missing data for longer periods were filled by data from nearby weather stations.

Reference Evapotranspiration

Screened weather data were used to estimate daily turfgrass reference crop (ET_{os}) evapotranspiration for eleven locations in North Carolina using software developed by Allen (2013). The software package REF-ET, uses a number of different methods to estimate reference evapotranspiration however, during this historical analysis, we utilized the standardized ASCE-EWRI equation for short crop canopies (Allen et al., 2005). The standardized ASCE-EWRI equation is expressed as:

$$ET_{os} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_{os} = grass reference crop evapotranspiration (mm d^{-1}), R_n = net radiation (MJ m^{-2} d^{-1}), G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), T = mean air temperature (°C), u_2 = wind speed (m s^{-1}), e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa), Δ = slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}), and γ = psychometric constant (kPa

°C^{-1}). Following daily ET_{os} calculation, values were adjusted by locally derived turfgrass crop coefficients to differentiate crop evapotranspiration (ET_c) between cool- and warm-season turfgrasses. Crop evapotranspiration was determined as the product of ET_{os} and a locally derived turfgrass crop coefficient (K_c) (Table 1). Crop evapotranspiration data were averaged by month at each location for both cool- and warm-season turfgrasses.

Effective Rainfall and Net Irrigation Requirements

Effective rainfall is the portion of rainfall that can be used to meet the evapotranspiration demands of growing plants. Monthly estimates of effective rainfall (ER) were made at all locations for both cool- and warm-season grasses as ET_c directly impacts soil water storage. Effective rainfall estimates were made according to the TR-21 method (SCS, 1971):

$$ER = SF \times \left[\left(\left(0.70917 \times \left(\frac{P_m}{25.4}\right)^{0.82416} - 0.11556\right) \times 10^{0.000955 ET_c}\right) \times 25.4\right] \tag{3}$$

where ER = monthly effective rainfall, mm; SF = soil water storage factor; P_m = average monthly precipitation, mm; and ET_c = monthly crop evapotranspiration, mm.

The soil water storage factor, SF, is given by the following equation (SCS, 1971):

$$SF = 0.531747 + 0.295164\left(\frac{D}{25.4}\right) - 0.057697\left(\frac{D}{25.4}\right)^2 - 0.003804\left(\frac{D}{25.4}\right)^3 \tag{4}$$

where D = usable soil water storage which is fraction of the available water holding capacity (AWHC, cm^3/cm^3) of the soil within the root zone, mm. Specifically, D was equal to 0.66 times the AWHC representative of the turf root zone (Obreza and Pitts, 2002). To allow for consideration of various soil and plant properties representative of each location, multiple ER simulations were performed. A high and low AWHC and two rooting depths (150 and 300 mm) resulted in four ER simulations at each location for both cool- and warm-season grasses (determined by varying turfgrass K_c). The AWHC was referenced for the five most common soil types within the county of each location that were not defined as muck, flooded, water, or marsh (NRCS, 2014). Among the five common soils at each location, the high and low AWHC was chosen for each rooting depth. Available water holding capacities ranged from 0.03 in Wilmington (150 and 300 mm depth) to 0.18 in Asheville and Boone (150 and 300 mm depth). Monthly ER for cool- and warm-season grasses were determined as the average of four ER simulations (2 AWHC x 2 rooting depths).

To account for soil water not replaced by ER, net irrigation requirements were determined on a monthly time step by the following equation:

$$NIR = ET_c - ER \tag{5}$$

where NIR = net irrigation requirement, mm. Net irrigation requirements for all locations were determined by ET_{os} estimates, turfgrass species, soil physical properties, and effective rainfall. Statistical analysis of data was conducted using SAS 9.4 (SAS Institute Inc., Cary, NC). The PROC MEANS procedure was used to calculate statistics for all variables considered in this analysis.

Results and Discussion

Weather Data Screening and Calibrations

Daily meteorological data downloaded from CRONOS and NCDC databases included few missing data totaling just over 0.04% of all data collected. Over half of the missing meteorological data occurred at the Charlotte weather station from 1996-1998. Missing maximum and minimum relative humidity data totaled 5.48%, accounting for all but three missing weather parameter observations for Charlotte (Table 2). Due to nearby weather stations being void of relative humidity data, the three years with missing data were not considered during irrigation simulations for Charlotte. After removal of this three year period, total missing data for all locations were just over 0.02%, similar to Romero and Dukes (2013).

Average daily maximum air temperature across North Carolina ranged from 16.8 °C in Boone, to 23.2 °C in both Fayetteville and Wilmington, while average daily minimum air temperature ranged from 6.1 °C in Boone to 12.4 °C in Wilmington (Table 3). As expected, mean air temperatures increased from higher elevations down to sea-level on the coast of North Carolina. Daily mean maximum relative humidity ranged from 88% in Charlotte and Greensboro, to 96% in Lewiston. Daily mean minimum relative humidity ranged from 45% in Hickory and Charlotte, to 52% in Elizabeth City. On average, higher relative humidity was measured in the coastal plain and mountain regions of the state compared to the piedmont. Average rainfall ranged from 1,035 mm yr^{-1} in Fayetteville to 1,442 mm yr^{-1} in Wilmington. After adjustment to 2 m height, daily average wind speeds ranged from 1.5 m s^{-1} in Hickory to 3.0 m s^{-1} in Elizabeth City. The two locations with the highest average wind speed (Elizabeth City and Wilmington) are both coastal locations where wind speeds are generally higher due to proximity to the Atlantic Ocean.

Daily R_s quality checks suggested by Allen et al. (2005) indicate that in a typical humid climate, R_s should not lie below or above the computed clear sky solar radiation envelope (R_{so}) by more than 3 to 5%. When using a constant $K_r = 0.18$ in North Carolina, R_s estimates on clear sky days would periodically deviate from R_{so} unacceptably, similar to what Jacobs et al. (2004) observed in Florida. One year of R_s data in Raleigh, NC is presented in Fig. 2. Estimated R_s sporadically exceeded R_{so} during the spring and fall by as much as 26%. Conversely, R_s was underestimated during July and August. As a result, regional calibration of R_s was performed as suggested by Allen et al. (2005). Following calibration, adjusted R_s followed the R_{so} curve more consistently, which subsequently improved the accuracy of ET_{os} estimates (Fig. 2). Mean adjusted daily solar radiation estimates ranged from 17.0 MJ m^{-2} day^{-1} in Elizabeth City to 17.9 MJ m^{-2} day^{-1} in Fayetteville and Wilmington. No trends were seen for solar radiation across locations. Previous research has also found the use of common K_r coefficients for estimating R_s from Eq (1) often results in erroneous data (Hargreaves, 1994; Allen, 1995; and Allen, 1996). Hargreaves (1994) recommended use of $K_r = 0.16$ and 0.19 for interior and coastal regions respectively, rather than universal use of $K_r = 0.16$. Allen (1995) presented K_r adjustment as a function of elevation but no longer recommends this method as the result of poor performance at elevations greater than 1,500 m.

Reference Evapotranspiration

Average monthly reference evapotranspiration (ET_{os}) fluctuated across North Carolina for the historical period analyzed (Table 4). Monthly ET_{os} were lower at the mountain locations compared to the piedmont and coastal plain regions. The lower ET_{os} observed in the mountains can be attributed to the lower air temperatures and higher relative humidity, while higher air temperatures in Wilmington and Fayetteville resulted in greater ET_{os} at both locations.

Annual ET_{os} ranged from 1,023 mm in Boone to 1,362 mm in Fayetteville, similar to what Peacock and Bruneau (2006) reported when using the Blaney - Criddle method to develop ET_o. The study also presented ET_{os} estimates for Asheville, Charlotte, Raleigh, Wilmington, and Kinston. The reference evapotranspiration estimates reported in Peacock and Bruneau (2006) were slightly lower for all similar locations included in this study. These differences can be attributed to the use of the Blaney - Criddle method which requires only daily air temperature and percent daylight hours to predict ET_o (Blaney and Criddle, 1962). Although the Blaney - Criddle method is an accepted method to predict ET_o, recent methods have proven to be more accurate due to more extensive data inputs (López et al., 2006 and Irmak et al., 2008).

Effective Rainfall and Net Irrigation Requirements

Mean rainfall totals from May – October ranged from 560 mm in Charlotte to 924 mm in Wilmington. The two locations (Wilmington and Elizabeth City) with the highest mean rainfall are the closest in proximity to the coast. Effective rainfall (ER) directly impacts water available for turfgrass evapotranspiration and as result, impacts net irrigation requirements. Overall, ER totals were similar across the state. Averaged across turfgrass species, estimated ER ranged from 269 – 344 mm. However, the proportion of mean ER/mean rainfall was much lower in Wilmington compared to other locations. Specifically, only 37% of the average rainfall from May – October was estimated to be effective, while at all other locations ER was slightly less than 50% of total rainfall. The lower proportion of effective rainfall estimated in Wilmington can be attributed to higher rainfall in combination with much lower AWHC potential of the coastal, sandy soil.

Net irrigation estimates from May through October ranged from 124 mm in Boone to 305 mm in Fayetteville (Fig 3). The average standard deviation of 90 mm was due to variation in turfgrass species, rooting depth, and AWHC. Variation between locations was higher than what Romero and Dukes (2013) found in Florida. This difference can be attributed to the investigation of both cool- and warm-season grasses in this study, compared to only warm-season grasses in the Florida study. Net irrigation requirements were highest in Fayetteville due to elevated air temperatures in addition to lower AWHC inherent to the coarser soils in southeastern North Carolina. Mean irrigation was reduced in Wilmington due to more frequent rainfall. When comparing North Carolina irrigation requirements reported by Peacock and Bruneau (2006) to estimates made during this analysis there were some noticeable differences. The Asheville, Raleigh, Kinston, Wilmington, and Charlotte locations were estimated to require 60, 56, 56, 57, and 56% less irrigation, respectively compared to estimates presented by Peacock and Bruneau. Large differences were found in part due to the use of turfgrass crop coefficients during this historical analysis to characterize the percent of ET_{os} used by each turfgrass species. Furthermore, the Peacock and Bruneau study did not use AWHC and rooting depth in their analysis to determine ER, but rather assumed 50% of the mean monthly rainfall to be effective, while taking the difference of ET_{os} and effective rainfall to estimate net irrigation requirements. Also, we did not adjust net irrigation requirements for distribution uniformity due to potential variability among individual irrigation systems.

Mean monthly irrigation requirements for cool- and warm-season grasses at eleven locations in North Carolina are presented in Table 5. Monthly totals are the average of four, period of record monthly simulations involving two rooting depths (15 and 30 cm) and a high and low water holding capacity for both cool- and warm-season grasses. On average, May and June required the most supplemental irrigation for cool-season grasses at most locations. This trend is not unexpected as the increased irrigation requirements during the spring follows K_c and seasonal growth patterns of cool-season grasses in the transition zone. As temperatures rise during early summer in July, turfgrass growth slows in effort to conserve water (Fry and Huang, 2004). This is observed at most locations as net irrigation requirements decrease in August compared to July. As temperatures begin to moderate in September, the plant begins to recover, however cool-season turfgrass water use is less than spring due to injury from summer heat stress. This can have significant impact on available moisture where cool-season grasses are managed. During spring and early summer, greater volumes of water are extracted from the soil as the result of increased cool-season turfgrass transpiration. Therefore, additional irrigation is often required during this time to avoid stress when rainfall is limiting. During mid-late summer, less water is extracted from the soil as the result of decreased cool-season turfgrass transpiration when air temperatures induce heat stress. Although transpirational water use is reduced, environmental conditions increase the evaporative demand during this period within the upper portion of the soil profile. Available water is often limiting during late summer as the majority of cool-season turfgrass roots are located in the upper portion of the soil profile. This creates the need for supplemental irrigation when rainfall is absent to replenish modest cool-season turfgrass water use during this time.

As expected, irrigation simulations for warm-season turfgrasses indicate June and July require the greatest supplemental irrigation. For example, there was at least a 43% increase in irrigation demand in Raleigh during June and July compared to other months. In June, simulated irrigation was fairly consistent at all locations outside of Asheville, Boone, and Elizabeth City. During July, mean irrigation varied more compared to June. Specifically, required irrigation ranged from 17 mm in Boone to 55 mm in Charlotte. Data presented in Table 6 shows the fluctuation in required irrigation across turfgrass species and time. The ratio of ER/ET_c shows the percentage of ET_c that has been accounted for by rainfall. For example, mean irrigation requirements for warm-season turfgrass in Wilmington (coastal location) were less than estimated irrigation totals in Asheville (mountain locations) during August and September. The higher ER/ET_c ratio in Wilmington indicates ER accounted for a greater proportion of turfgrass water use compared to Asheville and other locations throughout the state. This is due to increased rainfall from tropical systems that are prevalent on the southeastern coast during late summer. The higher the ER/ET_c ratio, the less irrigation required to replenish turfgrass water use.

Conclusions

A historical meteorological analysis was conducted for eleven locations in North Carolina. Meteorological parameters included maximum and minimum air temperature, maximum and minimum relative humidity, wind, and rainfall. Estimated R_s was calibrated according to standardized procedures and plotted over time to ensure agreement with R_{so}. All data were subjected to quality control procedures prior to ET_{os} calculations.

Annual reference evapotranspiration (ET_{os}) ranged from 1,023 mm yr^{-1} in Boone to 1,362 mm yr^{-1} in Fayetteville. The lowest monthly total ET_{os} measured was 33 mm in December at the Boone location, while the highest was 183 mm in Fayetteville during the month of July. Mean effective rainfall totals ranged from 269 – 344 mm. Only 37% of the total rainfall in Wilmington was estimated to be effective, while rainfall at all other locations was found to be at least 43% effective. Mean net irrigation estimates from May – October ranged from 124 mm in Boone to 305 mm in Fayetteville with variation due to turfgrass, rooting depth, and AWHC. These results provide residents of North Carolina with monthly irrigation estimates that can increase efficiency of landscape irrigation by matching applied irrigation with turfgrass water demands.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Table 1 Monthly crop coefficients, K_c used for irrigation simulations.

Month	Cool-season turf [a]	Warm-season turf
May	0.71	0.44
June	0.83	0.59
July	0.72	0.57
August	0.69	0.53
September	0.83	0.57
October	0.85	0.51

[a] Source (Pinnix and Miller., 2019)

Table 2 Missing meteorological data including air temperature (T), relative humidity (H), solar radiation, wind, and rainfall for eleven locations in North Carolina.

Parameter	Asheville	Boone	Hickory	Charlotte[a]	Greensboro	Raleigh	Fayetteville	Kinston	Lewiston	Elizabeth City	Wilmington
	Percent of Total Parameter Observations (%)										
T_{max}	0.00	1.16	0.02	0.01	0.10	0.00	0.14	0.50	0.11	0.22	0.00
T_{min}	0.00	1.16	0.02	0.01	0.10	0.00	0.14	0.50	0.11	0.22	0.00
Wind	0.00	1.95	0.02	0.01	0.10	0.00	0.02	3.34	0.26	0.25	0.00
H_{max}	0.00	4.45	0.03	5.48	0.10	0.00	0.14	0.54	0.09	0.22	0.02
H_{min}	0.00	4.45	0.03	5.48	0.10	0.00	0.14	0.54	0.09	0.22	0.02
Rainfall	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.58	0.09	0.12	0.00

a Weather data gathered for thirty year period (1984-2013). Due to high missing data for 3-year period (1996-1998), only 27 years were used for irrigation simulation.

Table 3 Daily meteorological data including air temperature (T), relative humidity (H), solar radiation, wind, and rainfall for locations across North Carolina.

	Weather parameters						
Locations	T_{max} (°C)	T_{min} (°C)	H_{max} (%)	H_{min} (%)	Solar Rad. (MJ m^{-2} d^{-1})	Wind (m s^{-1})	Rainfall (mm yr^{-1})
Asheville							
Mean	19.1	7.5	94	47	17.6	2.2	1,186
Max	36.7	22.8	100	100	36.7	9.9	1,911
Min	-13.9	-26.7	36	7	2.2	0.1	676
Boone							
Mean	16.8	6.1	93	50	17.4	2.2	1,250
Max	37.0	24.0	100	100	32.8	12.6	1,740
Min	-10.0	-22.0	32	2	2.6	0.0	744
Hickory							
Mean	20.7	9.4	89	45	17.3	1.5	1,128
Max	40.0	25.6	100	100	34.5	6.2	1,699
Min	-3.3	-16.7	33	1	2.4	0.0	630
Charlotte							
Mean	21.8	10.6	88	45	17.6	2.1	1,060
Max	40.0	26.1	100	100	36.1	7.6	1,592
Min	-6.1	-20.6	17	6	2.7	0.0	667
Greensboro							
Mean	20.5	9.6	88	46	17.4	2.4	1,070
Max	39.4	26.7	100	100	37.1	7.9	1,583
Min	-8.3	-22.2	25	8	2.0	0.0	754
Raleigh							
Mean	21.7	10.1	91	46	17.3	2.2	1,107
Max	40.6	26.7	100	100	34.4	6.7	1,503
Min	-8.9	-21.7	34	8	2.2	0.0	884
Fayetteville							
Mean	23.2	11.4	90	44	17.8	2.4	1,035
Max	41.7	27.8	100	100	33.6	8.1	1,399
Min	-2.2	-13.3	42	8	2.7	0.0	750
Kinston							
Mean	22.4	10.9	92	46	17.7	1.7	1,071
Max	39.1	26.6	100	100	33.3	7.0	1,288
Min	-4.3	-12.5	41	3	4.2	0.0	852
Lewiston							
Mean	21.6	10.1	96	48	17.4	1.7	1,099
Max	39.9	26.2	100	100	34.6	6.7	1,449
Min	-4.8	-18.7	55	10	3.4	0.0	801
Elizabeth City							
Mean	21.5	11.1	93	52	17.0	3.0	1,129
Max	38.3	28.3	100	100	33.8	12.9	1,542
Min	-5.0	-13.9	43	11	2.8	0.1	651
Wilmington							
Mean	23.2	12.4	93	50	17.8	2.6	1,442
Max	39.4	28.9	100	100	34.4	11.4	1,831
Min	-7.2	-17.2	37	10	2.7	0.0	848

Table 4 30-year average monthly reference evapotranspiration (ET_{os}) for locations across North Carolina.

Month	Asheville	Boone	Hickory	Charlotte	Greensboro	Raleigh	Fayetteville	Kinston	Lewiston	Elizabeth City	Wilmington
						ET_{os} (mm m^{-1})					
Jan	43	38	43	47	46	46	53	44	39	48	53
Feb	54	47	55	60	58	58	67	57	53	60	65
Mar	85	75	91	98	94	94	104	91	84	91	101
Apr	116	108	125	129	126	126	139	125	118	122	132
May	141	127	155	155	151	153	169	155	147	152	159
Jun	149	141	169	168	164	166	176	165	159	165	165
Jul	158	136	171	176	172	175	183	166	163	168	175
Aug	137	121	155	153	149	151	161	147	143	149	151
Sept	96	89	106	113	105	108	118	105	100	108	114
Oct	73	62	74	81	78	76	86	73	68	83	87
Nov	51	44	48	55	53	51	61	48	45	56	61
Dec	39	33	36	43	42	41	47	39	35	45	49
Total	1,142	1,023	1,228	1,278	1,237	1,245	1,362	1,213	1,153	1,245	1,312

Table 5 Mean monthly net irrigation requirements for cool- and warm-season grasses at eleven locations in North Carolina.

	Cool-Season						Warm-Season					
Location	May	June	July	Aug	Sep	Oct	May	June	July	Aug	Sep	Oct
	Depth (mm m^{-1})											
Asheville	54	63	55	38	33	28	19	32	35	19	11	5
Boone	59	62	35	13	9	14	27	32	17	0	0	0
Hickory	60	89	57	55	39	27	23	53	35	33	14	4
Charlotte	66	89	79	51	51	30	28	53	55	29	24	5
Greensboro	67	88	68	53	37	32	29	53	45	32	13	7
Raleigh	68	90	65	49	35	29	30	54	43	28	10	5
Fayetteville	84	95	74	47	49	46	42	57	50	25	21	19
Kinston	67	82	62	36	40	29	29	47	40	16	15	6
Lewiston	62	85	53	35	27	23	26	51	32	15	4	1
Elizabeth City	59	74	54	32	39	30	22	40	32	12	14	5
Wilmington	67	83	53	29	25	36	28	48	31	9	0	8

Table 6 Monthly proportion of effective rainfall (ER) to actual evapotranspiration (ET_a) for cool- and warm-season grasses at eleven locations in North Carolina.

	Cool-Season						Warm-Season					
Location	May	June	July	Aug	Sep	Oct	May	June	July	Aug	Sep	Oct
	ER/ET_c											
Asheville	0.46	0.49	0.51	0.60	0.59	0.55	0.69	0.64	0.61	0.64	0.82	0.86
Boone	0.34	0.48	0.64	0.84	0.88	0.72	0.52	0.63	0.79	0.94	1.22	1.17
Hickory	0.45	0.36	0.54	0.49	0.56	0.57	0.66	0.47	0.65	0.55	0.76	0.90
Charlotte	0.40	0.37	0.38	0.52	0.46	0.57	0.59	0.47	0.46	0.56	0.64	0.90
Greensboro	0.38	0.35	0.45	0.49	0.57	0.51	0.56	0.45	0.53	0.52	0.79	0.80
Raleigh	0.38	0.35	0.48	0.53	0.60	0.56	0.55	0.45	0.57	0.56	0.83	0.88
Fayetteville	0.29	0.35	0.43	0.58	0.50	0.37	0.43	0.45	0.52	0.63	0.68	0.57
Kinston	0.39	0.40	0.49	0.65	0.54	0.53	0.57	0.51	0.58	0.70	0.74	0.83
Lewiston	0.40	0.36	0.55	0.64	0.67	0.61	0.59	0.46	0.66	0.69	0.93	0.98
Elizabeth City	0.44	0.46	0.55	0.68	0.57	0.57	0.66	0.59	0.66	0.75	0.78	0.87
Wilmington	0.41	0.39	0.58	0.72	0.73	0.51	0.60	0.50	0.69	0.77	1.00	0.81

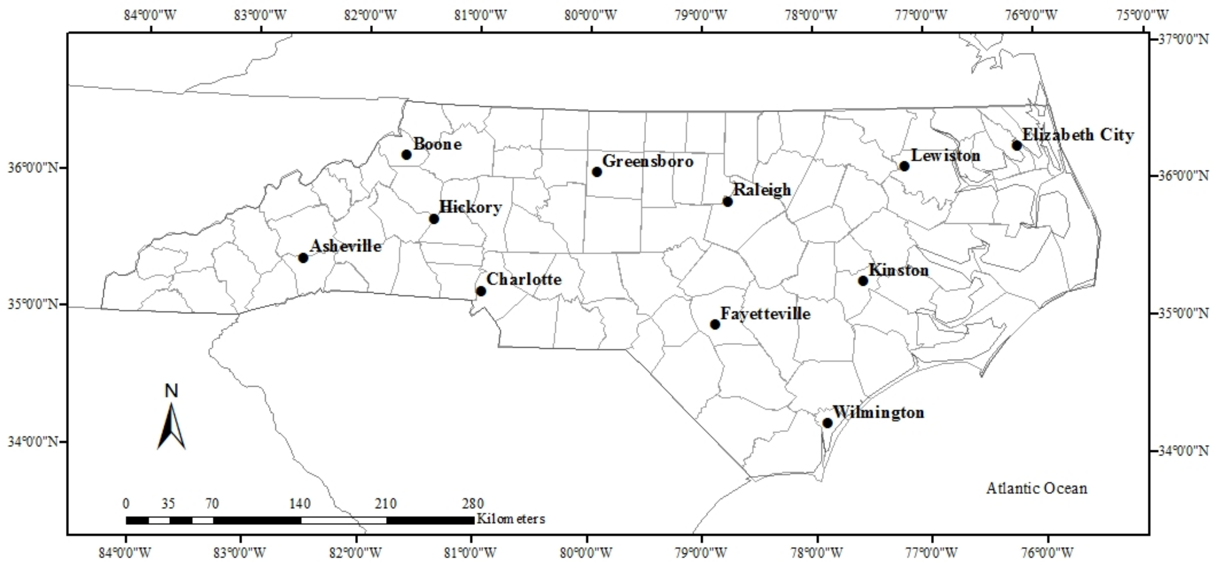

Figure 1. Eleven locations in North Carolina where historical weather data was analyzed.

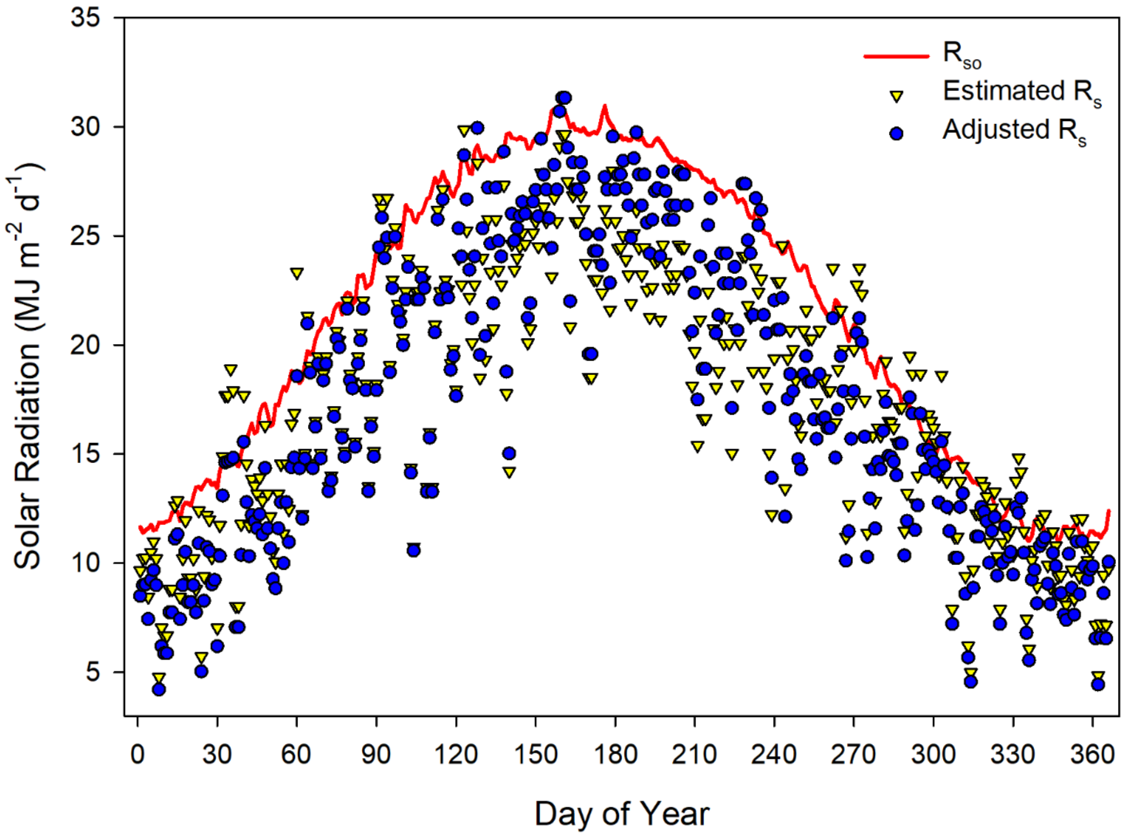

Figure 2. Estimated and adjusted solar radiation (R_s) plotted against the clear sky solar radiation curve (R_{so}) for one year in Raleigh, NC. Estimated R_s was the result of the Hargreaves and Samani equation (1985) and a constant K_r = 0.18 while adjusted R_s was the result of calibration procedures detailed by the ASCE Standardized Reference Evapotranspiration Equation (2005).

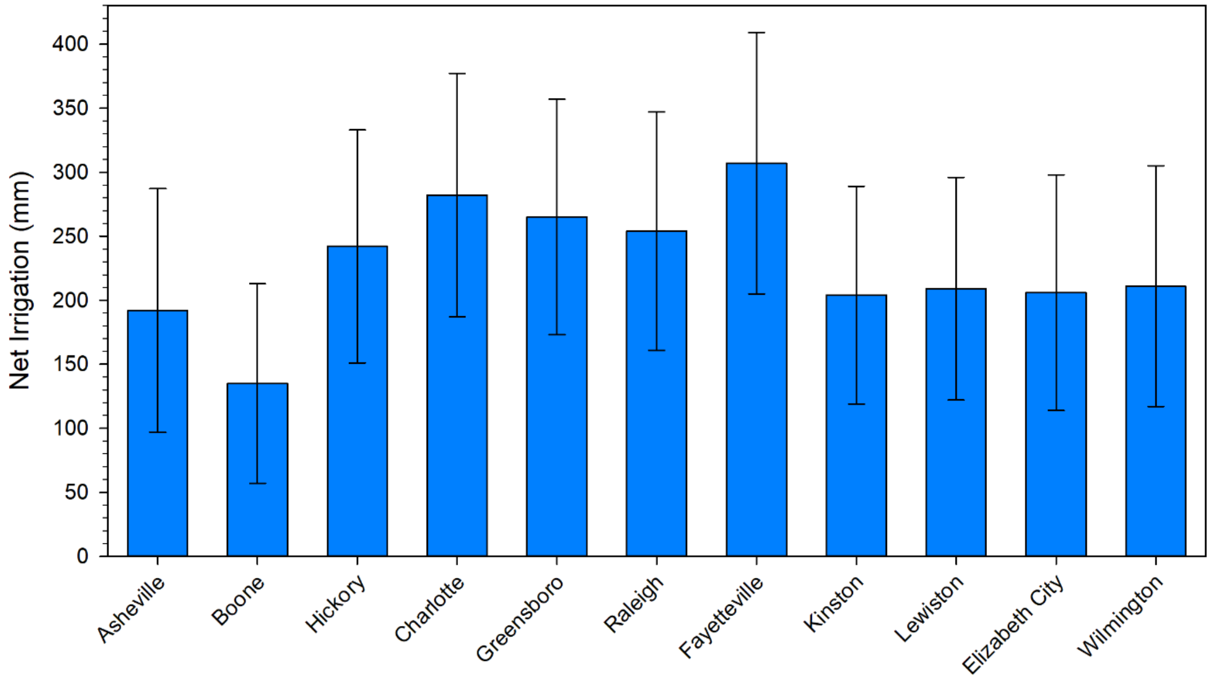

Figure 3. Estimated irrigation requirements (May-October) for eleven locations in North Carolina. Error bars represent one standard deviation due to variation in grasses (cool and warm), root zones (15 cm and 30 cm), and available water holding capacities that ranged from 3-18% across locations.

CHAPTER 3: COMPARING EVAPOTRANSPIRATION RATES OF TALL FESCUE AND BERMUDAGRASS IN NORTH CAROLINA

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Abstract

Increasing water conservation efforts across landscapes necessitate the establishment of turfgrasses that require less water to sustain functionality. Therefore, it is important to consider concurrent water use potential of popular grass species such as tall fescue (*Festuca arundinacea* Schreb.) and hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt-Davy]. The primary objective of this field study was to compare water use characteristics of 'TifTuf' a recently released bermudagrass cultivar with reported drought tolerance with a commonly planted tall fescue/bluegrass mix in North Carolina. A secondary objective was to quantify minimum irrigation requirements during establishment from sod when planted during spring and summer. Direct measurements of actual evapotranspiration (ET_a) were made through weighing of non-water stressed lysimeters planted with 'Triple Threat' tall fescue and TifTuf hybrid bermudagrass. Actual evapotranspiration rates during the first 14 days after planting (DAP) were 3.3 and 4.3 mm d^{-1} for bermudagrass and tall fescue, respectively, averaged across spring plantings. Tall fescue ET_a 14 DAP was no different during summer establishment, while bermudagrass ET_a increased to 4.3 mm d^{-1}. After 14 DAP, cumulative bermudagrass ET_a was 44% less than tall fescue when established in spring. Cumulative bermudagrass ET_a was similar to tall fescue (3% less) following summer establishment. Both grasses provided acceptable turf quality (TQ $\geq$ 6), when planted during spring, unlike tall fescue which resulted in unacceptable TQ following summer establishment. Results indicate the use of TifTuf bermudagrass can provide acceptable quality in the landscape while significantly reducing turfgrass water use compared to Triple Threat tall fescue when adapted to localized conditions.

Keywords: water; crop-coefficient; transition zone; irrigation; turfgrass; landscape

1. Introduction

Appropriate turfgrass selection is required to ensure functionality and survivability in the landscape. Air temperature, sunlight, rainfall, and other abiotic factors greatly affect the adaptability of turfgrasses across various environments. In the United States, the influence of these factors help define the three primary regions of turfgrass adaptation: the northern-cool region, the southern-warm region, and the transition zone. Furthermore, the northern-cool and southern-warm regions are often subdivided into arid and humid regions (Emmons, 2000; Fry and Huang, 2004; Turgeon, 2008). The cool-season grasses are best adapted to the northern-cool region while the warm-season grasses are most adapted to the southern-warm region. Between these two regions is the transition zone, defined as the 300-700 mile north to south area where the use of cool- and warm-season grasses overlap (Dunn and Diesburg, 2004). Due to lack of adaptation of a single turfgrass, careful consideration must be given when selecting a turfgrass in the transition zone based upon local environmental conditions.

North Carolina is geographically considered part of the transition zone and as a result, turfgrass managers often manage both cool- and warm-season grasses. The most recent comprehensive survey conducted in North Carolina indicated that 63% of single-family dwellings maintained a cool-season grass, while 37% maintained warm-season grass (NCDA, 1999). Tall fescue (*Festuca arundinacea* Schreb.) is overwhelmingly the most common lawn grass in North Carolina as it comprises 58% of North Carolina lawns. The improved drought and heat tolerance among the cool-season grasses in addition to maintaining year-round green color makes tall fescue an attractive choice for homeowners in the transition zone (Miller et al., 2016). Bermudagrass (*Cynodon sp.*) is a widely used warm-season grass that ranks second among North Carolina warm-season lawn grasses. The superior drought tolerance, ability to establish quickly, withstand wear, and recover quickly from injury encourages the use of bermudagrass. However, in order for grasses to remain functional in the landscape, inputs such as water supplied through supplemental irrigation are required during periods of extended stress.

The conservation of potable water continues to be a primary concern for many municipalities and water purveyors around the world. Landscape irrigation is often part of this concern as it has been reported that the majority of the 16 million ha of turfgrass in the United States is irrigated to some extent, which is three times the area of any other crop (Milesi et al., 2005). Mayer et al. (1999) reported that outdoor water use ranged from 22-67% of the total household water consumed throughout the US and Canada. Results from a study conducted in Florida indicated that 64% of household water use was dedicated to irrigation (Haley et al., 2007). In effort to reduce water consumption through landscape irrigation, some local governments have enacted ordinances restricting outdoor watering (Nautiyal et al., 2015). In addition to watering restrictions, some have offered incentives to install plants that are considered 'water-wise' (TOC, 2008). Specific to lawn grasses in the transition zone, this usually requires the substitution of a cool-season grass with a warm-season grass that may not be adapted to localized stresses. Although many use characteristics must be considered when selecting a turfgrass for use in the transition zone, it is imperative to consider water use potential of available turfgrasses as water conservation efforts continue.

Measured evapotranspiration (ET_a) rates under non-limiting soil moisture conditions are routinely used to define water use requirements for turfgrasses. Previous research has found that tall fescue ET_a rates range from 3.0 – 9.7 mm d^{-1} in arid and greenhouse environments (Kopec et al., 1988; Bowman and Macaulay, 1991). During field studies conducted in Griffin, GA, tall fescue ET rates were much lower ranging from 2.7 – 6.1 mm d^{-1} (Carrow, 1995; Carrow 1996).

The substantially lower ET_a rates are most likely due to differing measurement methodology, environmental conditions, and available moisture in which the measurements were collected. Studies quantifying bermudagrass ET found use rates are generally lower and fluctuate less (Kim and Beard, 1988; Carrow, 1995; Wherley et al., 2015; Amgain et al., 2018). Specifically, bermudagrass ET_a ranged from 2 – 6 mm d^{-1} in studies conducted in Texas, Georgia, Florida, and Oklahoma. The lower use rates were measured during winter months in Florida when seasonal bermudagrass growth is slow. During summer months when irrigation is more likely, ET_a rates typically ranged from 4 – 6 mm d^{-1}. Differences in tall fescue and bermudagrass ET_a have been noted during studies that included both grass species (Biran et al., 1981; Kneebone and Pepper, 1992; Qian et al., 1996). Tall fescue ET_a rates were measured to be on average 35 – 41% greater than bermudagrass. Furthermore, Carrow (1995) found tall fescue ET_a rates to be 15% greater than bermudagrass during a two-year study in Griffin, GA.

In order to ensure successful turfgrass establishment and survivability, many factors must be considered. The selection process becomes more challenging in the transition zone as both cool- and warm-season grasses experience elevated stress at various times annually. In order to best conserve water reserves, turf managers must consider turfgrasses that use less water. Many of the new turfgrasses available today have been developed to better tolerate drought conditions. In 2016, the University of Georgia released 'TifTuf' bermudagrass after extensive testing revealed exceptional drought tolerance suggesting enhanced adaptability in the landscape (Schwartz et al., 2018). In North Carolina, where tall fescue remains to be the most popular lawn grass, testing is needed to determine the water conservation potential by establishing turfgrasses such as TifTuf. The primary objective of this field study was to compare water use potential of TifTuf bermudagrass with a commonly used tall fescue/bluegrass mix in North Carolina. A secondary objective was to quantify minimum irrigation requirements during the establishment of both grasses from sod when planted during the spring and summer.

2. Materials and Methods

2.1 Lysimeter Establishment and Management

Turfgrass water use measurements were collected from May through October during 2017 and 2018 at the Lake Wheeler Turfgrass Field Laboratory in Raleigh, NC. Field lysimeters were constructed from 25.4-cm diameter Schedule 40 polyvinyl chloride (PVC) pipe cut to 33 cm lengths. Steel rods were inserted through the wall of the PVC pipe to support 6 mm PVC foam board bottom plate recessed 2.54 cm from the bottom of PVC pipe, resulting in an effective lysimeter depth of 30.5 cm and 15,444 cm^3 volume. Four 1.75 cm holes were threaded into the bottom PVC foam board allowing for drainage during the establishment of field capacity. Lysimeter bottom plates were also lined with geotextile fabric to prevent media loss through drainage holes. During active measurement, holes were plugged with 2.54 cm plugs to prevent water loss to drainage. Experimental lysimeters were filled with Profile Greens Grade porous ceramic soil amendment (Profile Porous Ceramic Greens Grade, Buffalo Grove, IL) and established with washed ‘Triple Threat’ tall fescue (*Festuca arundinacea* Schreb.) and ‘TifTuf’ hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt-Davy] sod measuring 510 cm^2 during May and July of 2017 and 2018 with four replications. After planting, lysimeters were inserted into in-ground plastic sleeves, which were installed to prevent native soil adherence to lysimeter outer walls. In-ground holes were also lined with rock below lysimeters to allow for drainage of excess water. Complete instructions detailing lysimeter construction can be found in a published manuscript by Wherley et al. (2009).

Lysimeters were maintained at 10.2 and 5.1 cm mowing heights for tall fescue and bermudagrass, respectively, using a Honda HRX217HZA walk-behind mower (Honda Power Equipment, Alpharetta, GA) with clippings returned. A starter fertilizer (SiteOne Landscape Supply, Roswell, GA) containing 18% N – 24% P_2O_5 – 12% K_2O was applied based on a P_2O_5 rate of 24.5 kg ha^{-1} during each lysimeter planting. Following planting, monthly fertility was applied to all lysimeters at N rates of 24.5 and 49 kg ha^{-1} depending on species and month. Tall fescue lysimeters received 49 kg N rates during May, September, and October while bermudagrass received 49 kg N rates during June, July, and August. A sulfur coated urea fertilizer (Reed & Perrine Sales, Tennent, NJ) containing micronutrients and an analysis of 25% N - 5% P_2O_5 – 10% K_2O was used for all monthly fertilizer applications. Preventative fungicide applications were made every 21 days from June through September to control brown patch (*Rhizoctonia solani*) and gray leaf spot (*Pyricularia grisea*) in tall fescue with axozystrobin at 0.6 kg a.i. ha^{-1}. All management practices were selected based upon recommendations detailed in Carolina Lawns (Miller et al., 2016).

2.2 Measurement of Actual and Reference Evapotranspiration

Lysimeters were housed underneath a portable rainout shelter (Four Season Tools, Kansas City, MO) to prevent rainfall interference allowing for continuous measurements. Managed vegetation surrounding lysimeters were identical to experimental lysimeters. Specifically, lysimeters planted with TifTuf, were surrounded by established TifTuf hybrid bermudagrass, while Triple Threat lysimeters were surrounded by established tall fescue resulting in a homogenous surface. The managed turfgrass area surrounding experimental lysimeters was hand-watered to prevent water stress, thus preventing micro-advective interference.

An S-Beam load cell (CAS S-Beam, NTEP CoC 96-073A1, East Rutherford, NJ) powered by a digital indicator (Salter Brecknell 200 SL, Salter Brecknell Weighing Products, Fairmont, MN) mounted to a tripod hoist (Cabela's Inc, Springfield, MO) was used to quantify turfgrass water use during all weighing events. Measurements of actual evapotranspiration (ET_a) were made daily from the initial plant date until 14 days after planting (DAP) between 0600 and 0800 hours during all establishment periods. Following 14 DAP, ET_a measurements were collected every 48 to 72 hrs until October of both years. In order to maintain adequate moisture while turfgrass sod began root establishment, water applied to all lysimeters during the first week of active measurement varied following each individual planting given the environmental conditions that were present. Following spring lysimeter establishment, water was added at increments of 3 mm up to 3 times daily (0800, 1200, and 1600 hours), resulting in a maximum daily total of 9 mm. Applied water depth was increased during summer establishment to 4 mm per application with the daily maximum equaling 12 mm. The number of applications were determined by the environmental conditions present each day with daily water depth totals found in Table 1. After the first week, water added was determined by turfgrass water use during the previous weighing interval. The corresponding mass was recorded for each lysimeter at planting. The difference in mass the following weigh event, plus water added was the result of ET_a. After the first month of data collection, lysimeters were saturated and allowed to drain for a period of 24 hours to establish field capacity. For the remainder of water use measurements, lysimeters were maintained at field capacity to maintain well-watered, non-stressed conditions throughout the study.

Meteorological data required for reference evapotranspiration (ET_o) calculation was collected at 30 min intervals by an on-site HOBO Micro Weather Station Data Logger (Onset

Corporation, Bourne, MA). Reference evapotranspiration was determined by the ASCE-EWRI Standardized Method for short grass canopies using the following equation (Allen et al., 2005):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_o is short grass reference crop evapotranspiration (mm d^{-1}), R_n is net radiation (MJ m^{-2} d^{-1}), G is soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), T is mean air temperature (°C), u_2 is wind speed (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}), and γ is the psychometric constant (kPa °C^{-1}). Turfgrass crop coefficients (K_c) were derived for each grass by dividing ET_a by ET_o during weeks two and three to identify irrigation required during grow-in.

2.3 Visual Turfgrass Quality Ratings

In addition to turfgrass water use measurements, turfgrass quality ratings were made every two weeks beginning one month after planting according to guidelines established by the National Turfgrass Evaluation Program (NTEP) using a 1-9 scale (1 = brown, low-quality turf, 9 = green, high-quality) (Morris and Shearman,1998). Turf quality ratings ≥ 6 were considered minimally acceptable.

2.4 Statistical Analysis

Statistical analyses for water use measurements and turf quality data were performed using Statistical Analysis System (version 9.4, 2013; SAS Institute Inc., Cary, NC). Experimental lysimeters were arranged in a RCBD and data subjected to ANOVA to determine treatment effects using the PROC MIXED procedure. Fixed and random effects were assigned based upon guidelines presented by Vargas et al. (2018). Significant interactions were identified and subjected to Fisher’s Protected LSD test at the 0.05 probability level.

3. Results and Discussion

3.1 Meteorological Conditions

Meteorological data collected throughout the study can be found in Table 2. Minimum air temperature ranged from 2.1 to 17.3°C during the two-year study. In May and October, nightly air temperatures were reduced closer to 4.4°C. However, minimum air temperature was nearly 5 degrees warmer in May 2018 compared to 2017. Maximum air temperature fluctuated much less compared to minimum air temperatures. During both years of data collection, maximum air temperature was < 32°C only once (October, 2017). Maximum air temperature had greater variation during 2017, with values ranging from 30.7 - 37.1°C. Relative humidity averages remained consistent throughout. September 2018 relative humidity was highest (80.1%) due to excess moisture as the result of two tropical weather events. As expected, incoming solar radiation was greatest during the summer months and was reduced during May, September, and October.

3.2 Initial Turfgrass ET_a Following Planting

Within 14 DAP, tall fescue and bermudagrass ET_a varied during spring and summer plantings across both years of the study ($P < 0.001$) (Fig 1). In 2017, tall fescue ET_a ranged from 1.0 – 8.0 mm d^{-1} following spring planting and from 3.4 – 7.3 mm d^{-1} following summer establishment. Bermudagrass ET_a ranged from 0.4 – 5.3 mm d^{-1} and 2.9 – 5.4 mm d^{-1} during spring and summer plantings, respectively in 2017. During spring of 2018, minimum ET_a for both tall fescue and bermudagrass was 1.4 mm d^{-1}. Maximum ET_a measured was 5.3 and 4.8 mm d^{-1} for tall fescue and bermudagrass, respectively. Tall fescue and bermudagrass ET_a was similar following the 2018 summer planting with ranges of 1.9 – 6.5 mm d^{-1} and 1.4 – 5.9 mm d^{-1}. On average, tall fescue used 30% more (4.3 vs 3.3 mm d^{-1}) water than bermudagrass during the 14

DAP when established in May. However, averaged water use was not different between the two grasses when established in July (both averaged 4.3 mm d^{-1}). Differences in daily turfgrass water use following establishment in May 2017 were more frequent compared to 2018 as 8 out of 14 days indicated significant differences in turfgrass ET_a. Similar results occurred following summer establishment in 2017 and 2018 (8 and 5 days, respectively). As expected, turfgrass water use for all plantings was heavily influenced by environmental conditions. Lower ET_o measured 1 and 3 DAP during spring 2017 resulted in lower ET_a for both grasses (Fig 1). Overall, ET_a was rarely ≥ 6 mm d^{-1} for either grass, regardless of ET_o due to lack of rooting and subsequent lower transpirational water loss. Unlike bermudagrass, increases in tall fescue ET_a were not measured following both summer plantings. This was likely due to the elevated heat stress experienced by the cool-season turf resulting in greater water conservation through the closing of plant stomata (Fry and Huang, 2004).

3.3 Turfgrass Crop Coefficients (K_c) Following Planting

Crop coefficients were derived for tall fescue and bermudagrass during the second and third weeks following planting. Turfgrass crop coefficients were not determined during wk 1 as the result of watering to ensure adequate moisture (rather than according to turfgrass ET_a) during new root development. Derived K_c for tall fescue and bermudagrass was lower than previously reported values as the result of a less developed root system (Carrow, 1995). When established in May, averaged turfgrass K_c was 0.65 and 0.51 for tall fescue and bermudagrass, respectively. During July establishment, bermudagrass K_c dropped to 0.48, while tall fescue K_c was reduced by 32% to 0.44. Irrigation amounts are often in excess during turfgrass establishment in order to prevent stress. This is particularly true for cool-season grasses that are established in stress inducing conditions, similar to conditions present during July in the transition zone. Although water was applied based upon previous day use, tall fescue continued to conserve water following July establishment, unlike bermudagrass. Furthermore, results indicated that irrigation amounts immediately following planting in May can be reduced without inducing water stress in the transition zone. Specifically, scheduling irrigation based upon a percentage of ET_o for both tall fescue (0.65) and bermudagrass (0.51) can be an effective way to conserve potable water during the second and third week after turfgrass establishment. In the subsequent weeks following summer bermudagrass establishment, irrigating to 0.48 of ET_o can be implemented in effort to conserve water.

3.4 Seasonal Turfgrass ET_a

Water use was consistently different among the two grasses resulting in significance of the highest order date(year × planting × species) nested term ($P < 0.001$). Therefore, interspecific differences among species were measured over short time periods. As a result, ET_a was averaged for monthly use during both years of the study. Tall fescue water use ranged from 3.0 – 7.8 mm d^{-1} when established in spring (Table 3). Measured tall fescue ET_a was lower compared to previous trials (Kopec et al., 1988; Bowman and Macaulay, 1991). Humid conditions experienced in the lower transition zone likely contributed to lower ET_a. Lower water use rates were consistently measured during October of both years. Furthermore, a major difference in tall fescue ET_a was measured during May 2017 compared to May 2018. Tall fescue ET_a was much lower in 2018 (3.3 mm d^{-1}) compared to 2017 (6.1 mm d^{-1}), while bermudagrass ET_a remained consistent. In 2017, tall fescue used 53% more water compared to bermudagrass, while in 2018, tall fescue ET_a was 13% less. Warmer air temperatures in late May 2018 limited ideal growing conditions for tall fescue and as a result, ET_a was reduced for tall fescue while bermudagrass was unaffected. Spring established tall fescue used the most water during June and

July both years. In 2017, tall fescue water use peaked in July at 7.4 mm d^{-1} while in 2018, the highest measured water use of 7.8 mm d^{-1} occurred in June. During these two months, tall fescue ET_a was 51 and 42% higher than bermudagrass, respectively. Spring established bermudagrass was much more consistent across years. Bermudagrass ET_a ranged from 1.9 mm d^{-1} in October 2017 to 5.5 mm d^{-1} in June 2018, consistent with ET_a measured in previous studies (Kim and Beard, 1988; Carrow, 1995; Wherley et al., 2015; Amgain et al., 2018).

Trends in turfgrass ET_a were varied when established during the summer (Table 3). Tall fescue ET_a was much lower following establishment in July, compared to May. During the months following summer establishment, tall fescue water use ranged from 2.1 mm d^{-1} in July 2018 to 5.0 mm d^{-1} in September 2017 over the two years of study. When comparing summer established tall fescue ET_a to that of tall fescue planted in the spring, water use was reduced by 65, 27, 17, and 6% from July-October, respectively. This reduction was likely due to reduced root development as the result of increased heat stress during the first two months following the summer planting of tall fescue sod. By October, tall fescue water use was similar for both spring and summer established sod as cooler temperatures in September and October promoted recovery of summer established tall fescue. Conversely, bermudagrass ET_a was consistent with the exception of July. Summer established bermudagrass used 16 and 30% less water in July 2017 and 2018, respectively, compared to bermudagrass planted during the spring of both years. This can be attributed to a less developed root system resulting in lower water use. However, one month following planting (August), summer established bermudagrass ET_a was no different compared to bermudagrass established in spring. The ability to better tolerate heat during the summer allowed for adequate bermudagrass root development and subsequent establishment.

3.5 Cumulative Tall Fescue and Bermudagrass ET_a

Cumulative ET_a of tall fescue and bermudagrass maintained under non-limiting soil moisture was summarized from May-October in 2017 and 2018. Data indicated spring established tall fescue required 44% more water than bermudagrass when averaged across both years of study (Fig 2). Specifically, consumptive water use of tall fescue was 30 and 22 cm more than bermudagrass during 2017 and 2018, respectively. In a Manhattan, KS study, researchers found tall fescue water use rates to be 35% greater than bermudagrass. Similar differences were found in two studies conducted in desert-like, arid conditions (Kneebone and Pepper, 1992; Qian et al., 1996). Data collected during this field study indicated a larger discrepancy in water use, suggesting greater water saving potential with newer bermudagrass cultivars. Although a shorter measurement period, differences in cumulative tall fescue and bermudagrass ET_a were less when planted during summer. In 2017, tall fescue better recovered from heat stress experienced during July establishment compared to 2018 as evidenced by the increased water use in September and October (Fig 2). Cumulative water use among the two grasses in 2018 was identical following July establishment.

To bring potential cost savings into perspective, monthly water rate fees were referenced from the Town of Cary (TOC), North Carolina. The TOC has a tiered rate structure for single-family residential properties that charge $6.85 USD per 3,785 L up to 56,781 L. For monthly use volumes exceeding 56,781 L, the rate per 3,785 L increases to $12.94 USD. Based upon measured monthly turfgrass ET_a and historical effective rainfall data for the TOC, cumulative irrigation usage and associated costs can be found in Fig 3. Data indicated irrigating a 716 m^2 tall fescue lawn from May-October requires 464,589 L of water accounting for a total cost of $1,437.19 USD in order to replace water lost to evapotranspiration. Bermudagrass required

272,949 L of irrigation that totaled $727.42 USD, nearly half the cost of irrigating tall fescue. Depending on adaptability and level of irrigation management, considerable water and monetary savings can be achieved when managing bermudagrass in place of tall fescue in the transition zone.

3.6 Turfgrass Quality

Visual turfgrass quality ratings were also collected throughout water use measurements. Lysimeters were maintained to prevent stress, therefore, spring established turf quality was rated above the minimally acceptable value of 6 during all rating dates for both grasses (Fig 4). Bermudagrass quality was rated higher than tall fescue during all months. Bermudagrass quality remained static throughout evaluations as monthly averaged quality ratings failed to fall below 8. Similar to bermudagrass, tall fescue quality varied little with ratings ranging between 7 and 8 from June-October. When established during summer, tall fescue quality ratings failed to reach an acceptable level (Fig 5). Bermudagrass quality was rated at least 43% higher than tall fescue from August – October for all summer established lysimeters. Growth patterns of the two turfgrass species provide explanation for differences in turf quality since majority of data collection occurred during summer favoring bermudagrass growth (Christians, 2004). Research completed by Peacock (2001) indicated that tall fescue sod required at least 70 mm cumulative irrigation one week after planting during the summer in order to maintain a minimally acceptable turf quality of 6. During the first week after 2017 and 2018 summer plantings, we applied 84 and 72 mm of irrigation, respectively, and failed to maintain acceptable tall fescue quality. Similar environmental conditions were present during both studies, however, the 2001 trial had additional rainfall to supplement the 70 mm irrigation.

4. Conclusions

This two-year field study was completed to evaluate the water conservation potential of TifTuf bermudagrass compared to Triple Threat tall fescue when managed in the transition zone. Results indicated that maintaining TifTuf can potentially conserve up to 30 cm of irrigation over a six month period compared to tall fescue when managed under non-limiting soil moisture conditions. Immediately following planting (14 DAP), tall fescue required 30% more water than bermudagrass when planted in spring. However, water use rates following summer establishment were similar for both grasses due to water conservation strategies employed by tall fescue while experiencing heat stress. These strategies also resulted in unacceptable turf quality. During the subsequent weeks following planting, scheduling irrigation as a percentage of ET_o can be an effective way to conserve water during establishment. Tall fescue K_c during the second and third weeks following spring planting was determined to be 0.65 while bermudagrass K_c was ~0.5 following both spring and summer plantings. Although applied irrigation matched turfgrass water use, tall fescue was unable to maintain minimally acceptable turf quality when established during the summer. When planted in the spring, both tall fescue and bermudagrass were able to maintain acceptable turf quality.

TifTuf bermudagrass water use from May – October was lower compared to Triple Threat tall fescue in North Carolina demonstrating its water saving potential in the transition zone. Using less water and the ability to maintain functionality during periods of heat stress, make TifTuf an attractive option in the landscape. However, there are often limitations to bermudagrass use in the landscape, most notably in areas with extensive shade. Therefore, much consideration should occur to determine turfgrass adaptability to localized environments prior to establishment. When landscape microclimates are conducive for bermudagrass growth, the use of new cultivars like TifTuf can be an effective way to conserve potable water as a result of decreased irrigation.

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Table 1 Water supplied to each lysimeter during both Spring and Summer establishment periods in 2017 and 2018.

DAP[a]	2017		2018	
	Spring[b]	Summer	Spring	Summer
	mm d^{-1}			
0	9	12	6	12
1	9	12	6	12
2	6	12	6	12
3	3	12	6	8
4	0	12	9	4
5	6	12	9	12
6	9	12	9	12
7	9	12	9	12
> 7	Re-supply water used during previous weighing interval.			

a. DAP, Days after planting.
b. Spring (May 9, 2017 and May 8, 2018); Summer (July 10, 2017 and July 3, 2018)

Table 2 Meteorological data collected from May through October 2017 and 2018. Data are averages unless otherwise noted.

Year	Month	Temp (min)	Temp (max)	Relative Humidity	Solar Radiation	Wind Speed	Dew Point
		°C	°C	%	w/m^2	m/s^{-1}	°C
2017	May	6.9	32.8	74.1	244.8	1.3	15.4
	June	13.0	32.9	75.7	265.0	0.9	18.8
	July	15.1	37.1	75.9	269.3	0.9	21.7
	Aug	15.2	35.3	77.4	215.1	0.8	20.6
	Sep	11.6	33.8	77.7	192.4	0.8	17.7
	Oct	3.3	30.7	79.6	158.2	0.7	13.6
2018	May	11.5	34.2	75.9	232.6	0.8	19.8
	June	17.3	36.2	69.6	269.2	0.8	20.6
	July	15.4	36.1	72.2	256.4	0.7	20.9
	Aug	14.7	35	76.8	241.5	0.7	21.8
	Sep	16.9	35.1	80.1	189.6	0.4	21.5
	Oct	2.1	33.6	77.2	149.9	0.6	15.8

Table 3 Monthly turfgrass evapotranspiration rates following spring and summer plantings. Water use rates are averaged over all weighing events for respective months during a two-year field study in Raleigh, NC.

		Spring Establishment[a]			Summer Establishment		
		Bermudagrass	Tall Fescue	LSD	Bermudagrass	Tall Fescue	LSD
		—— $mm\ d^{-1}$ ——			—— $mm\ d^{-1}$ ——		
2017	May	4.0	6.1	2.0	-	-	-
	June	4.7	6.9	0.5	-	-	-
	July	4.9	7.4	0.4	4.1	2.8	0.3
	Aug	3.9	5.8	0.4	3.8	4.4	0.4
	Sep	3.8	5.7	0.5	3.4	5.0	0.3
	Oct	1.9	3.0	0.2	1.8	3.1	0.3
2018	May	3.8	3.3	0.7	-	-	-
	June	5.5	7.8	0.9	-	-	-
	July	4.7	6.6	0.4	3.3	2.1	0.3
	Aug	4.2	5.8	0.6	4.5	4.1	0.6
	Sep	3.2	4.5	0.4	3.3	3.5	0.4
	Oct	2.2	3.7	0.4	2.1	3.1	0.4

a. Spring (May 9, 2017 and May 8, 2018); Summer (July 10, 2017 and July 3, 2018)

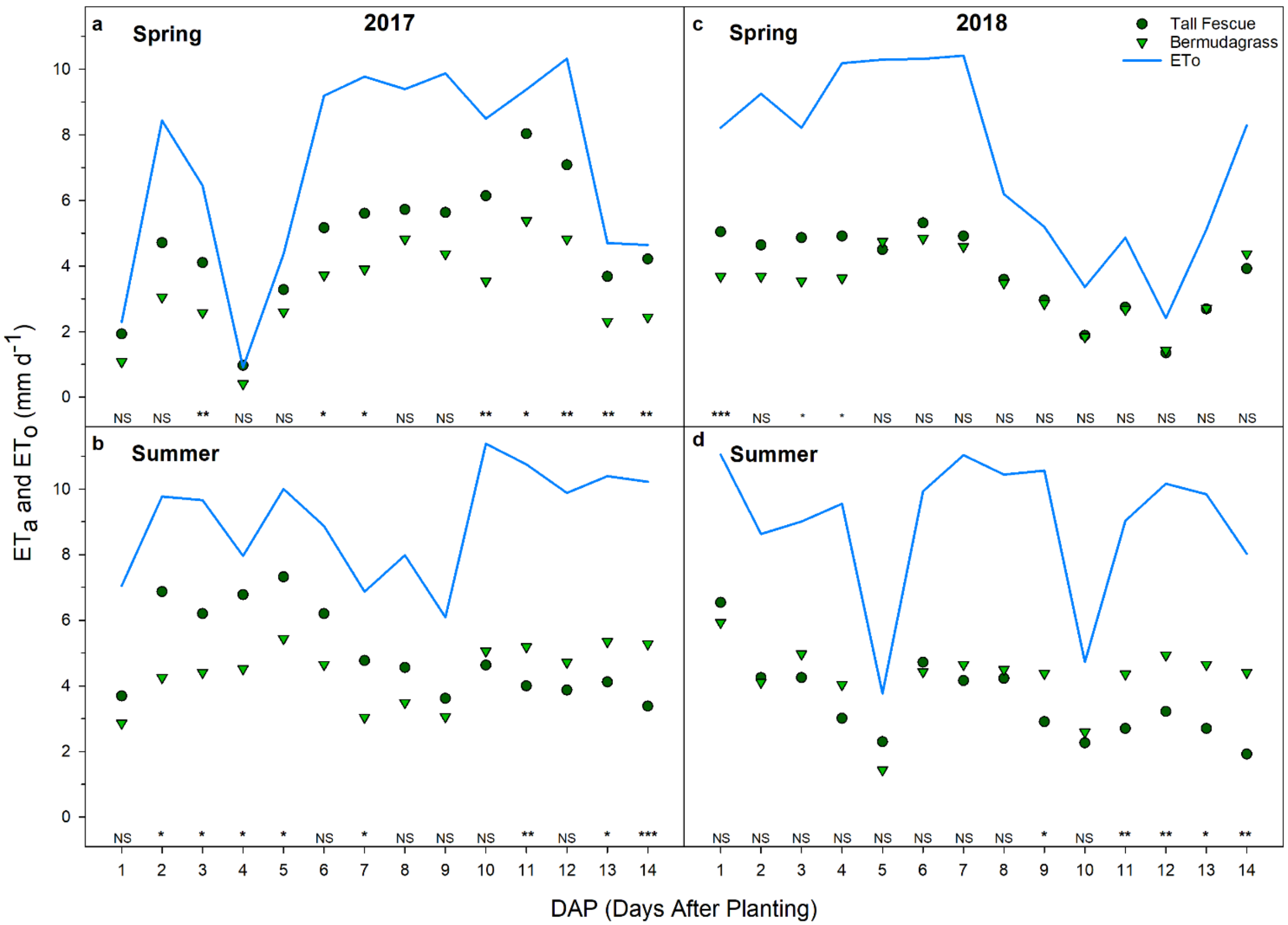

Figure 1. Turfgrass evapotranspiration immediately following spring (a and c) and summer (b and d) plantings during 2017 and 2018. *, **, and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. NS indicates no significance at P = 0.05.

Figure 2. Cumulative turfgrass evapotranspiration from May – October following spring (a and c) and summer (b and d) establishments in 2017 and 2018.

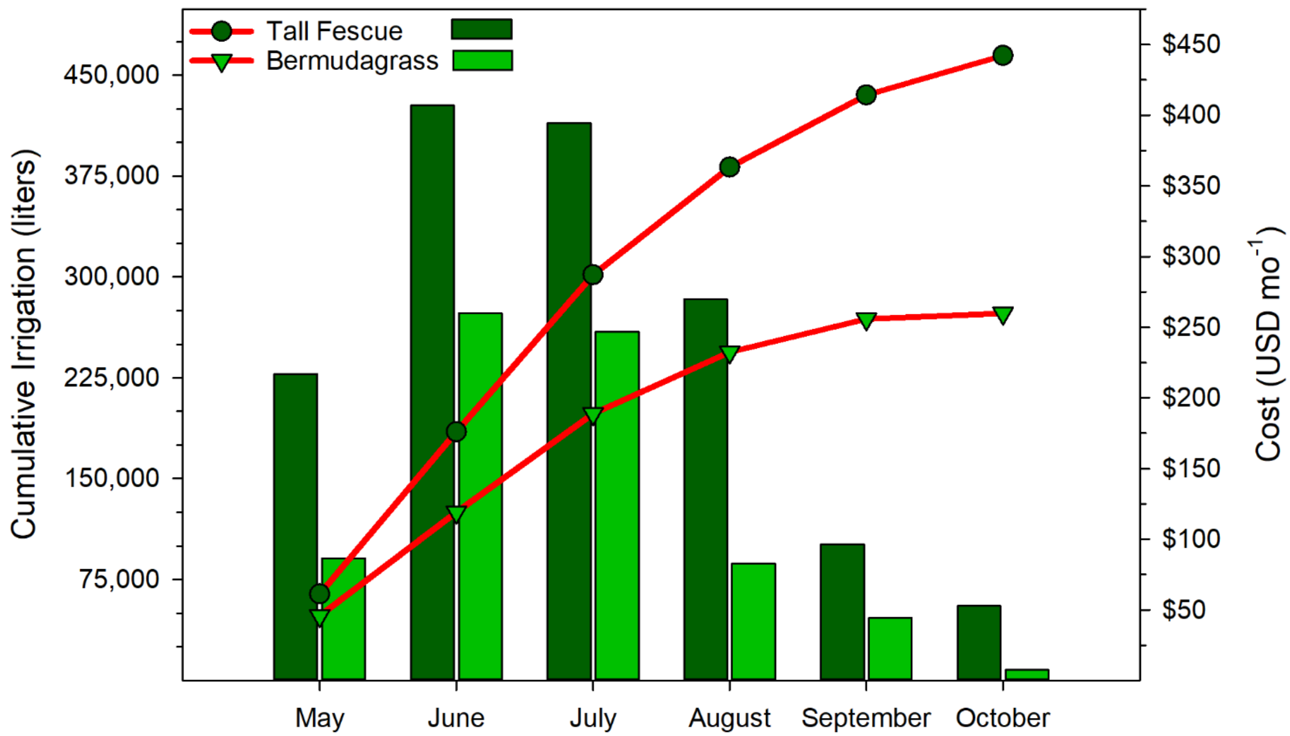

Figure 3. Cumulative turfgrass water requirements and price comparisons based upon water rate fees referenced from the Town of Cary, North Carolina. Line graph denotes cumulative irrigation amounts (L) required for a 716 m^2 (average TOC lawn) lawn while bars represent monthly cost (USD) comparisons when irrigating to replace water lost to evapotranspiration minus effective rainfall.

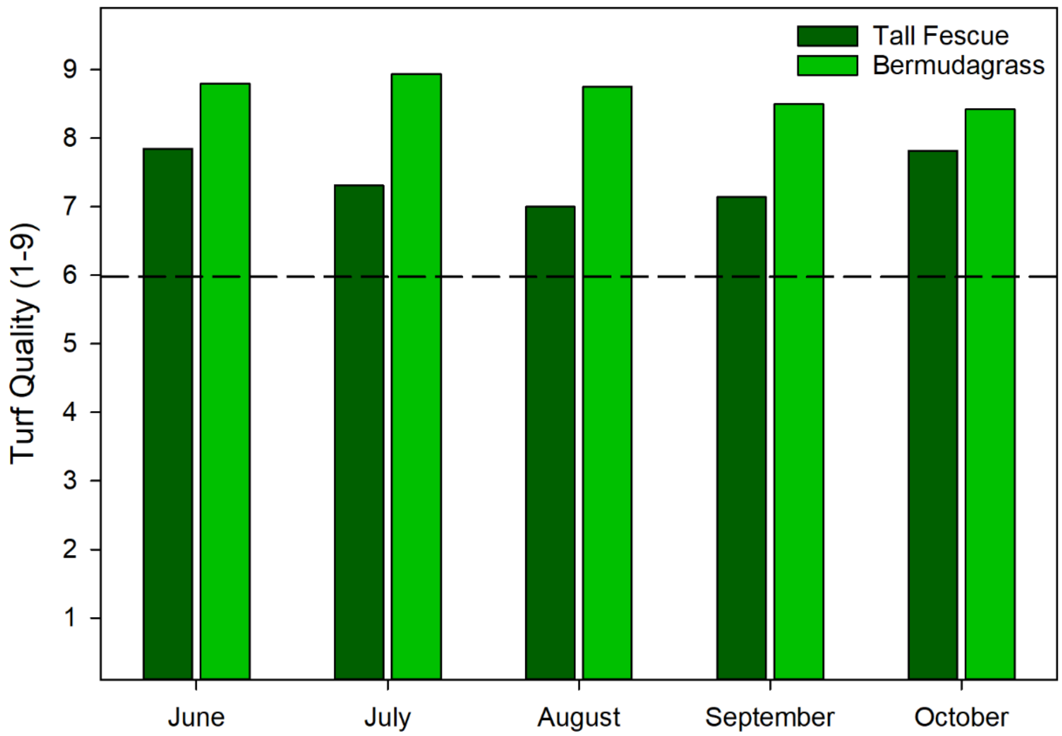

Figure 4. Turfgrass quality ratings averaged over month and year following spring establishment in 2017 and 2018. Horizontal line denotes minimally acceptable turf quality.

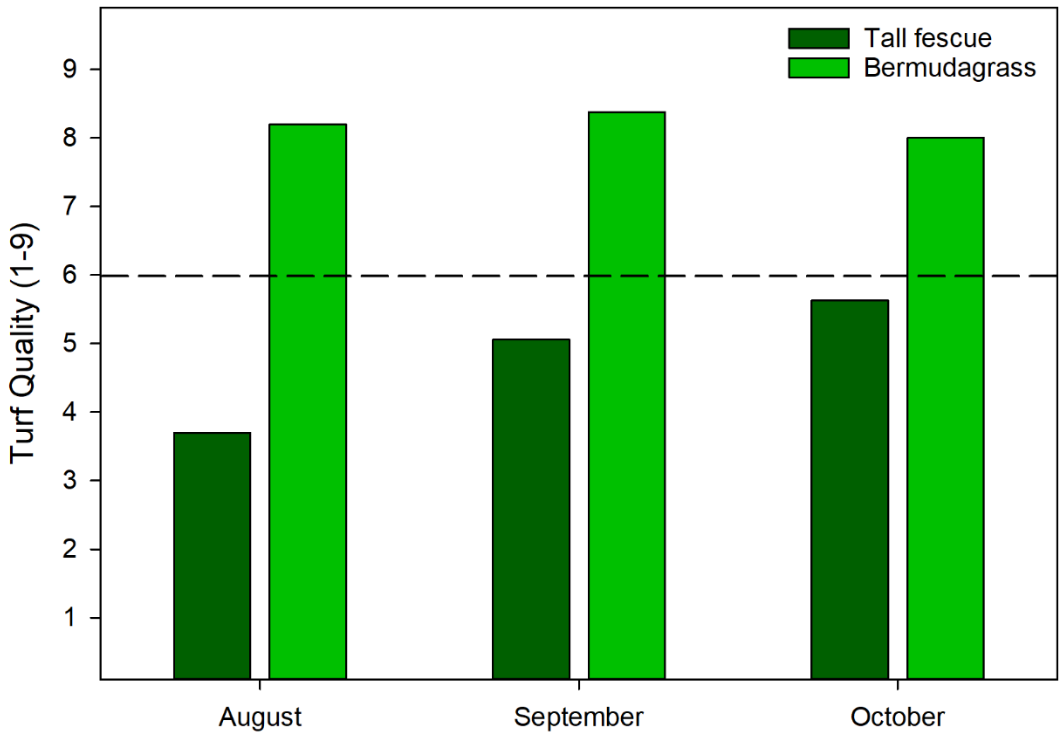

Figure 5. Turfgrass quality ratings averaged over month and year following summer establishment in 2017 and 2018. Horizontal line denotes minimally acceptable turf quality.

CHAPTER 4: SURFACE RENEWAL ESTIMATES OF TURFGRASS EVAPOTRANSPIRATION IN THE SOUTHEASTERN UNITED STATES

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Abstract

Precise measurement of turfgrass water use is critical to better understand water use characteristics of managed turfgrass systems. Methodology that directly measures actual turfgrass evapotranspiration (ET_a) across diverse environments without extensive site criterion may aid in the understanding of water use dynamics in such systems. The objective of this field research was to compare ET_a measurements from the surface renewal (SR) technique to ET_a measured by eddy covariance (EC) and micro-Bowen ratio (MBR) techniques over ‘El Toro’ zoysiagrass (*Zoysia japonica* Steud.) in the southeastern US. Turfgrass ET_a measurements were made by partitioning available energy to latent heat flux density (*LE*) from Bowen ratio computations and the residual of the surface energy balance using sensible heat flux (*H*) measurements from EC and SR techniques. Surface renewal estimates of zoysiagrass actual evapotranspiration (ET_a) were well correlated with EC ($R^2 = 0.99$) and MBR ($R^2 = 0.79$) ET_a. As a result, differences in cumulative SR ET_a compared to EC (< 2 mm) and MBR (< 8 mm) methods were minimal during two-month campaigns during 2017 and 2018. Linear correlation coefficients for ET_a were greatest between SR and EC estimates due to required calibration of SR sensible heat flux density measurements against EC derived *H*. Results from this two year field study indicate SR is an acceptable method to measure zoysiagrass ET_a in the southeastern United States. The use of SR to further investigate water use characteristics of managed turfgrass systems can assist in the conservation of fresh water through accurate partitioning of energy flux components and subsequent ET monitoring.

1. Introduction

Turfgrasses provide ecological, environmental, and aesthetic benefits to landscapes of all types. Dust abatement, carbon sequestration, erosion control, filtering of pollutants, and heat dissipation are a few of the many benefits turfgrasses provide. Additionally, turfgrasses contribute to social interactions and positive mental health through the maintenance of safe and durable recreational areas (Beard and Green, 1994; Stier et al., 2013). Like all plants, turfgrasses require water to maintain functionality in the environment. As a result, supplemental irrigation is desirable during times when rainfall is unable to meet water demands required for turfgrass growth and survival (Huang, 2008). However, potable water dedicated to turfgrass irrigation is often subjected to heightened scrutiny in the US due to the 16 million hectares occupied by turfgrass (Milesi et al., 2005). Therefore, developing turfgrass irrigation regimes that efficiently use water to maintain turfgrass functionality are imperative to best manage water reserves (Beard and Kenna, 2008; Devitt et al., 2008).

An accurate estimate of plant evapotranspiration (ET) is required in order to achieve maximum irrigation efficiency. However, the accurate measurement of ET presents many challenges, leading researchers to continually investigate both standard and novel methodology that can lead to effective water use measurements. The use of field lysimetry has historically been considered the standard for measuring ET by computing the difference in mass of a closed system between weighing events over a known period of time (Allen et al., 1989; Fry et al., 1997; López-Urrea et al., 2006; Trajkovic, 2010, Peterson et al., 2017). Consequently, lysimeters are usually not considered an option for continuous, long-term ET measurement due to costs of infrastructure, long-term maintenance, and subsequent labor requirements. As an alternative, empirical models have been used for many years (Thornwaite, 1948; Penman, 1948; Blaney and

Criddle, 1950; Monteith, 1965; Hargreaves and Samani, 1985). Such models require a combination of meteorological data and various other parameters to estimate plant ET. Monteith (1965) proposed the Penman-Monteith model which allowed for the estimation of ET at various time steps. Since then, the Penman-Monteith model has been modified several times to apply plant and environmental parameters that are representative of various climates and as a result, is often considered the standard model when estimating ET (Allen et al., 1998; ASCE-EWRI, 2005). However, many assumptions regarding site maintenance must be met in addition to strict data collection procedures in order to satisfy model criteria. Furthermore, ET estimates must also be adjusted by appropriate crop coefficients that may not reflect localized conditions.

Evapotranspiration can also be obtained through the measurement of energy flux components that complete the surface energy balance. A simplified expression of the surface energy balance was presented by Brutsaert (1982) which eliminated energy components of minimal significance:

$$R_n = G + H + LE \tag{2}$$

where R_n is net radiation; G is soil heat flux density; H is sensible heat flux density; and LE is latent heat flux density. Measuring R_n and G is relatively simple while H and LE require advanced instrumentation and data processing due to boundary-layer turbulence that dominates both components (Monteith and Unsworth, 1990). Furthermore, instrumentation that directly measures LE can be costly. As a result, measuring R_n, G, and H is the most economical approach to calculate LE as the residual of the surface energy balance (Shapland et al., 2012):

$$LE = R_n - G - H \tag{3}$$

Once *LE* has been calculated, it is then divided by the latent heat of vaporization (L) to derive ET:

$$ET = \frac{LE}{L} \tag{4}$$

Sensible heat flux density can be measured via multiple techniques. The eddy covariance (EC) technique measures *H* by quantifying the covariance of the vertical wind speed with sonic temperature (Swinbank, 1951). Such measurements are commonly collected using a sonic anemometer (Shapland, 2012). Advanced knowledge of turbulent theory and biophysics coupled with the challenge of post-processing large amounts of data from EC can be daunting for many agricultural researchers (Allen et al., 2011). However, many advances in instrumentation have been made since early iterations described by Tanner (1988) resulting in expanded use (Wilson et al., 2002). The Bowen (1926) ratio method measures vapor pressure and air temperature gradients near the evaporating surface in order to arrive at *LE* and *H* and is considered a standard technique in partitioning energy at earth's surface (Tanner, 1960; Sinclair et al., 1975). Micro-Bowen ratio (MBR) systems remain a novel concept as they are simply a scaled-down version of a Bowen ratio system tailored to measure a small footprint (Holland et al., 2013). Early use of the MBR system focused on measuring evaporation near bare surfaces (Ashktorab et al., 1989). Additional studies have since evaluated MBR system's ability to quantify evaporation under canopies such as corn and vineyards (Zeggaf et al., 2008; Holland et al., 2013). Micro-Bowen ratio measurements of ET have also agreed well with lysimeter and eddy covariance ET measurements from vegetation in vineyard interrows (Holland et al., 2013).

The surface renewal (SR) method measures *H* using fine-wire thermocouples to quantify high frequency temperature fluctuations in coherent air parcels above the crop surface (Paw U et al., 1995; Synder et al., 1996). Shapland et al. (2013) provides detailed explanation of flux measurement theory and current SR methodology. Required instrumentation are inexpensive and sampling procedures are simple compared to similar techniques; however, data computations are complex much like EC systems. Performance testing of ET estimation by the SR method has been investigated over a variety of cropping systems including rangeland grass, orchards, vineyards, rice, tomato, and tall fescue turfgrass (Castellví and Snyder, 2008; Castellví and Snyder, 2009; Castellví and Snyder, 2010; Castellví et al., 2012; Rosa et al., 2013; Suvočarev et al., 2013). Results from these trials demonstrate agreement of SR derived *H* and ET with standard measurement techniques. Aside from instrumentation costs, advantages of the SR method include the ability to collect data on sloped terrain, lack of needed axes correction that is required by EC systems, and as a result, reduced fetch requirements (Snyder et al., 2008; Castellví, 2012).

The availability of logger programs and analysis tools for flux density measurements make the SR method an attractive option for researchers when measuring ET. Surface renewal ET measurements are especially intriguing for use in managed turfgrass settings where standard direct measurements of ET may not be representative of large areas of interest and where fetch requirements are often inadequate for other micrometeorological techniques. Surface renewal stations have been deployed and provided accurate ET in managed turfgrass sites with unique microclimates in California (Synder et al., 2015). However, environments in California are much different than those inherent to the humid southeast where hot, humid summer days often lead to severe weather events resulting in intense rainfall. Raindrop energy from these intense thunderstorms call into question the durability of fine wire thermocouples needed for SR measurements. The objective of this field study was to compare SR ET estimates against EC and MBR ET estimates over managed zoysiagrass in the southeastern US.

2. Materials and Methods

2.1 Experimental Location and Management

Instrumentation was deployed at the NC State University Lake Wheeler Turfgrass Field Laboratory in Raleigh, NC (35.7796° N, 78.6382° W). Data were collected from June 21 – August 21, 2017 and from June 6 – August 6, 2018 from 'El Toro' zoysiagrass (*Zoysia jacponica* Steud.) maintained on a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) clipped to 6.3 cm with clippings returned. The experimental site measured 929 m^2 with 14.3 ha of various managed turfgrass species surrounding. Fertilizer was applied during May and July both years at an N rate of 49 kg ha^{-1} for a total applied rate of 98 kg N ha^{-1} yr^{-1}. A sulfur coated urea fertilizer (Reed & Perrine Sales, Tennent, NJ) containing micronutrients and an analysis of 25% N - 5% P_2O_5 – 10% K_2O was used for fertilizer applications. Pest management was not required during data collection due to high shoot density and pest tolerance during peak growth throughout summer months. Irrigation was not applied during active data collection, which resulted in minimal stress. All turfgrass management practices were selected based upon recommendations detailed in Carolina Lawns (Miller et al., 2016).

2.2 Micro-Bowen Ratio System

The MBR system was equipped with a LI-840A CO2/H2O gas analyzer (LICOR, Lincoln, NE) to measure water vapor concentration of the air (ppt). Water vapor concentration measurements were subsequently converted to vapor pressure (kPa) using ambient atmospheric pressure (kPa) measured by a barometer (Vaisala, model PTB101b). Air sampling was controlled by a solenoid programmed with a CR10X data logger (Campbell Scientific, Logan, UT) which alternated between top (6 cm above turfgrass canopy) and bottom (1 cm) air intakes every 5 min. A thermistor (BetaTHERM USA, LLC, Shrewsbury, MA) housed inside a nylon barb tee (Thogus, Avon Lake, OH) in-line each air intake measured air temperature. Travel time for air from the inlet to the thermistor was < 0.25 s.

Supplemental data collected to compute the surface energy balance included net radiation (R_n), soil heat flux (G), soil water content, and soil temperature. Net radiation was measured by a net radiometer (NR Lite2, Kipp and Zonen, Bohemia, NY) mounted 1.3 m above the zoysiagrass surface. Soil heat flux was measured by a soil heat flux plate (HFP01-L, Campbell Scientific, Logan, UT) installed 5 cm below the soil surface. A volumetric soil water content sensor (Decagon EC5, METER Group, Pullman, WA) and soil thermocouples (TCAV, Campbell Scientific, Logan, UT) were installed to span the volume of soil above the heat flux plate. Soil water content and temperature data were used to account for energy storage change above the heat flux plate (Sauer and Horton, 2005). The heat storage term was added to the flux measured by the heat flux plate to derive G at the soil surface. A complete explanation of MBR setup can be found in Holland et al. (2013).

Measurements were recorded every 10 s with subsequent averages output every 5 minutes. Data for the first minute of each 5-min interval were discarded prior to data averaging to allow time for gas line purging due to alternating between measurement heights. As a result, three 4-min averages from each measurement height were output each 30-min interval totaling six 4-min averages of air temperature and vapor pressure. These data were used to compute average air temperature (ΔT, K) and vapor pressure differences (Δe, kPa) for each 30-min interval and subsequent Bowen ratio (β; Bowen, 1926) according to (Arya, 2001):

(5)

$$\beta = \frac{H}{LE} = \frac{\left[P_a C_p (\Delta T)\right]}{[\lambda \varepsilon (\Delta e)]}$$

where H and LE are sensible and latent heat fluxes (W m^{-2}), respectively; P_a is atmospheric pressure (kPa); C_p is specific heat capacity of air (1004.67 J kg^{-1} K^{-1}); λ is latent heat of vaporization for water (2.45 MJ kg^{-1}); and ε is the ratio of molecular weights of air and water (0.622). Following β computation, LE is derived as:

$$LE = \frac{R_n - G}{1 + \beta} \tag{6}$$

where Rn is net radiation (W m^{-2}) and G is soil heat flux (W m^{-2}).

Confidence intervals (95%) were established for MBR LE data during 2017 and 2018 campaigns. Data found to be erroneous usually occurred at sunset or sunrise when the direction of ΔT is opposite the direction of Δe (Perez et al., 1999). Also, there is less certainty in the direction of ΔT and Δe because their magnitudes become less than the resolution of the sensors (0.02 °C and 0.018 kPa for air temperature and vapor pressure concentration, respectively).

2.3 Eddy Covariance/Surface Renewal Flux Station

Sensible heat flux density derived from eddy covariance was determined by a sonic anemometer (81000RE, R.M. Young Company, Traverse City, MO, U.S.A) measuring three-dimensional wind velocities and sonic temperature sampled at 10 Hz. Prior to deployment in the field, factory settings of the sonic anemometer were reconfigured to output desired signals (Shapland, 2013). Fluctuations in turbulent wind speed and air temperature were used to quantify H (Swinbank, 1951):

$$H = \rho C_p \left(\overline{w' T'_s}\right) \tag{7}$$

where ρ is the air density (g m^{-3}); w is vertical wind velocity (m s^{-1}); T_s is sonic temperature (K). The prime designation signifies the instantaneous departure from the mean and the overbar denotes a time-averaged interval.

Surface renewal calculated H by analyzing the energy budget of air parcels above the zoysiagrass canopy during the turbulent exchange process using a 76 μm diameter fine-wire thermocouple (FW3, Campbell Scientific Inc., Logan, UT) mounted 1.2 m above the zoysiagrass canopy and sampled at 10 Hz (Paw U et al., 1995). The amplitude and period of ramp-like shapes in turbulent temperature data are used to calculate H:

$$H = \alpha z \rho C_p \left(\frac{a}{\tau}\right) \tag{8}$$

where α is the alpha calibration factor, z is the measurement height (m), a is the ramp amplitude (K), and τ is the ramp period (s). Alpha was determined by the slope of the least squares linear regression forced through the origin of H data measured by SR against EC during a single, 1 month field campaign prior to beginning technique comparisons in 2017 (Synder et al., 2008).

Additional instrumentation required to compute the surface energy balance included a net radiometer, soil heat flux plate, soil water content sensor, and soil temperature probe as previously described in section 2.2. Following measurement of H via EC and SR in addition to other variables, LE and ET were calculated using Eqs. 2 and 3, respectively.

A turnkey data logger program developed by Shapland et al. (2013) was used to collect data measurements from the EC/SR flux station with a CR3000 data logger (Campbell Scientific, Logan, UT). Data output from the program were inserted into tandem spreadsheets to perform quality control procedures and final analyses (R.L. Synder, Personal communication, 2014).

Detailed explanation regarding flux tower deployment and data collection can be found in Shapland et al. (2013).

3. Results and Discussion

3.1 Surface Energy Balance

Energy flux densities measured by each technique during one clear sky day in 2017 and 2018 are presented in Fig. 1. Between 1900 and 0600 hrs, energy fluxes remained near zero as R_n was slightly negative. As R_n increased during morning hours, *LE* also increased at a similar rate. Soil heat flux density gradually increased until early afternoon, while *H* varied during both days. Sensible heat flux density was greatest from sunrise until mid-morning as R_n warmed the zoysiagrass surface, thus warming the air above the canopy. Approaching 1200 hrs, majority of available energy was partitioned to *LE* which is expected during summer. As *LE* increased, *H* stabilized or gradually declined toward zero.

In 2017 (Fig. 1 A-C), trends in measured flux densities were consistent among all methodologies. Measurements of R_n, *LE*, and *G* increased until ~ 1200 hrs while *H* was greatest between 0800-0900 hrs. The LE/R_n relationship for all techniques agreed well during the respective date in 2017. Similar consistency was observed in SR and EC system results for the clear sky day in 2018 while the MBR method partitioned majority of available energy towards *LE* (Fig. 1 D-F). During 2018, *G* and MBR derived *H* combined sum was near zero around 1200 hrs. As a result, MBR LE/R_n was greater compared to SR and EC derived ratios. Although EC derived *H* spiked during mid-morning, most likely from instability created by wind gusts, the partitioning of available energy appeared to be reasonable for all systems when collected during summer months. Additionally, the SR method agreed with the partitioning of energy measured by the EC and MBR techniques during the two clear sky days presented. Therefore computed

ET_a was also similar among all systems during respective dates. Surface renewal derived ET_a was within 0.7 mm of standard methodology ET_a for clear sky days shown in Fig. 1.

3.2 Evapotranspiration Measurements

Zoysiagrass ET_a varied between 0.3 – 6.4 mm d^{-1} as measured by MBR, SR, and EC techniques during 2017 (Fig 2). However, measured ET_a was only below 2 mm two days during sixty-one consecutive days of measurement in 2017. Daily averaged zoysiagrass ET_a was 4.3, 4.1, and 4.1 mm as determined by MBR, SR, and EC techniques, respectively. In 2018, measured ET_a was more erratic compared to 2017 (Fig 3). Although the range was similar (0.1 – 6.4 mm d^{-1}), ET_a fell below 2 mm six times in 2018. Sharp declines in ET_a were attributed to rainfall, prolonged cloud cover, and lower ET demand on respective days. Daily averaged ET_a from MBR measurements was 4.2 mm in 2018, which was slightly lower than 2017. Similar differences in daily averaged ET_a were determined for SR and EC measurements during 2018 with 2% increases. Regardless of year, averaged zoysiagrass ET_a agreed well with previous work documenting El Toro zoysiagrass ET_a (Green et al., 1991).

Cumulative ET_a during 2017 and 2018 were similar for all measurement techniques (Table 1). In 2017, the SR method measured 257.1 mm ET_a from June 21 – Aug 21. Cumulative MBR and EC ET_a differed by -3 and 0.01% from SR ET_a, respectively. Surface renewal ET_a was within 6% of MBR ET_a during June, July, and August measurement periods. Insignificant differences were found between SR and EC ET_a due to required calibration procedures of SR derived H against EC H (Snyder et al., 2008). In 2018, cumulative SR ET_a agreed with MBR ET_a (-0.2% difference). Similarly, there was a minimal difference in ET_a measured by the SR and EC techniques.

Snyder et al. (2008) measured ET_a over improved, well-irrigated and water stressed pastureland in California. Averaged turfgrass ET_a was 37% higher in California compared to results from this study, however the California study measured ET_a of an improved tall fescue (*Festuca arundinacea* Schreb.) (C3 plant) pasture, whereas, this study was conducted over managed zoysiagrass (C4 plant). Previous studies have found C3 turfgrasses to have increased water use rates compared to C4 turfgrasses (Kneebone and Pepper, 1992; Qian et al., 1996). Differences in plant anatomy, level of turfgrass maintenance, and geographic location are primary reasons for differences in measured ET_a between current results and previously published work.

The use of ET_o in tandem with a crop coefficient (K_c) is an economical and popular alternative to estimate turfgrass ET_a compared to many meteorological techniques that directly measure ET_a (Wherley et al., 2015; Pinnix and Miller, 2019). However, the accuracy of this technique is dependent on site conditions being similar to those where the turfgrass K_c was developed. Water use rates and subsequent K_c for individual turfgrasses are typically developed under non-limiting soil moisture (i.e. all water used by the plant is replenished). Turfgrasses, however, can often maintain acceptable visual quality when plant water use exceeds water resupplied through irrigation and/or rainfall until reaching wilting point. Therefore, as a way to conserve water without compromising visual appearance, many turfgrass managers irrigate at a deficit or rate less than what is used by the turfgrass. Conversely, if one uses ET_o and K_c to schedule irrigation, the intent is to replenish all water used by the turfgrass. This can be troublesome in certain areas prone to prolonged drought or employ deficit irrigation strategies.

Averaged cumulative ET_a and ET_o presented in this manuscript, indicate a zoysiagrass K_c of 0.51 (Table 1). A recent three-year lysimeter study found zoysiagrass K_c to be 0.69 under non-limiting soil moisture conditions (Wherley et al., 2015). The 26% reduction in K_c derived from data reported in this manuscript is due to lack of irrigation resupplied during active measurement. Despite the lack of irrigation and reliance on rainfall to replenish water used by the turf, the visual appearance of the zoysiagrass was not negatively impacted. This is supported by a bermudagrass (*Cynodon spp.*) field study which monitored water use via lysimeters and visual quality under varying soil moisture (data not presented). Data from the bermudagrass lysimeter study were collected concurrently with those reported in this manuscript approximately 150 m to the northeast. Under non-limiting soil moisture conditions, bermudagrass K_c was found to be 0.63. However, when water was resupplied only to prevent visual stress (rather than resupplying total plant water use), bermudagrass K_c was 0.48. As a result, the bermudagrass K_c was reduced by 24% without compromising visual aesthetics of the turf. Although a different warm-season turfgrass species, this reduction is near identical to that between the subsequent K_c measured by the MBR, SR, and EC techniques over non-irrigated zoysiagrass in this manuscript and that reported by Wherley et al. (2015). This demonstrates the ability of the SR technique to accurately measure turfgrass ET_a regardless of management conditions (i.e. limiting or non-limiting water conditions). This can be advantageous over methods such as using ET_o and K_c which may not be representative of current environmental conditions or align with desired irrigation management.

3.3 Comparing Surface Renewal ET_a to Micro-Bowen ratio and Eddy Covariance ET_a

Surface renewal ET_a measurements during 2017 and 2018 were well correlated to MBR (R^2 = 0.79, Fig. 4) ET_a. The slope of the linear regression between MBR and SR ET_a was slightly below 1 (slope = 0.82) indicating SR underestimated zoysiagrass ET_a compared to MBR. Previous research in North Carolina has reported increased accuracy of ET estimates over turfgrass compared to measurements collected over bare soil by MBR systems. Actual evapotranspiration of clipped tall fescue measured by MBR was well correlated (R^2 = 0.99) with mini-lysimeters in western North Carolina (Holland et al., 2013). Conversely, mixed results were found when ET was measured over bare ground at open field (R^2 = 0.89) and vineyard (R^2 = 0.66) sites. Holland et al (2013) also reported slight overestimation of MBR tall fescue ET_a as the slope of linear regression equaled 1.17. Data presented in this manuscript agrees with those conclusions as SR underestimated zoysiagrass ET_a compared to MBR measurements.

Prior to initiating data collection for technique comparisons, surface renewal estimates of *H* were calibrated against EC measured *H* during a one month period in 2017. Therefore ET_a calculated as the residual of Eq. 2 should be similar among the two techniques. Linear regression was performed on SR and EC ET_a (Fig. 5). As expected, ET_a from SR measurements were well correlated with EC ET_a (R^2 = 0.99). These results agree with previous research that developed use of this methodology and logger programs (Shapland et al., 2012; Shapland et al., 2013). Furthermore, results from this two-year field study indicate the SR technique can be successfully adapted to managed turfgrass systems in the southeastern US as SR ET_a measurements were comparable to ET_a measured by standard methodologies.

4. Conclusions

Techniques that continuously measure turfgrass ET_a with a high degree of accuracy are desirable in order to better understand water dynamics of managed turfgrass systems. Direct measurement of turfgrass ET_a is labor intensive and is rarely representative of expansive areas, therefore, alternative methodologies need to be investigated. Flux densities measured by the SR method were comparable to those measured by MBR and EC systems during two month measurement periods in 2017 and 2018. Surface renewal ET_a correlated well with measured ET_a

by MBR and EC techniques. Surface renewal underestimated ET_a compared to the MBR system. However, differences in measured ET_a were considered to be insignificant. Furthermore, it was unknown how fine-wire thermocouples needed for SR measurements would withstand the climate inherent to the humid southeastern US. Throughout our evaluations, the 76 µm thermocouple withstood damage from severe weather events. Due to high correlations with standard ET methodologies and proven durability, the use of SR to measure turfgrass ET in the southeastern US appears to be a viable approach. With the availability of data capture and analysis programs in addition to less costly instrumentation, the SR method is an attractive alternative to standard evapotranspiration measurement systems for use in ET-based research.

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Table 1. Measured reference evapotranspiration (ET_o) and cumulative ET_a determined by Micro-Bowen ratio, Surface Renewal, and Eddy Covariance techniques during measurement periods in 2017 and 2018 in Raleigh, NC.

2017	MBR†	SR	EC	ET_o	**2018**	MBR	SR	EC	ET_o
	mm					mm			
6/21 – 6/30/2017	40.6	41.5	41.3	81.5	6/6 – 6/30/2018	108.4	108.6	108.5	214.2
7/1 – 7/31/2017	148.5	139.7	140.3	276.9	7/1 – 7/31/2018	133.3	133.4	131.9	257.3
8/1 – 8/21/2017	76.4	75.9	75.2	152.9	8/1 – 8/6/2018	20.3	19.5	19.4	40.5
Total	**265.5**	**257.1**	**256.8**	**511.3**		**262.0**	**261.5**	**259.8**	**512.0**

† MBR, Micro-Bowen ratio; SR, Surface Renewal; EC, Eddy Covariance

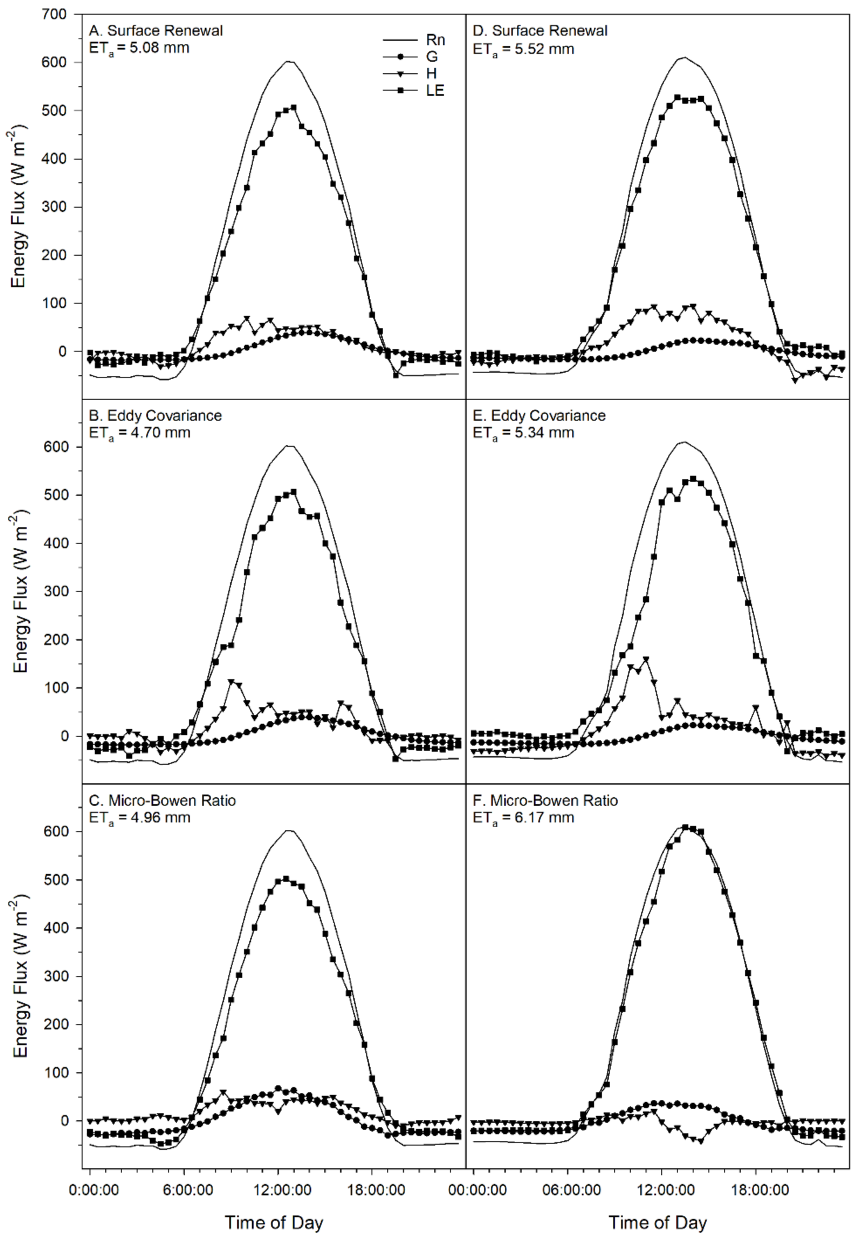

Figure 1. Partitioned energy balance terms measured at 30 min. intervals by Surface Renewal, Eddy Covariance, and Micro-Bowen ratio systems over managed zoysiagrass on clear sky days in 2017 and 2018. Energy balance terms (R_n, net radiation; G, soil heat flux; LE, latent heat flux; H, sensible heat flux; and ET$_a$, actual evapotranspiration in mm) presented in A-C were measured on 6-28-2017 while D-F were measured on 7-8-2018.

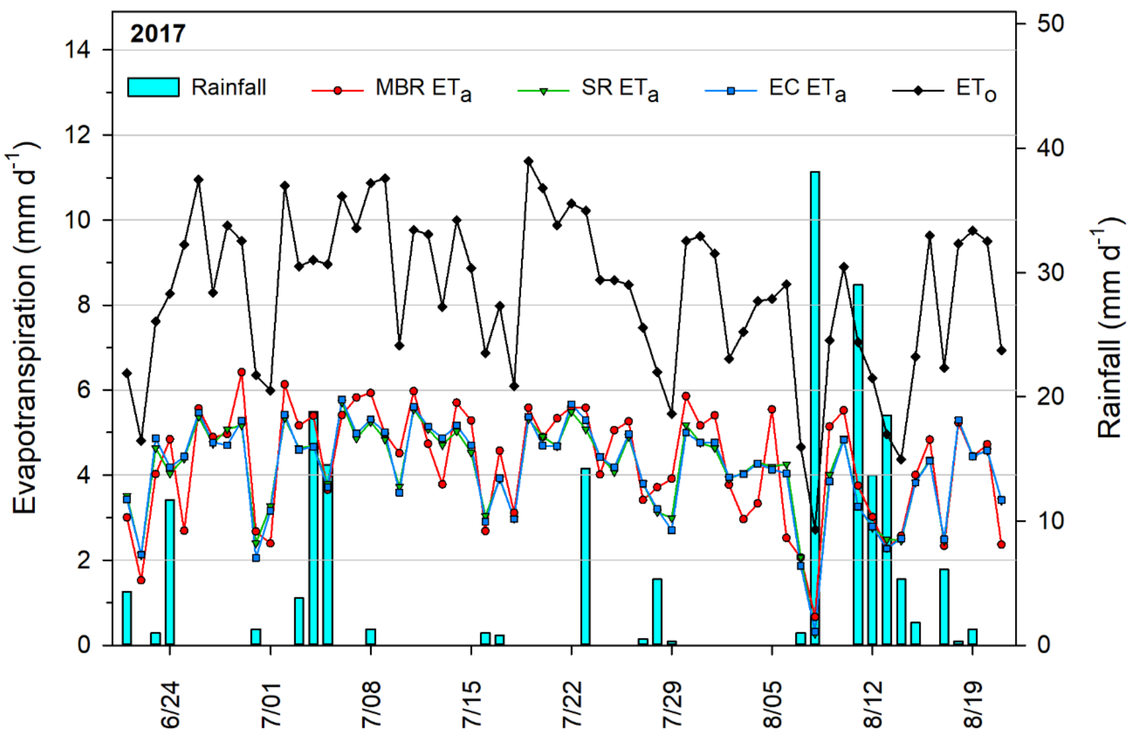

Figure 2. Rainfall events in addition to reference evapotranspiration (ET_o) and actual turfgrass evapotranspiration (ET_a) measured by Micro-Bowen ratio (MBR), Surface Renewal (SR), and Eddy Covariance (EC) systems from June 21- August 21, 2017 in Raleigh, NC.

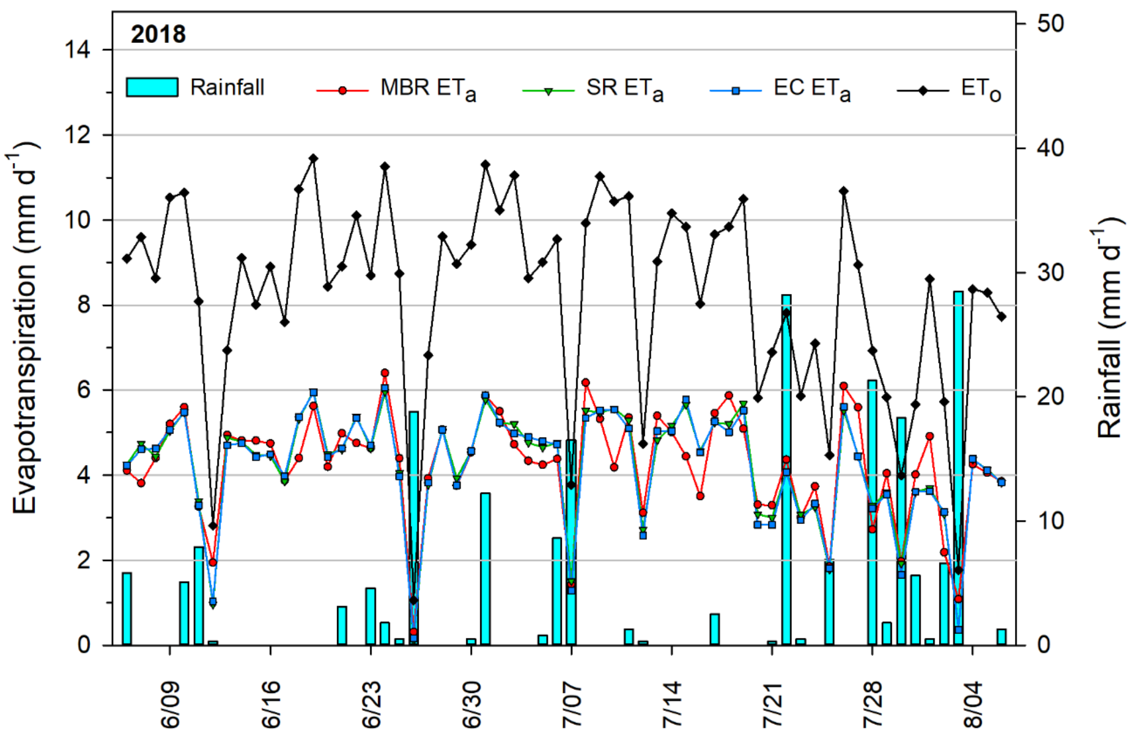

Figure 3. Rainfall events in addition to reference evapotranspiration (ET_o) and actual turfgrass evapotranspiration (ET_a) measured by Micro-Bowen ratio (MBR), Surface Renewal (SR), and Eddy Covariance (EC) systems from June 6- August 6, 2018 in Raleigh, NC.

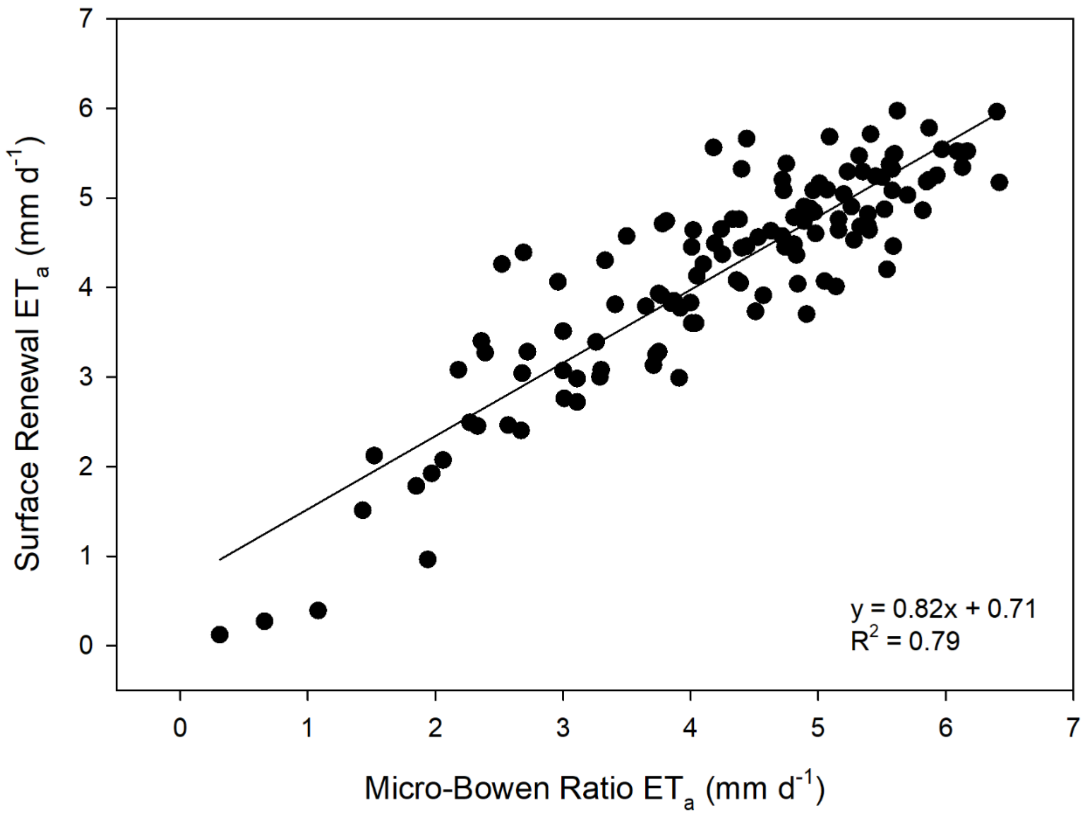

Figure 4. Linear regression of Micro-Bowen ratio and Surface Renewal actual evapotranspiration (ET_a) measurements collected during two month campaigns during 2017 and 2018 in Raleigh, NC.

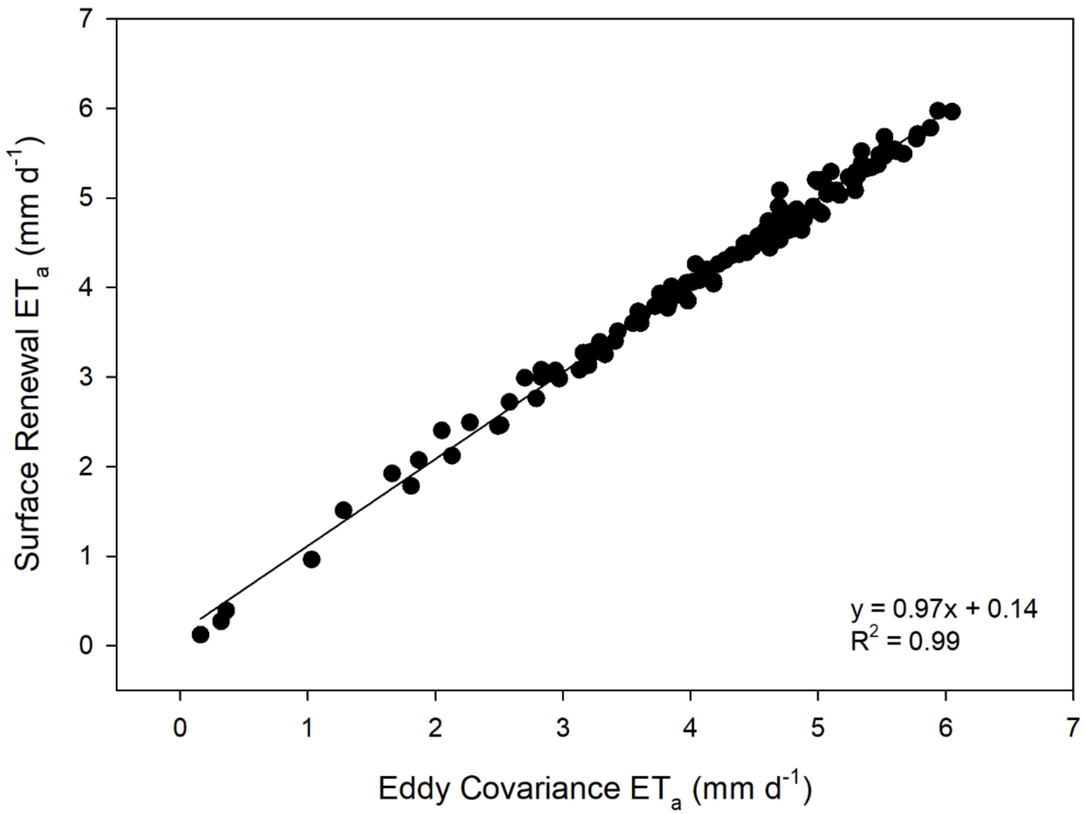

Figure 5. Linear regression of Eddy Covariance and Surface Renewal actual evapotranspiration (ET$_a$) measurements collected during two month campaigns during 2017 and 2018 in Raleigh, NC.