ABSTRACT

KETCHUM, CORY. Development of Irrigation Coefficients in the Transition Zone (Under the direction of Dr. Grady Miller).

Use of cultivar or species-specific irrigation coefficients within a geographic location allows for more exact irrigation planning. Crop coefficients (K_c) are often utilized with ET_o values to reflect actual evapotranspiration (ET_a) of turfgrass stands. In the absence of data default crop coefficients are often used. The current reported industry standard is 0.6 for warm-season turfgrass species. This standard does not account for geographic location, species, or cultivar utilized, which may limit the effectiveness of using crop coefficients. If K_c values based on location and cultivar are utilized in irrigation planning, it could prevent over and under application of irrigation.

Stress coefficients (K_s) are a new form of irrigation coefficient that relates to the decrease in ET_a when the turfgrass is under water-limited conditions. Stress coefficients take K_c's relationship with ET_o and ET_a a step further by measuring the decrease in ET_a when plants experience water stress. While K_c values are applicable during non-stressed conditions, K_s values are applicable during water-stressed conditions. The K_c values do not account for the ability of turfgrasses to restrict evapotranspiration (ET) when under moderate drought stress. Stress coefficient values provide water conservation by estimating minimum water use, while maintaining minimally acceptable turfgrass quality.

The objective of chapter one was to derive K_s values for four bermudagrass (*Cynodon spp.*) cultivars grown in the transition zone. Direct measurements of actual evapotranspiration were made through weighing of lysimeters during 2018 to 2020 at Lake Wheeler Turfgrass Field lab from June to October. The experimental units were allowed to naturally dry down to near wilting and then maintained at a steady state to allow K_s value calculation for each cultivar.

‘Latitude 36’ was the best performing cultivar with a mean K_s value of 0.774 and ‘Celebration’ was the worst preforming at 0.977. The intermediate cultivars were ‘TifTuf’ and ‘Tifway’. All the cultivars saw a decrease in ET_a when compared to non-stressed turf, while maintaining a minimally acceptable turf quality.

The objective of the second chapter was to calculate K_c and K_s values for multiple species of warm-season turfgrasses in the transition zone. The results shown in chapter two are preliminary results from the first year of a three-year study. The field study evaluated hybrid bermudagrass [*Cynodon dactylon (L.)* Pers. *x Cynodon transvaalensis* Burt-Davy], St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze), zoysiagrass (*Zoysia spp. (Z.)*), and seashore paspalum (*Paspalum vaginatum*) grown in weighing lysimeters..‘Tahoma 31’ bermudagrass had the lowest $K_{c\ mean}$ value at 0.771, while ‘FAES1319’ a zoysiagrass genotype had the highest value at 1.02. Within K_s values ‘DALSA1404’ St. Augustine, had the lowest mean K_s value at 0.743, while ‘DALZ1606’ zoysiagrass had the highest K_s mean value at 1.17. Both studies looked to determine K_s and K_c values that could be used to more accurately predict irrigation needs for North Carolina.

Development of Irrigation Coefficients in the Transition Zone

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Crop Science

Raleigh, North Carolina
2022

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DEDICATION

This work is dedicated to all of those who have influenced me to this point and time.

BIOGRAPHY

Cory Cleveland Ketchum was raised in Anthony, FL, where his family currently resides. Cory's introduction into turfgrass came from his step-father, who at the time of his parents' marriage was working on his Master's in Weed Science at the University of Florida. Cory continued to be involved in the turfgrass industry as his father completed his PhD in Weed Science at the University of Tennessee and then served as an assistant professor of Weed Science at the University of Missouri. In 2008, Cory and his family returned to Anthony, with his mother working as a nurse and his step-father working on their family's farm. Growing up Cory participated in numerous sports ranging from baseball to golf, was an avid FFA (Future Farmers of America) member, and generally enjoyed spending time outdoors hunting, fishing, or working. Cory graduated from North Marion High School in 2015 with a desire to enter the medical field as a MD. To pursue that goal, he moved to Gainesville, FL and enrolled in Santa Fe College.

During his freshman year Cory began working for his step-father's fledging contract research company testing pesticides on turfgrass for chemical companies. After working for his step-father for a year and half Cory realized he preferred working with turfgrass outside over the prospects of spending days indoors as an MD. After completing his associates degree at Santa Fe, Cory transferred to the University of Florida. At the University of Florida (UF) Cory would be employed part-time at a local golf course during of his time at UF as well as participating in a summer internship with a seed producer in Lebanon, Oregon before his senior year. Cory received his B.S. degree in Plant Science in fall of 2019. IN spring of 2020 he moved to Raleigh (NC) to begin his Master of Science degree under the direction of Dr. Grady Miller researching turfgrass irrigation coefficients.

ACKNOWLEDGMENTS

I would first to extend my sincere appreciation to Dr. Grady Miller, who has taught me a great deal both professionally and personally. I can be a difficult person to deal with at times, but Dr. Miller always showed a great deal of patience and dedication to ensure I would grow both professionally and personally during my time at NC State. I hope that the effort I gave to your program will be remembered fondly after I leave. I would also like to acknowledge fellow committee members Dr. Susana Milla-Lewis and Dr. Chadi Sayde for their assistance during my two years at NC State.

To my parents, Travis and Jennifer Teuton, I cannot put into words the impactful roles you both have played in my life. Mom, you have always placed the needs of your children before your own and have always tried to ensure our happiness above all else. Dad, Dakota and I never shared your name, but you always acted like we did. Without you neither of us would be where we are today. To my older brother, Dakota, your friendship has been one the most important things in my life. You have continually looked out for me since we were little kids and always tried to help me as best you could. To my little brother Luke, you have brought me much joy and pride watching you grow up. Being separated by eleven years, I have been able to watch you mature as a young man. From your days playing t-ball to you getting to play high school baseball now. To my father, John Dustin Ketchum, it’s been over two decades since I last saw you, but you have played a major role in shaping me into the person I am today. You blessed me with a fantastic mother and brother, and your memory has pushed me to become the person I am today. There are many more family members worth acknowledgement too many to list, but all of you have played such a vital role in my upbringing. The same can be said about my personal friends, who have been instrumental in the development of my character.

I have had the privilege of working with so many outstanding individuals at NC State. First, I would like to thank Dr. Raymond McCauley, your dedication to your work is truly an outstanding sight. You have helped me grow tremendously both as a person and a worker. I would also like to thank Daniel Freund, Mathieu LeCompte and Tripp Rogers for your invaluable advice and friendship during my time at NC State. I am thankful to you all and look forward to continued friendships.

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LITERATURE REVIEW

Evapotranspiration

With the increased amount of urbanization, turfgrass has become the dominant plant type in the U.S. accounting for 163,800 square kilometers of area, or three time the area of any other irrigated crops (Milesi et al., 2005). Thus, the need for greater irrigation conservation is increasing. The first step in understanding irrigation allocation and requirements of turfgrass is understanding evapotranspiration. Evapotranspiration (ET) accounts for soil evaporation and plant transpiration (Brown, 2014). The term is meant to equate the loss of available water both from evaporation of water in the substrate and through metabolic processes in plants. Morphological and growth characteristics like shoot and leaf density, leaf extension rate, leaf width, number of leaves per unit area, vertical leaf extension rate, and leaf and shoot orientation can affect ET rates (Amgain et al., 2018).

Evapotranspiration is often estimated using weather parameters as seen in the equation below (Equation 1), where R_n is net radiation (MJ $m^{-2}day^{-1}$), G is soil heat flux density at soil surface (MJ $m^{-2}day^{-1}$), T is mean air temperature (°C), u_2 equals wind speed (ms^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ equals slope of saturation vapor pressure-temperature curve (kPa $°C^{-1}$), and γ is the psychometric constant (kPa $°C^{-1}$) (Jensen and Snyder, 2005).

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

Reference evapotranspiration (ET_o) is used along with crop coefficients to calculate crop or actual evapotranspiration. The ET_o value is calculated using weather variables from weather stations around the intended irrigation event (Subedi and Chavez, 2015). The American Society of Civil Engineers (ASCE) standardized reference evapotranspiration formula for short grass canopies (equation 1) is a widely used formula for ET_o calculation (Blonquist et al., 2010).

Actual evapotranspiration (ET_a) is the amount of water loss by the plant during a given period. Calculating ET_a can be difficult, however an accurate means of measuring water-use is through lysimeters, while allowing for water loss measurement (Romero and Dukes, 2016 and Young et al., 1997). Actual evapotranspiration can be estimated using lysimeters, allowing for calculation of mass changes of the lysimeter which are directly tied to plant water use and evaporation of water from the soil. The difference in mass from a weighing event to the previous provides the actual evapotranspiration during that time period (Pinnix and Miller, 2019a). During peak growing season ET rates of most turfgrass species range from 3 to 8 mm d^{-1} and may be as high as 12 mm d^{-1} (Beard, 1973). Research has shown that water use amongst species varies greatly. Bermudagrass ET_a rates are generally lower and fluctuate from 2-6 mm d^{-1} in studies conducted in Texas, Georgia, Florida, and Oklahoma (Kim and Beard, 1988; Carrow, 1995; Wherley et al., 2015; Amgain et al., 2018). Zoysiagrass water use has been reported to range from 2.7- 9.9 mm d^{-1} (Green et al., 1991) and St. Augustinegrass from 3.28-7.8 mm d^{-1} (Atkins et al., 1991)

As irrigation restrictions become more abundant, the ability to efficiently irrigate turfgrass has become integral to maintaining healthy stands of turfgrass. Efficient irrigation is achieved by applying the amount of water necessary for the plant to thrive without excess. To estimate water requirements, crop coefficients (Kc) are utilized in conjunction with reference evapotranspiration (ET_o) to calculate actual evapotranspiration (ET_a) (Allen et al., 1998). Crop coefficients are derived directly by measuring plant water loss therefore providing a useful tool to determine watering requirements for specific turfgrass species and cultivars.

Crop Coefficients

Crop coefficient values have been widely investigated to ensure proper K_c values for species, cultivars, the geographic location (Romero and Dukes, 2016). They are calculated through the division of actual evapotranspiration by reference evapotranspiration, $K_c = ET_a / ET_o$. Crop coefficients act as a deficit coefficient to explain the decreases seen in actual evapotranspiration (Bodner et al., 2007).

Turfgrass researchers have measured the K_c variability among different species. A study in central Florida from 2008 to 2010 looked at K_c calculations for 'Tifway' bermudagrass, 'Empire' zoysiagrass, 'Floratam' St. Augustinegrass, and 'Argentine' bahiagrass (Wherley et al., 2015). In the first year the reported mean seasonal K_c averages for Tifway, Empire, Floratam, and Argentine were 0.66, 0.68, 0.54, and 0.67, respectively. The second and third year provided mean values of 0.53, 0.59, 0.58, and 0.70, respectively. These individual species level K_c values allow for more accurate allocation of irrigation when compared to using the industry standard value (0.6) for warm-season turfgrass species (Meyer et al., 1985).

New genotypes have also been found to have different K_c values. Atkins et al. (1991) conducted a study to measure ET_c of ten St. Augustinegrass genotypes utilizing mini-lysimeters established in controlled environments. They reported that genotypes that were prone to have higher ET_c values would have higher K_c values. This is due to the fact K_c values are directed from the difference between ET_o and ET_a. They saw variability in ET_c amongst genotypes and how changing conditions impacted ET_c measurements, with the greatest variability observed when the entries were growing in optimal conditions.

With the diverse weather conditions seen in the southeastern U.S., and in particular the transition zone, geographically accurate K_c vales need to be calculated to prevent over or under irrigation of turfgrass (Carrow, 1995). These values can change from within a state as reported by Jia et al. (2009). In their study K_c values for well-watered bahiagrass in central Florida were compared to K_c values measured by Stewart and Mills (1967) in south Florida. Jia et al. (2009) found that K_c values in south Florida were 21 percent greater than those reported for central Florida. The disparity seen within the state of Florida illustrates the geographical need for accurate K_c values.

Stress Coefficients

Although crop coefficients and reference evapotranspiration are useful tools for turfgrass managers, they are most applicable during non-limited conditions. Water stress coefficients (K_s) are an estimate of the difference in plant water use between a well-watered status and water-limited condition (Allen et al., 1998). Stress coefficients work in a similar manner as crop coefficients (K_c), as both are meant to provide a reliable means of understanding the correlation between reference and actual evapotranspiration. However, K_s values provide an even greater understanding of the actual ET during times of limited irrigation or water stress as the turfgrass will steadily decrease ET as the limited conditions worsen.

$$\mathbf{K}_{\boldsymbol{s}} = \frac{\mathbf{ET}_{\boldsymbol{c\ adjusted}}}{\mathbf{ET}_{\boldsymbol{o}} \times \boldsymbol{K}_{\boldsymbol{c}}} \qquad \text{(Equation 2)}$$

Determination of Ks can be made using Equation 2, where K_s is stress coefficient, $ET_{c\ adjusted}$ is actual evapotranspiration during limited conditions, and ET_o is reference evapotranspiration. The reduced water use of the plant (ET_c adjusted) can be calculated using Equation 3, where, $ET_{c\ adjusted}$ is actual evapotranspiration during water-limited conditions, ET_o is reference evapotranspiration, K_c crop coefficients, and K_s is stress coefficients. (Allen et al., 1998).

$$\mathbf{ET}_{\boldsymbol{c\ adjusted}} = \mathbf{ET}_{\boldsymbol{o}} \times \boldsymbol{K}_{\boldsymbol{c}} \times \boldsymbol{K}_{\boldsymbol{s}} \qquad \text{(Equation 3)}$$

The application of stress coefficients uses the concept of adjusted evapotranspiration ($ET_{c\ adjusted}$). As ET_c is the crop's actual evapotranspiration rate on a given day, $ET_{c\ adjusted}$ is the plant's water use measurement as impacted by soil water stress on ET_c. Whereas ET_c is the measurement of the crops ET rate growing under non-limited water conditions, $ET_{c\ adjusted}$ is the measure of ET rate during limited water conditions. Adjusted actual evapotranspiration values are derived in the same manner as ET_c values, through weighing of lysimeters to determine water loss (Allen et al., 1998). Therefore equation 2 relates the impact that stress coefficients (K_s) and crop coefficients (K_c) values have on $ET_{c\ adjusted}$.

As previously discussed, stress coefficients (K_s) are similar to crop coefficients (K_c) since they reduce estimated ET_o values. So, they would have more specific application for low input or low maintenance turfgrass areas or other turfgrass areas during water limited conditions such as periods of drought or water restrictions (Allen et al., 1998). Since K_c values are calculated at soil field capacity, K_c values will have to be concurrently derived or use approved K_c values for the crop and the geographic area. A water stressed turfgrass stand will produce a K_s value under one, whereas a K_s measurement equal to one would indicate a turf that is not water stressed and is being held at field capacity. Garrot and Mancino (1994) performed short soil dry downs to the point of wilting before applying irrigation. Their study provided K_c values that ranged from 0.1 to 1.5, which indicated the values were influenced by the increase of water in the soil. They labeled the values as "deficit K_c values", but since the values occurred under limited conditions, they would be considered K_s values in the context of our studies. When water was present in the soil, the values increased; whereas when water was limited, the values decreased. Their study found that increased levels of water presence caused deficit irrigation coefficients to have values over 1, indicating no restriction of water by the turfgrass.

A question can arise to the relevancy of stress coefficients. If a turfgrass grower or manager maintains the turfgrass in soils at field capacity, then they seem to have no practical use. But considering that many states and cities having started employing restrictions on water use for lawns, their application could gain importance. Irrigation restrictions are abundant in high population centers such as Miami, Florida, where landscape managers contend with irrigation blackout days (Miami Dade, 2020). Blackouts and restrictions are steadily increasing across the U.S.; however, some locations have taken a more aggressive approach. At least one North Carolina city has initiated a buyback program to reduce cool-season specie yards by replacing them with warm-season species (TOC, 2008). The city of Phoenix, Arizona offers a monetary sum of 200 dollars for every 1000 square feet of turfgrass removed from a yard (City of Phoenix, 2020). This is of course due to the limited water available for irrigation in the south-western states but provides a concerning situation for the turfgrass industry in the area. Both situations provide a use for K_s values, by better estimating minimum water needed for turfgrass quality. In addition, as breeders try developing more drought resistant turfgrass cultivars, understanding the critical point of required soil water becomes more necessary (Ferreira, 2017). Stress coefficients provide a measurable understanding of how turfgrass cultivars handle this critical point of limited soil water content, while also maintaining acceptable turfgrass quality. This allows breeders to better understand the drought resistance of current cultivars and continue to improve the drought resistant traits present as they develop new breeding lines.

With the need for more efficient irrigation practices, stress coefficients (K_s) provide a more exact way to calculation minimum irrigation needs of turfgrasses before reaching a critical point of stress. This critical point of stress is when soil water decreases to a level that plant stress becomes evident, resulting in a decrease in quality and ET rates (Zhang et al., 2017). The reason for ET reduction at this critical point of stress is the restriction of the stomatal openings, causing a decrease in the gradient seen from the release of water vapor and absorption through the roots of the plant (Verstreten et al., 2008). This decrease in ET from stomatal restriction is the factor that K_s is measuring, which translates into the minimum water requirement for the plant to maintain acceptable quality.

Turfgrass Selection

Environments like North Carolina provide a special challenge for turfgrass managers. Located in the middle of the transition zone, a wide 300 to 700 mile band where cool-season and warm-season turfgrass species overlap in use (Dunn and Diesburg, 2004). Tall fescue (*Festuca arundinacea S.*) is well- adapted for use in North Carolina. It is a popular lawn grass in central and western North Carolina due to its ability to remain green year-round and a strong tradition of use (Miller, 2018). Although it thrives in clay and loam, it struggles in sandy areas with full sun that is common in the coastal areas of North Carolina.

With warm-season turfgrass species the ability to sustain color and growth throughout the year is not possible. The first frost of the year will cause warm-season turfgrass species to become dormant and then they slowly regain color in the spring. Three common warm-season turfgrass species used in North Carolina that have been improved through breeding programs include bermudagrass (*Cynodon spp.*), zoysiagrass (*Zoysia spp.*), and St. Augustinegrass (*Stenotaphrum secundatum* (Walter) O. Kuntze). Each of these grasses have positive and negative attributes when used in North Carolina. Bermudagrass is an extremely drought-tolerant turfgrass that establishes quickly and handles traffic extremely well; however, it is not shade tolerant and requires more maintenance than most other turfgrasses during peak growing months. Zoysiagrass is slow growing and rebounds from damage significantly slower than bermudagrass but requires less frequent mowing then bermudagrass. It has moderate shade and cold tolerance and requires little irrigation in North Carolina once fully established. St. Augustinegrass is a fast-growing turfgrass that is shade tolerant but is considered the least cold-hardy of the warm-season turfgrasses used in North Carolina. Due to the lack of cold tolerance, St. Augustinegrass is limited to warmer parts of the state like the coastal plains and eastern parts of the piedmont region. Seashore paspalum (*Paspalum vaginatum* Sw.) is not widely used in North Carolina and the transition zone, due to a lack of cold tolerant cultivars. Due to its high tolerance to saline conditions, if new germplasm had greater cold tolerance, it may have more applications to coastal North Carolina (Reynolds, 2014). Previous studies have indicated that high-density, low growing turfgrasses, such as hybrid bermudagrass, zoysiagrass, buffalograss, and centipedegrass exhibited the lowest turfgrass water use rates, and where adapted, are the suggested turfgrasses to use in water stressed areas (Beard and Kenna, 2008).

Water Use and Drought Resistance

Most water that enters a turfgrass plant is utilized in transpiration. Water enters the plant through root absorption, either in the apoplast pathway, cellular pathway, or both (Taiz and Zeiger, 2010). Transpiration serves as the main driving force for the rate of absorption of water from the roots (Kopp and Jiang, 2013). The release of water vapor into the atmosphere causes a negative hydrostatic pressure in the plant. As water vapor is released, more water is pulled from the xylem into the mesophyll, where it is evaporated and exits through the stomata. This process generates energy and releases energy which cools the plant.

A major factor that can negatively impact turfgrass ET is the impact of the boundary layer resistance (Fry and Huang, 2004). The boundary layer is a stratum of unstirred air around the plant which reduces the vapor pressure gradient, therefore restricting plant transpiration. The stomatal openings of the leaves regulate the gas exchange of water vapor, by constricting during times of water stress. With 90% of water loss occurring through the stomatal openings, the ability to restrict stomatal openings is the initial point of control for the plant to limit water use (Huang, 2008).

Drought resistance is the ability of a plant to survive prolonged drought stress through various mechanisms, like drought tolerance and avoidance (Jesperson and Schwartz, 2018). Drought tolerance is the overall hardiness of the turfgrass as the plant adjusts to low tissue water deficits and escapes drought. Drought avoidance is the mechanisms that the turfgrass utilizes to maintain adequate tissue water content allowing for an avoidance or postponement of water stress (Pornaro et al., 2020). One of the observed traits in avoidance is limiting of evapotranspiration through closure of stomatal openings. Beard (2004), as summarized by Huang et al. (2014), reported that common bermudagrass, hybrid bermudagrass, and seashore paspalum as having superior drought tolerance and zoysiagrass as excellent.

Miller (2000) evaluated turfgrass drought avoidance by evaluating plant response as the fraction of transpirable soil water (FTSW). Sinclair and Ludlow (1986) had previously shown that the rate of plant transpiration in corn (*Zea mays* L.) was directly linked to the fraction of total extractable water in the root zone. In their studies, a plant that maintains its transpiration rate until a lower FTSW compared to other treatments, expresses a level of drought avoidance. For turfgrasses, Miller (2000) indicated that turfgrass treatments that were able to maintain transpiration further into the declining soil water were able to also maintain higher turfgrass quality. Comparably, a turfgrass treatment that would have a decrease its transpiration rate at higher FTSW would show drought stress earlier (lower turf quality).

Evapotranspiration Calculation Devices

Lysimeters are watertight vessels used to measure water lose from the contained plants. The lysimeters used in our studies were constructed from 10-inch polyvinyl chloride (PVC), cut into 13-inch lengths (Wherley et al., 2009). The bottoms had eight 0.25-inch holes centered at five-eighth of an inch above the bottom, drilled through the sides. Three 0.5-inch holes centered at 0.375-inch below the top edge was drilled to allow for hooks to be used when hoisting the lysimeter. Polyvinyl chloride boards were cut and sanded to fit tightly within the lysimeter bottom Four holes were drilled and tapped to allow 0.25-inch, threaded plugs to be placed in the lysimeter bottom. Steel rods along the perimeter supported the PVC bottoms of the lysimeter. Sleeves were constructed using 5-gallon buckets with their bottoms removed. The buckets sides were expanded by cutting down the middle and removing ridges for a 5.5-inch-wide vertical slice. The expanded sides were riveted on the outside with 8, 0.125-inch pop rivets. Once properly placed, the inside diameter of the sleeve ranges from 11 to 11.125-inches. A 12-inch soil auger bit was utilized to drill 15-inch deep holes for the sleeves. The holes were cleaned by hand to fit the sleeve. Porous geotextile fabric was placed at the bottom with a gravel base placed in the hole to allow for rapid draining of water under the lysimeter. The sleeves were inserted to the point of it being flush with the surrounding soil. Once placed into the sleeves, the lysimeters sat flush with the surrounding turfgrass. Surrounding the sleeves healthy stands of turfgrass were maintained with a mowing height of 2-inches.

The University of Idaho in Moscow, Idaho developed reference evapotranspiration (ET_o) software (REF ET, Allen, R. G., 2013). This software uses relevant weather data to calculate several ET_o values for short canopy grasses from a selection of ET equations. For our ET_o calculations we utilized the ASCE standard Penman-Monteith equation. The ASCE formula is designed for grasses of 0.5 meters tall (19.6 inches), but by allowing for certain assumptions in the formula, it will calculate resistances for grasses at 0.12 meters (4.7 inches) of height. In the case of warm-season turfgrasses, the assumptions were applied to utilize for the formula to measure grasses at 0.12 meters. In our studies, St. Augustinegrass were maintained at 0.089 meters (3.5 inches), while bermudagrass and zoysiagrass species were maintained at 0.051 meters (2 inches).

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CHAPTER 1: STRESS COEFFICIENTS FOR HYBRID BERMUDAGRASS IN THE TRANSITION ZONE

Formatted for publication in *Crop, Forage, and Turfgrass Management*

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Abstract

It is desirable to use more drought resistant turfgrass cultivars that are efficient with their water use, while also maintaining an acceptable level of quality. Crop coefficients (K_c) have traditionally been utilized to assist in reducing irrigation by comparing reference evapotranspiration (ET_o) to actual evapotranspiration (ET_a) of specific crops. However, K_c values are most relevant during times of non-limiting conditions and do not account for the ability of turfgrasses to restrict evapotranspiration (ET) when under moderate drought stress. Stress coefficients (K_s) provide a means to estimate water needs, while maintaining minimally acceptable turfgrass quality. The objective of this study was to derive K_s values for four bermudagrass (*Cynodon spp.*) cultivars grown in the transition zone. Direct measurements of actual evapotranspiration were made through weighing lysimeters during a 2-year period. The turfgrasses were allowed to naturally dry down to near wilting and then maintained at a steady state to allow for calculation of K_s values for each cultivar. 'Latitude 36' was the best performing cultivar with a K_s value of 0.774 and 'Celebration' was the worst preforming at 0.977. 'TifTuf" and 'Tifway" were between the two in the study. All the cultivars had a decrease in ET_a when compared to non-stressed turf, providing accurate K_s values for bermudagrass cultivars in North Carolina, while maintaining a minimally acceptable turf quality.

Introduction

There is increasing interest and regulation related to reducing irrigation water applied to landscape turfgrasses. For example, the Town of Cary (TOC), North Carolina passed an initiative to reduce landscape irrigation by offering a $500 USD incentive for property owners to replace turfgrass in their lawns (Town of Cary, 2008). One option they offered was replacing turfgrass with a natural landscape. States and cities in the southwest United States such as Phoenix, Arizona offer the same incentive looking to reducing amount of outside irrigation (City of Phoenix, 2020). A second option from the TOC was a monetary incentive to homeowners who switched from cool-season turfgrass species to a warm-season turfgrass species. The intended purpose of the initiative was to reduce excess water use by having homeowners switch to turfgrass species that are more water efficient during the summer months. This along with other intact irrigation restrictions are an attempt to decrease water use and provide a greater degree of sustainability for a state like North Carolina that gets most of its potable water from groundwater.

As water restrictions become more common, the ability to efficiently irrigate turfgrass has become integral to maintain healthy stands of turfgrass. By quantifying ET, water consumption can be measured, and irrigation regimens can be modified to fit the plant's water requirements. To improve irrigation scheduling, crop coefficients (K_c) have been utilized in conjunction with reference evapotranspiration (ET_o) to calculate actual evapotranspiration (ET_a) (Allen et al., 1998). Crop coefficients are the ratio used to define the difference in reference evapotranspiration and crop evapotranspiration. They may be developed based on month of the year, species, and cultivar (Romero and Dukes, 2016). Crop coefficients are derived directly from the plant's response therefore providing a useful tool in determining watering requirements for specific turfgrass species and cultivars.

Although crop coefficients and reference evapotranspiration are useful tools for turfgrass managers, they are determined during non-limited conditions (Parades et al., 2018). Water stress coefficients (K_s) relate to the impact that drought stress has on transpiration of the plant. The K_s values function similarly to crop coefficients (K_c), as both are meant to provide a way to correlate reference evapotranspiration to actual evapotranspiration. However, K_s provides an even greater understanding of the actual ET during times of limited irrigation or water stress as the plant will steadily decrease ET as the limited conditions worsen.

As soil moisture decreases, more stress becomes evident and quality will decrease along with ET rates (Zhang et al., 2017). By utilizing K_s values, the turf could be irrigated to a point in which quality is considered minimally acceptable, with reduced overall water needs. Considering irrigation recommendation for warm-season turfgrass is often one inch of irrigation per week in the absence of rainfall (Miller, 2018), a water-stressed turfgrass with a K_s value of 0.75 could reduce the water applications needs by 25 percent compared to not using a K_s values. By better understanding stress coefficients, water purveyors, landscape managers, and homeowners can use K_s values to schedule their needs, while maintaining an acceptable level of turfgrass quality.

One of the more difficult locations to properly gauge irrigation requirements for turfgrass species is the transition zone (Fu et al., 2004). The transition zone is a unique area in the United States where cool- and warm-season turfgrasses adoption overlap. The southern edge of transition zone is defined by the southern borders of North Carolina, Tennessee, Arkansas, and Kansas (Dunn and Diesburg, 2004). The transition zone creates a unique issue for growers as summer months create water stress for cool-season turfgrass species, while warm-season turfgrasses may experience winter kill during the winter. The objective of this field study was to determine Ks for four bermudagrass (*Cynodon* spp.) cultivars for use in the transition zone.

Lysimeter Use

Lysimeter construction was previously detailed by Wherley et al. (2009) and their use by Pinnix and Miller (2019a). The lysimeters were filled with Profile Greens Grade porous ceramic soil amendment (Profile Products LLC, Buffalo Grove Illinois). The lysimeters were established with ‘Latitude36’, ‘Tifway’, and ‘TifTuf’ hybrid bermudagrass [*Cynodon dactylon (L.)* Pers. *x C. transvaalensis* Burt-Davy] and ‘Celebration’ common bermudagrass [*Cynodon dactylon (L.)*], with three replications of each entry.

Turfgrasses were established in lysimeters prior to the start of the study to allow maturity before initiating water use measurements. Once the turfgrass established to one hundred percent coverage, lysimeters were inserted into in-ground plastic sleeves to prevent native soil adherence to the lysimeters’ outer walls (Pinnix and Miller, 2019a). Once placed into the sleeves, the soil surface of the lysimeters matched the surrounding soil levels. Turfgrasses grown in the lysimeters and healthy stands of TifTuf surrounding the sleeves were clipped at a mowing height of 2-inches using a single-blade rotary mower (Honda HRX217HZA Honda Power Equipment, Alpharetta, GA) with the clippings returned. The lysimeters were maintained under a portable rainout shelter covered with clear plastic (Four Seasons Tools, Kansas City, Missouri).

Water Use Measurement and Turfgrass Quality

Measurements of water loss were made three times a week in 2-3 day intervals using a tripod hoist with an S-beam load cell (CAS S-Beam, NTEP CoC 96-0373A1, East Rutherford, NJ) connected to a digital indicator (Salten Brecknell 200SL, Fairmont, MN). Prior to data collection, the soil profile in the lysimeters was saturated and allowed to drain for 24 h. After the draining period, the field capacity of each lysimeter was derived and lysimeter bottoms were plugged and maintained at field capacity for two weeks. The dry down commenced after these two weeks and ended for cultivar groups once visible stress for an individual experimental unit was noted. Visible drought stress was defined as leaf wilting or any form of turfgrass canopy discoloration, which was generally a color change to bluish-gray. Once an experimental unit showed visible drought stress its lysimeter weight was recorded and used as a baseline weight going forward. The other two lysimeter's weights within the cultivar group were recorded independently at this point to establish their baseline weights.

Water was added after each weighing interval to achieve baseline weights and to maintain minimally acceptable turf quality. The difference in mass between the baseline weight and the weight of lysimeters during the next weighing interval equaled crop evapotranspiration (ET_c) for the days separating the two weighing intervals. This methodology resulted in each turfgrass being maintained under continual water-limiting conditions. With each experimental unit held under water-limited conditions any decrease in expected evapotranspiration (reference evapotranspiration) was viewed as the cultivar's ability to restrict ET due to the water stress. This limited ET_c was considered adjusted crop evapotranspiration ($ET_{c\ adjusted}$), allowing us to measure the decrease in ET_c caused by water stress.

Turf quality was visually accessed every two weeks using guidelines established by the National Turfgrass Evaluation Program using a 1 to 9 scale (1 = brown, low-quality turfgrass, 9 = green, high quality turfgrass) (Morris and Shearman, 1998). In this study, 5 was considered to be minimally acceptable turf quality.

Reference Evapotranspiration Calculation and Crop Coefficients

Weather data were measured and logged on thirty-minute intervals with a weather station located under the rainout structure. Data recorded were maximum and minimum air temperature, solar radiation, relative humidity, average wind speed, and maximum gust speed. Recorded data was used to calculate ET_o per hour with Ref-ET software (Allen, 2013) using the ASCE standardized reference evapotranspiration formula for short grass canopies (Jensen and Snyder, 2005). Since all measurements other than the initial two weeks occurred under limited conditions, crop coefficients previously determined for bermudagrass at this location (Pinnix and Miller, 2019b) were utilized in our calculations.

Determining Stress Coefficients

$ET_{c\ adjusted}$ was calculated through the weighing intervals of lysimeters after the dry-down. The relation between the drought stress coefficient (K_s) and ET_c can be explained using the equation: $ET_{c\ adjusted} = K_s * K_c * ET_o$. If a plant conserves water, then during times of water stress the interaction of $ET_{c\ adjusted}$, ET_o, and K_c should provide a K_s value less than 1. The deficit measured in ET_c would represent the impact that water stress had on ET_c (Allen et al., 1998). If a plant was not stressed, then $ET_{c\ adjusted}$, ET_o, and K_c would ideally balance out to provide a K_s value of 1.

Statistical Analysis

Three years of data were collected under rainout structures at Lake Wheeler Turfgrass Field Laboratory in Raleigh, NC dating from June 2018 to September 2020. Data points were utilized from only 2018 and 2020 due to the limited data points from 2019. Statistical Analysis System (SAS) software was utilized to perform analysis of variance (ANOVA) with mean separation tests made with a Fisher's Protected LSD test at the 0.05 probability level. The univariate procedure in SAS was utilized to evaluate data distributions by cultivar as well as to determine possible data outliers. Data is presented by cultivar and by day of year (DOY) during the two years of data collection.

Meteorological Conditions

In 2018, the maximum ET_o value of 0.401 inches day^{-1} and the minimum ET_o value was 0.101 inches day^{-1} with an interquartile range of 0.154 (Fig 1). In 2020, the maximum value was 0.341 inches day^{-1}, minimum value was 0.113 inches day^{-1}, and the interquartile range was 0.085. Greater variability was noted in 2018 then compared to 2020.

Turfgrass Quality

Visual turfgrass quality ratings were recorded on two-week intervals in 2018 and 2020 (Fig. 2). TifTuf had the highest turfgrass quality (6.1), followed by Tifway (5.9), Latitude 36 (5.8), and Celebration (5.5). Quality rating means for all cultivars were above the minimally accepted turfgrass quality rating of 5. It was not the intention of this study to encourage differences in turfgrass quality among cultivars, but to evaluate water use near the lower threshold of turfgrass quality.

Derived Stress Coefficients

Because each cultivar hit benchmark weights on different time frames, the number of measurement days for each cultivar differed, with Tifway having 93 measurements, Latitude 36 having 89, Celebration having 80, and TifTuf having 59. These measurements for each cultivar were then structured into thirteen weeks based on intervals of seven numerical day of year (DOY) in 2018 and 2020 (Fig. 3). This was considered a measurement of drought escape as the cultivars restricted water use and maintained quality.

Differences in cultivar, year and the interactions that occurred among them are reported in a partial analysis of variance (ANOVA) table (Table 1). Cultivar, year, cultivar x year, cultivar x week, and cultivar x week x year had significant F-values. This indicated different cultivars resulted in different K_s value responses in those years. The variation in weather conditions played a role in turfgrass ET (figure 1). Latitude 36 and TifTuf had the lowest mean K_s values at 0.774, followed by Tifway (0.827), and Celebration (0.977). Mean separation test indicated Latitude 36, TifTuf, and Tifway were similar, and Celebration had a greater K_s value than the other cultivars. These K_s values suggest that Celebration was not as adaptive as the other cultivars in restricting ET when experiencing water stress. This is further expressed the interquartile ranges of the K_s values amongst cultivars. Tifway had the lowest K_s interquartile range at 0.278. Latitude 36, TifTuf and Celebration had interquartile ranges of 0.304, 0.342 and 0.482, respectively. This increased inner quartile range illustrated the greater variability with the Celebration data compared to the other cultivars (Fig. 4), suggesting a more inconsistent plant response during the study compared to other cultivars.

Variability in K_s values over time was partially in response to evapotranspiration rate. This is due to the contribution of weather conditions which impacted ET_o. Since weather influences are realistic in field research, the outliers in the data set were retained, which can be seen in figure 4. These outliers influenced the K_s means, so interquartile lengths were utilized to show distributions around K_s mean values.

Water Savings

The direct application of stress coefficients is to maximize water conservation with irrigation scheduling, while maintaining acceptable turfgrass quality. For example, the average lawn in the TOC, North Carolina is 7,707 square feet (Pinnix and Miller, 2019a). If the recommended irrigation for bermudagrass is 1 inch per week, that equates to 0.623 gallons per square foot. For the average lawn in TOC, a total of 4,801 gallons of water would be needed to irrigate a bermudagrass lawn each week in absence of rainfall. Utilizing the highest (Celebration) mean Ks value and lowest (TifTuf and Latitude 36) mean K_s values from this study, Latitude 36 and TifTuf would require 3,718 gallons of irrigation water and Celebration would require 4,691 gallons of irrigation water each week. The resulting 26 percent increase in water conservation is significant, especially as the area of managed turf increases.

Stress coefficient values could be utilized as a tool for water purveyors to maximize conservation with water allocations for turfgrass applications. In other cases, K_s values could be a part of water conservation strategies during droughts or times of low water availability. With aquifer depletion and overall water availability concerns, the ability to reduce irrigation while maintaining plant quality could be a very valuable tool in the future (Konikow, 2014).

Monetary value of using Stress Coefficients

The TOC uses a tiered system for water use costs. If the household were to utilize between 8,001 to 23,000 gallons in outside irrigation per month, a price of $6.71 USD per 1,000 gallons would be used (Town of Cary, 2021). The average TOC yard irrigation expense would be $32.17 USD a week. If mean stress coefficients were utilized, the same sized yards with Latitude 36 and Celebration would have expenses of $24.94 and $31.47 USD per week, respectively. The utilization of K_s values would allow for a reduction in irrigation costs and the conservation of water.

Improved Selection Strategies

Stress coefficient values are a measure of the degree in which turfgrasses are able to restrict their rate of transpiration, which can be useful for describing drought adjustment capacity of the turfgrass. Certain drought resistance traits allow for turfgrass and other plants to retain hydration while reducing water use (Carrow, 1995). An example of this is limiting ET through stomatal openings (Jespersen et al., 2019). Turfgrass' ability to prevent leaf firing and maintain acceptable quality provides insight into the genotype's drought resistance as quality is maintained during drought stress. These drought resistance characteristics can be considered drought escape as the plant prevents the decrease in quality while reducing water use (Colmer and Barton, 2017). Stress coefficients could be utilized as a quantitative measure of a cultivar's drought tolerance, therefore providing turfgrass breeders with another tool to assess drought tolerance when evaluating germplasm.

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Table 1. Analysis of variance table used to evaluate K_s values. Week was defined as 7 day of year (DOY) intervals during the study. Years tested were 2018 and 2020. The P-values presented are considered significant at an alpha level of 0.05 or lower.

Source of Variation	Degrees of Freedom	F- Value	Probability
Cultivar (C)	3	6.46	0.0006
Year (Y)	1	9.48	0.0062
Week (W)	10	2.51	0.6112
C*Y	3	0.61	0.0052
C*W	26	2.42	0.0007
W*Y	3	2.06	0.1192
C*W*Y	4	2.74	0.0386

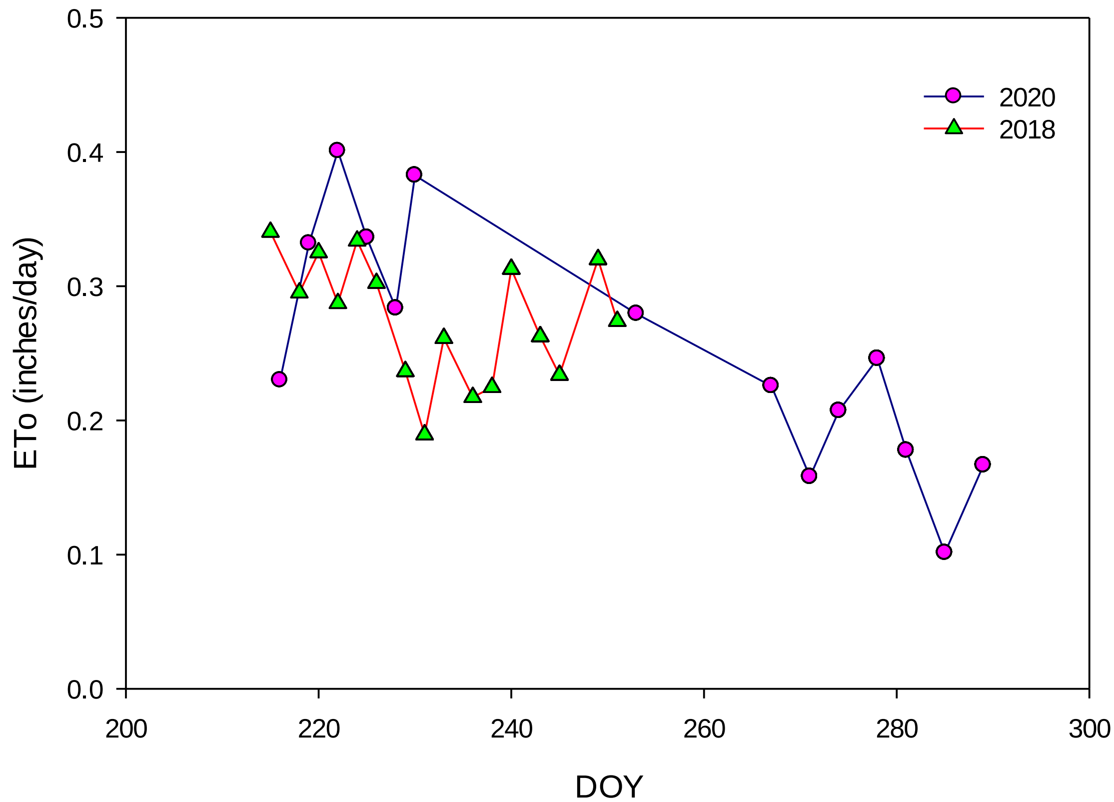

Figure 1. Reference Evapotranspiration Values from 2018 and 2020.

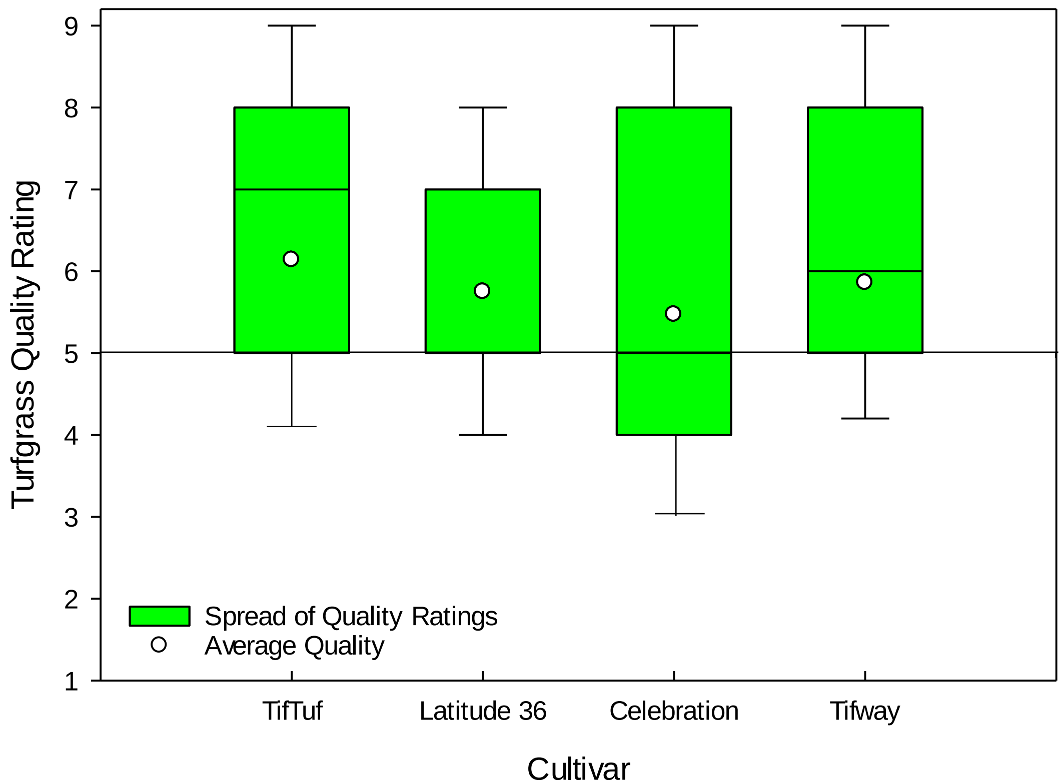

Figure 2. The distribution of visual turfgrass quality ratings of each cultivar. The single open symbol inside each boxplot denotes the mean turfgrass quality rankings for each cultivar and the line within the boxplots are median turfgrass quality rating. Whiskers denote the 5th and 95th percentile of turfgrass quality ratings.

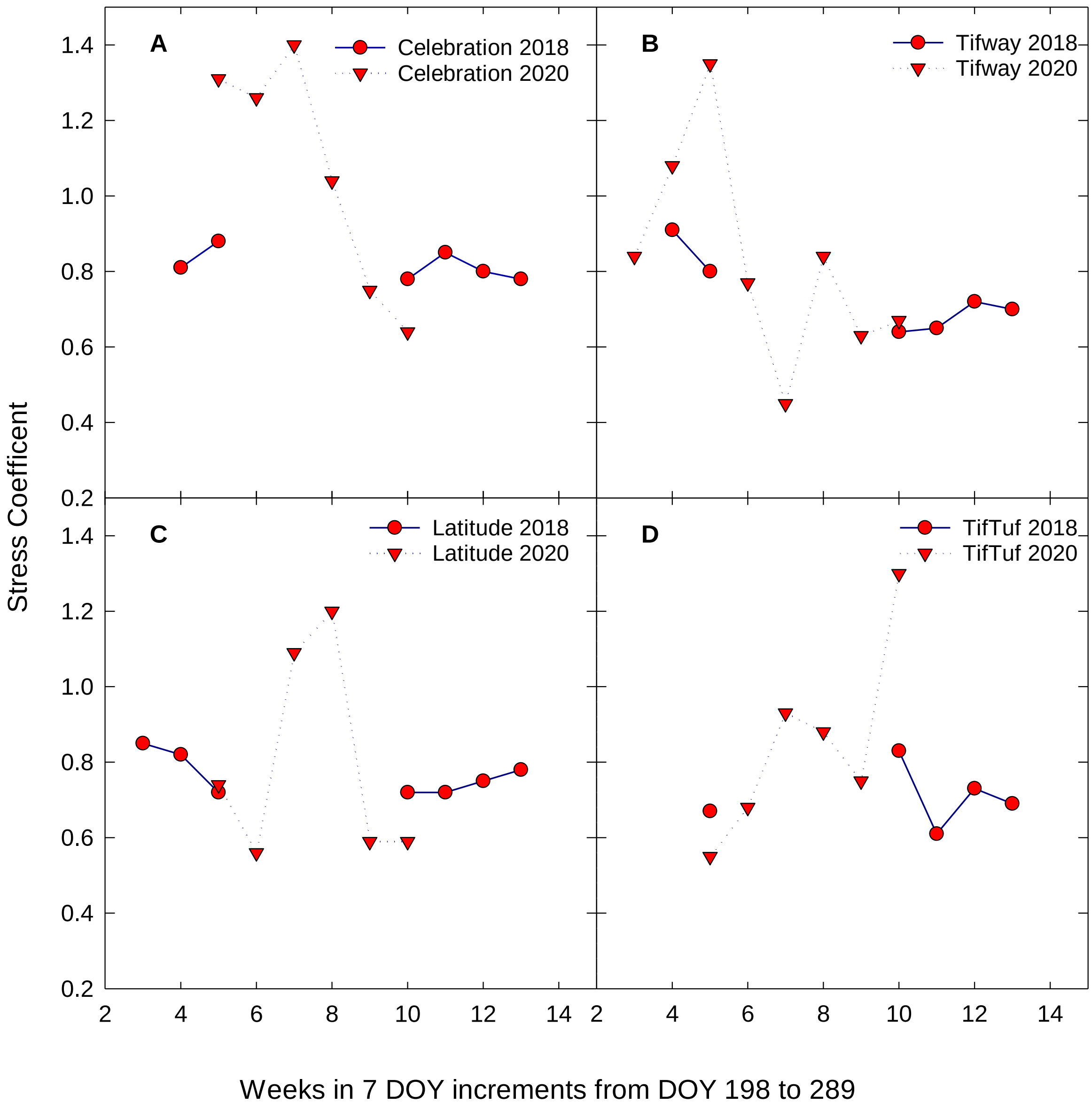

Figure 3. Calculated weekly stress coefficients during 2018 and 2020 for (A) Celebration, (B) Tifway, (C) Latitude 36, and (D) TifTuf. Each value represents a mean of 7 days starting at DOY 198 and ending at DOY 289. In 2018 there is a gap in between week 5 to week 10 due to a tropical rain event that disrupted data collection.

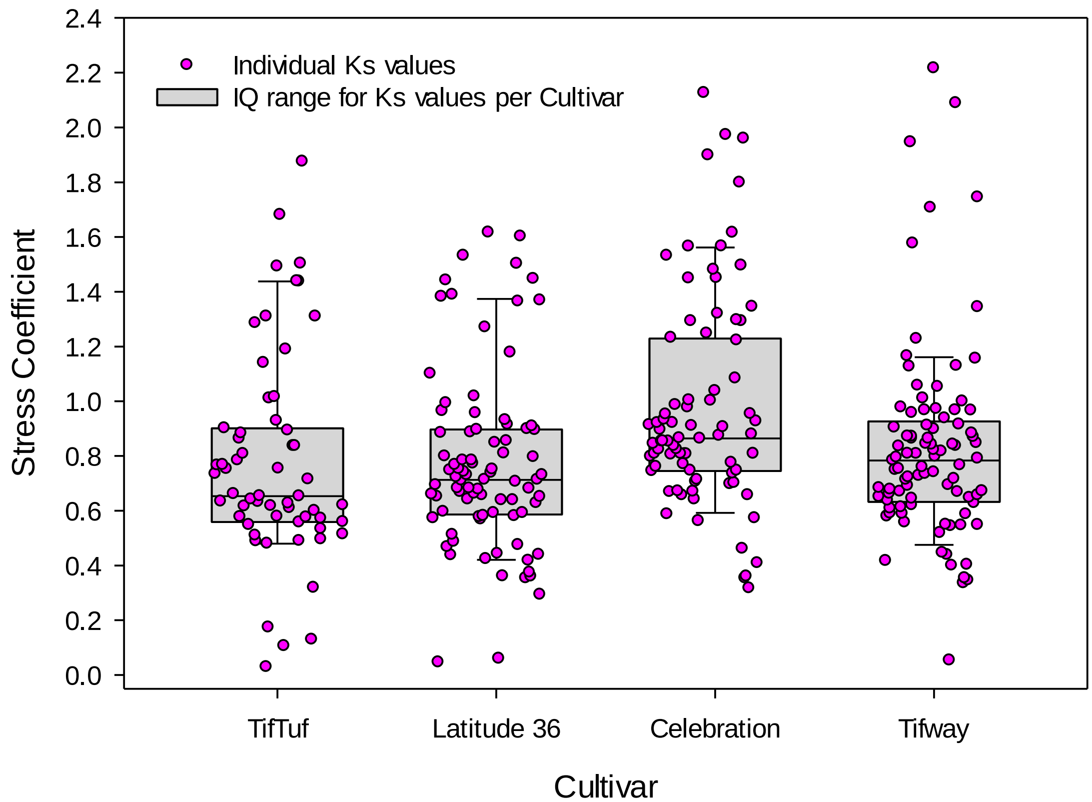

Figure 4. The interquartile (IQ) range of K_s values for each cultivar from data collected in 2018 and 2020. Each data point represents a calculated K_s values. Whiskers denote the 5th and 95th percentile of values.

Chapter 2: Development of Crop and Stress Coefficients for Turfgrass Species in the Transition Zone

Formatted for publication in *Crop, Forage, and Turfgrass Management*

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Abstract

Crop coefficients (K_c) are a common method to conserve irrigation applications by determining actual evapotranspiration (ET_a) from reference evapotranspiration (ET_o). Stress coefficients (K_s) takes K_c's relationship with ET_o and ET_a a step further by measuring the decrease in ET_a when plants are water stressed. While K_c are utilized to determine proper irrigation amounts to equate a turfgrass demand, K_s values are used to determine minimum water requirements while maintain minimally acceptable turfgrass quality. The objective of this study was to calculate K_c values and K_s values for warm-season turfgrasses in the transition zone. A secondary objective was to compare new drought resistant breeding lines to industry standard cultivars. Multiple genotypes were utilized with hybrid bermudagrass [*Cynodon dactylon (*L.*)* Pers. *x Cynodon transvaalensis* Burt-Davy], St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze), and zoysiagrass (*Zoysia spp. (*Z.*)*). A seashore paspalum (*Paspalum vaginatum*) industry standard was also included. All experimental units were established in watertight lysimeters and weighed to determine ET_a from May through September 2021. For K_s calculations, water was restricted until the point drought stress was evident. For K_c values 'Tahoma 31' bermudagrass had the lowest mean value at 0.778, while FAES1319 zoysiagrass had the highest value at 1.020. For species, bermudagrass had the lowest mean K_c value at 0.806, followed by seashore paspalum (0.808), St. Augustinegrass (0.837), and zoysiagrass (0.980). The K_s values ranged from 0.743 for DALSA1613 St. Augustinegrass to 1.170 for DALZ1606 zoysiagrass. For Ks values among species, the lowest was seashore paspalum (0.786), followed by St. Augustinegrass (0.856), bermudagrass (0.931), and zoysiagrass (1.040). Stress coefficient values allow for further estimation of minimum water requirements while still maintaining acceptable quality, which could be useful for irrigation conservation practices.

Introduction

North Carolina lies directly in the transition zone, a unique area in the United States where cool- and warm-season turfgrass use overlap. The southern edge of transition zone is defined by the southern borders of North Carolina, Tennessee, Arkansas, and Kansas (Dunn and Diesburg, 2004). This overlap of turfgrass use creates both issues and opportunities for turfgrass managers based on their location. It provides a situation that warm-season species thrive in the summer months, then go into dormancy with a chance of 'winter kill' during the winter (Miller, 2018). Parts of North Carolina have endorsed buyback programs to reduce the growing of cool-season grasses by replacing them with warm-season grasses (TOC, 2008).

With the increased amount of urbanization in the United States, turfgrass has become the dominant plant type in the U.S. accounting for 163,800 square kilometers of area. This is more than three times the area of other irrigated crops (Milesi et al., 2005). With the increase in turfgrass area, an emphasis has been placed on greater conservation of water resources used for irrigation. A widely adapted component of irrigation management is the use of weather stations to calculate reference evapotranspiration (ET_o) along with the application of appropriate crop coefficients (K_c) (Wherley et al., 2015). Crop coefficients are irrigation coefficients that once applied to ET_o calculations, provide a more accurate estimation of actual plant evapotranspiration (ET_a). Crop coefficients may be developed based on month of the year, species, and cultivar (Romero and Dukes, 2016). Crop coefficients are calculated by dividing actual evapotranspiration with reference evapotranspiration (Allen et al., 1998). With the diverse weather conditions seen in the southeastern U.S., and particularly in the transition zone, geographically accurate K_c vales need to be calculated to prevent over or under irrigation of turfgrass. Jia et al. (2009) calculated well-watered K_c values for bahiagrass (*Paspalum notatum*

Flugge) in central Florida and compared them to K_c work performed by Stewart and Mills (1967) in south Florida. Their results indicated that K_c values in south Florida were 21 percent greater than in central Florida. This disparity seen within the state of Florida illustrates the need for geographically accurate K_c values.

Crop coefficients are useful tools to increase irrigation efficiency but were intended to be utilized in non-limited water conditions (Parades et al., 2018). With the need for more efficient irrigation, stress coefficients (K_s) provide a means for further reducing irrigation by determining the water requirements needed to achieve the critical point of stress. This critical point is when soil moisture decreases to the point where plant stress becomes evident and quality decreases along with ET rates (Zhang et al., 2017). The ET reduction is from the restriction of stomatal openings, reducing transpiration losses (Verstreten et al., 2008). This decrease in ET from stomatal restriction is the factor that K_s is measuring. This translates to the plant's ability to survive drought stress while maintaining minimal quality.

Lysimeter Use

Lysimeter construction was previously detailed by Wherley et al. (2009). The lysimeters were filled with Profile Greens Grade porous ceramic soil amendment (Profile Products LLC, Buffalo Grove Illinois). The lysimeters were established to one hundred percent coverage with 'Tahoma 31', 'Tifway', 'TifTuf', or TIFB16117 hybrid bermudagrass [*Cynodon dactylon (L.)* Pers. *x C. transvaalensis* Burt-Davy]; 'CitraBlue', 'Floratam', DALSA1618, or DALSA1404 St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze); 'Empire', FAES1319, DALZ1606, or DALZ1613 zoysiagrass (*Zoysia spp. (Z.)*); and 'SeaStar' seashore paspalum (*Paspalum vaginatum* (Sw.)), with three replications of each.

Turfgrasses were established in lysimeters the year prior to the start of the study to allow maturity before initiating water use measurements. Following establishment, lysimeters were inserted into an in-ground plastic sleeve to prevent native soil adherence to the lysimeter's outer walls (Pinnix and Miller, 2019a). Once placed into the sleeves, the soil surface of the lysimeters matched the surrounding soil levels. The bermudagrass, zoysiagrass, and seashore paspalum treatments in the lysimeters, surrounded by a healthy stand of TifTuf, were clipped at a mowing height of 2-inches using a single-blade rotary mower (Honda HRX217HZA Honda Power Equipment, Alpharetta, GA) with the clippings returned. The St. Augustinegrass experimental units surrounded by 'Triple Threat' tall fescue (*Festuca arundinacea* Schreb.), were mowed at a height of 3.5 inches using the same mower, with the clippings returned. The lysimeters were maintained under a portable rainout shelter covered with clear plastic (Four Seasons Tools, Kansas City, Missouri). In-between growing seasons the grasses were overwintered underneath the rainout shelters and or at a nearby greenhouse for the less cold-hardy species.

Reference Evapotranspiration Calculation and Crop Coefficients

Reference evapotranspiration (ET_o) was derived through the ASCE standardized reference evapotranspiration formula for short grass canopies (Jensen and Snyder, 2005). Meteorological data to calculate ET_o was gathered from a nearby Cardinal Station (Lake Wheeler Road, Lat. 35.728°N, Long. 76.679°W). The industry standard crop coefficient of 0.6 for warm-season turfgrasses was utilized for stress coefficient calculation (Meyer et al., 1985), due to the lack of a complete, validated dataset to calculate relevant K_c values when K_s values were calculated.

Water Use Measurement and Turfgrass Quality

To date, one year of data has been collected at the Lake Wheeler Turfgrass Field Lab in Raleigh, North Carolina. Measurements of water loss were made three times a week in 2 to 3-day intervals using a tripod hoist with a S-beam load cell (CAS S-Beam, NTEP CoC 96-0373A1, East Rutherford, NJ) connected to a digital indicator (Salten Brecknell 200SL, Fairmont, MN). Prior to data collection, the soil profile in the lysimeters was saturated and allowed to drain for 24 h. After the draining period, the field capacity of each lysimeter was derived and lysimeter bottoms were plugged and maintained at field capacity for crop coefficient development for eleven weeks. After the eleven weeks of K_c calculations, a soil dry down was initiated. The point of visible stress for an individual experimental unit was noted. The weight at that point was recorded as the baseline weight for future use. Visible drought stress was defined as leaf wilting or any form of turfgrass canopy discoloration, which was generally a change to bluish-gray color. All lysimeter weights of the same genotype were recorded individually at this point as well. Light box images were taken during the dry down and throughout the data gathering period for K_s values. Detailed building instructions for the light box can be found in Zhang et al., 2016. Image analysis occurred through Image J (Ferreira and Rasband, 2010) with a turf analysis macro developed by North Carolina State University (NCSU Turf DIA) (Zhang et al., 2016).

Water was added after each weighing interval to achieve baseline weights and to maintain minimally acceptable turf quality. The difference in mass of the baseline weight and the weight of lysimeters during the next weighing interval equaled crop evapotranspiration (ET_c) for the days separating the two weighing intervals. This methodology resulted in each turfgrass being maintained under continuous water-limiting conditions. With each experimental unit held under water-limited conditions any decrease in expected evapotranspiration (reference evapotranspiration) was viewed as the cultivars ability to restrict ET due to the water stress. This limited ET_c was considered adjusted crop evapotranspiration ($ET_{c\ adjusted}$), allowing us to measure the decrease in ET_c caused by water stress. Soil water at field capacity was based on previous work (Banvel et al., 1976). Soil water content during the study was established based on water loss from field capacity due to ET. This allowed an estimation of soil water content at the point when genotypes reached their critical point of stress.

Turf quality was visually accessed every two weeks using guidelines established by the National Turfgrass Evaluation Program using a 1 to 9 scale (1 = brown, low-quality turfgrass, 9 = green, high quality turfgrass) (Morris and Shearman, 1998). In this study, 5 was considered to be minimally acceptable turf quality. Digital image analysis was made using a turfgrass analysis macro to quantify percent green cover as an objective way to quantify points of stress (Zhang et al., 2017).

Determining Stress Coefficients

The relationship between the drought stress coefficient (K_s) and ET_c can be explained using the equation: $ET_{c\ adjusted} = K_s * K_c * ET_o$ (Allen, 1998). The K_s calculation was achieved by dividing $ET_{c\ adjusted}$ by the interaction of K_c and ET_o. A K_s values less than 1 indicate the deficit in $ET_{c\ adjusted}$ due to the water-limited conditions; whereas a K_s values at 1 or greater indicate no water-stress (Garrot and Mancino, 1994). Garrot and Mancino, reported when water was present in the soil, K_s values increased. Whereas when water was limited the K_s values decreased.

Statistical Analysis

The univariate procedure within Statistical Analysis System (SAS) software was utilized to evaluate data distributions by genotypes as well as to determine possible data outliers. Based on the analysis, data were presented by entry and by day of year (DOY). SAS was utilized to perform analysis of variance (ANOVA), with contrast statements constituted to evaluate species and compare check cultivars to newer germplasm with a species. Means separation tests were made using Fisher's protected LSD (0.05 probably level) for turfgrass quality ratings and Tukey's test (0.05 probably level) for K_c and K_s data analysis.

Turf Quality

All entries maintained a mean turf quality rating above the threshold of 5.0 throughout the study. Turfgrass quality ratings analysis indicated that zoysiagrass maintained the highest mean turfgrass quality rating as a group at 7.1. St. Augustinegrass maintained the second highest mean quality at 6.6, which was similar to bermudagrass with a mean quality at 6.3. Seashore paspalum had the lowest mean quality rating at 5.9. Figures 1 and 2 report the quality ratings for entries within their species group, and as well as the quality ratings among species. Among the St. Augustinegrass entries, DALSA1618 had the highest turfgrass quality mean quality at 7.0, followed by CitraBlue at 6.8, DALSA1404 at 6.4, and Floratam at 6.2. Based on mean separation tests, DALSA1618 and CitraBlue were similar, with DALSA1618 greater than DALSA1404, and Floratam. CitraBlue was greater than Floratam which maintained the lowest quality of the St. Augustine entries. Tahoma 31 bermudagrass had the highest mean quality rating at 6.6 with TifTuf, TIFB16117, and Tifway having mean values of 6.6, 6.2, 5.7, respectively. Tahoma 31 and TifTuf were similar, but greater than TIFB16117 and Tifway which were similar. Tifway had the lowest overall quality of bermudagrass entries. FAES1319 zoysiagrass had the highest mean quality rating among the zoysiagrass entries at 7.3, with DALZ1606 at 7.2, DALZ1603 at 7.2, and Empire at 6.6. FAES1319, DALZ1606, DALZ1613 were similar, but each were greater than Empire. SeaStar maintained a mean turf quality rating of 5.9.

Quantifying Critical Point of Stress

Through digital analysis, the minimum visual turfgrass quality threshold of 5 had a correlating average green cover of 50 percent. All entry groups maintained a percent green cover over 50 percent. Digital image analysis identified 66.07 as the mean percent green cover for the point of critical stress. When correlating this to visual turfgrass quality ratings the closest was experimental units given a visual turfgrass quality of 6 which provided a percent green cover of 62.44 percent. The possible cause of this is that the three experimental units of an entry were averaged to visually determine critical point for the group. This resulted in some experimental units within an entry group to have higher quality than others within the group. As well as the drought characteristics of certain turfgrass species and genotypes which allow for a higher retention of quality when stressed.

Soil water content at critical points of stress were compared (Fig. 3). The genotype that had the lowest percent soil water content at the critical point of stress was CitraBlue at 14.7 percent. The genotype with the highest soil water content percentage was Tifway at 17.8 percent. The genotype with the largest variability in soil water was TifB16117 with an interquartile range (IQ) of 0.045 percent, while SeaStar had the lowest amount of variability with an IQ range of less than 0.001 percent. The value of recognizing soil water content at these critical points of stress was presented by Zhang et al. (2017). Their study found that turfgrass species with an earlier break-point will begin the conservation of water quicker than turfgrasses with break point closer to permanent wilting point. This indicates species with break points at greater soil water content conserve more water, than species with break points at lower soil water. Their results for the break points for St. Augustinegrass and zoysiagrass cultivars were similar in year one to first-year data in this study. Break-point values allow for additional measurements of the critical stress point that is integral to K_s value calculations.

Derived Crop Coefficients

At the species level, bermudagrass had the lowest mean K_c value at 0.806, followed by seashore paspalum (0.808), St. Augustinegrass (0.837), and zoysiagrass (0.980). Tukey's significant difference test indicated that bermudagrass, seashore paspalum, and St. Augustinegrass were similar, but different from zoysiagrass, which had the highest mean K_c value. These lower values suggest that the bermudagrass entries were more efficient with water use compared to other species.

An analysis of variance with contrasts statements can be found in table 1. The contrasts comparisons between K_c values that were significant included St. Augustinegrass genotypes less than bermudagrass genotypes (*P*=0.0002), zoysiagrass genotypes less than St. Augustinegrass (*P*=<0.0001), zoysiagrass genotypes less than bermudagrass (*P*=<0.0001), St. Augustine genotypes less than seashore paspalum (*P*=0.0214), and zoysiagrass genotypes less than seashore paspalum (*P*=<0.0001). Within species, St. Augustine experimental germplasm was less than St. Augustinegrass check (*P*=0.0085). The lower mean K_c values measured within the checks (0.812 vs. 0.844) suggests the current industry standard cultivars for St. Augustinegrass utilize less water than the experimental germplasms tested. The contrast comparing the check cultivars of all the species tested vs experimental germplasms as a group was significant (*P*=0.0065), with the checks having a lower mean K_c value. The current industry standard cultivars utilized less water than their experimental germplasms counterparts during the first year of research. This indicates cultivars that have been widely utilized are efficient in their water use. This was not a great surprise since most of these check cultivars have been successful commercially, in part, due to their drought tolerance.

Table 2 shows K_c mean values and the corresponding interquartile ranges per genotype. Among St. Augustinegrass entries DALSA1404 had the lowest mean K_c value of 0.801, followed by Floratam, CitraBlue, and DALSA1618 with mean K_c values of 0.812, 0.852, and 0.882, respectively. Among bermudagrass entries, Tahoma 31 had the lowest mean K_c value of 0.772 with Tifway, TIFB16117, and TifTuf at 0.781, 0.789, and 0.885, respectively. The only seashore paspalum cultivar evaluated (SeaStar) had a mean value of 0.808. Zoysiagrass entries DALZ1613, DALZ1606, Empire, and FAES1319 produced mean K_c values of 0.938, 0.975, 0.985, and 1.02, respectively

Turfgrass genotypes that produce consistent K_c values under a range of environmental conditions allow for more accurate irrigation scheduling, particularly during times of high variability. The interquartile (IQ) range of bermudagrass had the least amount of variability with a range of 0.162. Zoysiagrass had the second least amount of variability with an IQ range of 0.233. St. Augustine with an IQ range of 0.234, seashore paspalum had largest degree of variability within its K_c value with an IQ range 0.243 (Figure 3). The entry with the least amount of variability in K_c values was TIFB16117 at 0.123; whereas the cultivar with the largest variability was SeaStar at 0.243. The K_c values were measured over time to estimate stability under different environments (Figure 4 and 5). The K_c variability in this study was similar to the response reported by Atkins et al. (1991). In their study of ten St. Augustinegrass genotypes, ET_c was measured in controlled environments. They observed variability in ET_c amongst the genotypes and the effect of time on ET_c measurements, with the greatest variability measured when the entries with high ET rates. Variability in K_c values in our study supported the response found by Atkins et al., suggesting that germplasm is responsive to weather conditions. Figure 5 shows the general trend formed amongst the species over time, and how responsive K_c values were to changes in environmental effects.

Derived Stress Coefficients

Genotypes that produce lower K_s values indicate an increased ability to restrict water use during times of drought-stress, allowing for greater water conservations during times of drought. Mean K_s values at the species level indicated that seashore paspalum had the lowest mean K_s value at 0.786, followed by St. Augustine (0.856), bermudagrass (0.931), and zoysiagrass (1.040). Tukey's significance test found Seashore paspalum and St. Augustine were similar, but only St. Augustinegrass was similar to bermudagrass. The values for zoysiagrass were also different from bermudagrass.

Within species, St. Augustine DALSA1404 had the lowest mean K_s value at 0.744, followed by Floratam (0.861), CitraBlue (0.906), and DALSA1618 (0.924). Bermudagrass cultivars Tahoma 31 had the lowest mean K_s value of 0.812, followed by Tifway, TifTuf, TIFB16117 with mean K_s values of 0.890, 1.00, and 1.03, respectively. Within the zoysiagrasses Empire had the lowest mean K_s value at 0.948, followed by FAES 1319 (1.01), DALZ1613 (1.03) and DALZ1606 (1.17). SeaStar seashore paspalum cultivar had a mean K_s value of 0.786. Indicating that at the DALSA1404 was able to conserve more water during drought conditions then other genotypes.

Table 1 shows all the K_c mean values and the corresponding interquartile ranges for each genotype. An analysis of variance table with contrasts can found in table 2. The Ks values of St. Augustine genotypes were lower than zoysia genotypes (*P*=0.0396). This indicates greater drought resistance in the St. Augustinegrass entries compared to zoysiagrass entries. The seashore paspalum check was lower than St. Augustine genotypes (*P*=0.0024). The seashore paspalum check was lower than zoysiagrass genotypes (*P*=<0.0001). Seashore paspalum was lower than bermudagrass genotypes (*P*=0.0010). The contrast between check cultivars vs experimental germplasms (*P*=0.0003), indicated the industry standard check cultivars had a lower mean K_s than the experimental germplasms. This suggests that the industry checks were more successful at limiting ET than the experimental germplasms that were tested.

Large differences in K_c values were reported in water deficit K_c studies in Arizona for common and hybrid bermudagrasses. Garrot and Mancino (1994) performed short soil dry downs to the point of wilting before applying irrigation. Their study provided K_c values that ranged from 1.50 to 0.10, which they indicated were influenced by the presence or absence of water in the soil. They framed the values as deficit K_c values, but since the values occurred under limited conditions they are similar to K_s values reported in our study. As with their study, when water was readily available in the soil the values increased, when water was limited, the values decreased. Their study indicated that water presence causes deficit irrigation coefficients to have values over 1 indicating use of water by the turfgrass when water is available.

The species with the smallest interquartile (IQ) spread of K_s values was zoysiagrass with an IQ range of 0.208 indicating the least amount of variability. Bermudagrass had a K_s range of 0.243, St. Augustinegrass 0.268, and seashore paspalum had the largest degree of variability with a range of 0.303. Figure 6 shows the interquartile spread for all the entries. The lowest variability within K_s values was Empire at 0.109, and the largest variability was DALSA1618 at 0.326.

The variability in K_s values within species from week to week is illustrated in figure 7, and genotype Ks variability over time in figure 8. Weather can be an uncontrollable factor resulting in time periods where K_s values are inapplicable (denoted when the K_s values are great than 1). Garrot and Mancino (1994) reported that weather could result in situational variability in stress coefficients.

Crop Coefficient Use

Crop coefficient use is much more widespread and common than that of stress coefficients. Because K_c values are a reflection of actual evapotranspiration compared to reference evapotranspiration, they have practical use throughout the turfgrass industry (Romero and Dukes, 2016). A study conducted from 2008 to 2010 in central Florida, calculated K_c values for Tifway, Empire, Floratam, and 'Argentine' bahiagrass (Wherley et al., 2015). The study reported mean K_c seasonal averages for Tifway, Empire, and Floratam of 0.66, 0.68, and 0.54, respectively in the first year and 0.53, 0.59, and 0.58, respectively in the second and third year. In the first year, our study reported K_c growing season means of 0.78 for Tifway, 0.99 for Empire, and 0.81 for Floratam. Even with this being first year data, the differences measured in Raleigh, North Carolina, compared to central Florida shows the need for geographically correct K_c values. This is important to ensure accurate irrigation allocation. For example, when ET_o for a given day is 0.50 inches/day the first year, Florida K_c value for Tifway had an ET_a of 0.33 inches of actual water loss, compared to this study's 0.39 inches. If utilizing Florida's K_c values in Raleigh, over-irrigation would occur based on our first-year data. Additional years of data collection will allow for more accurate K_c values to be generated, ensuring decreases in the chance of over and under-irrigation (Carrow, 1995).

Water Allocation and practical use of K_s values

Stress coefficient values are different in use and practicality compared to K_c values. As K_c values for cultivars and species were reflected in K_s values, K_s values were only a measure of ET reduction from drought stress. Stress coefficient values have their cultivar or species-based

K_c values along with properly calculated reference ET to accurately reflect actual evapotranspiration during times of limited conditions. In our study Tahoma 31 had a mean K_s value of 0.812 using the industry standard of 0.6 for K_c value. These coefficients combined decrease reference ET by 51.3 percent. This is due to the interaction of K_s and K_c in the formula $ET_{c\ adjusted} = K_s{*}\ K_c{*}ET_o$. Both coefficient values assist with accurately interpreting $ET_{c\ adjusted}$ from ET_o. An example would be if a grower needs 6,100 gallons of water based on ET_o calculation for a stand of Tahoma 31 or Empire while utilizing their K_s values. In the case of Tahoma 31, the actual amount needed if the grower is utilizing a standard K_c value (0.6) would on be 3,660 gallons. If the grower were to utilize our K_s values that amount decreases to 2,972 gallons. This is a 51 percent decrease in overall water application compared the 40 percent decrease that would be seen with K_c values alone. Comparing this to Empire zoysiagrass with reported a mean K_s of 0.948, Empire would require 3,470 gallons of water or 43 percent less than using just the ET_o calculation.

It is also important to consider at how K_c values can impact K_s values, as they are integral to the calculation of K_s values. In the Wherley et al. (2015) study, the K_c calculations with Floratam reported a first-year value of 0.54 compared to 0.81 in this study. If a three-day span in Raleigh provided a mean ET_o of 0.7 inches, while ET_a was 0.35, then a Florida K_c value produces a K_s value of 0.93, whereas our study produced a K_s value of 0.62. This shows the influence that non-geographically accurate K_c values can have on K_s calculations.

Species and Cultivar Selection

The K_s values can be a measure of the plant's individual survival mechanisms, as K_s values are physically measuring the ET reduction seen from stomatal restrictions during times of stress. The mean K_s value of bermudagrass was 7.2 percent less than zoysiagrass. Miller and

Pinnix (2019b) derived crop coefficient values for hybrid bermudagrass and tall fescue cultivars. In their study, the decrease of K_c values for hybrid bermudagrass ranged from 16 to 34 percent from May to October of 2017 and 2018. Accurate geographical K_c and K_s values can benefit municipalities and landscapers in properly identifying species and cultivars that can conserve water.

Assistance in Selection Strategies

Drought resistance is the ability of a plant to survive prolonged drought stress through various mechanisms, like drought tolerance and avoidance (Jespersen and Schwartz, 2018). Drought avoidance is the mechanism that turfgrasses utilize to maintain adequate tissue water content, allowing for an avoidance or postponement of water stress. Previous work has been conducted at measuring drought avoidance at the species level through determining critical points of water stress or break points. Zhang et al. (2017), brought their turfgrass treatments to a permanent wilting point, whereas this study brought the turfgrasses to the point of visible stress. This distinction is noteworthy as our experimental units were irrigated to maintain the minimally acceptable turfgrass quality that was measured at the critical point of stress. Genotypes with lower break-points in our study, such as CitraBlue, were able to avoid showing visible signs of stress longer than genotypes like Tifway which had a higher break point, in similar environmental conditions.

As the main observed traits with drought avoidance is limiting evapotranspiration, there is the possibility that genotypes that produce higher K_s values fail to restrict their ET effectively while maintaining minimal turf quality during times of water stress, (Pornaro et al., 2020) as can be seen with the differences between Tahoma 31 and TifTuf in figure 3. Tahoma 31 produced a significantly lower K_s value at 0.812 versus TifTuf's 1.001, but it's break point was at a higher soil water content compared to TifTuf. This indicates that Tahoma 31 is able conserve more water than TifTuf, however, it will incur visible signs of stress earlier than TifTuf due to Tahoma 31 having a breaking point at higher soil water content. Miller (2000) evaluated the effects of bermudagrass drought stress when grown in different soil amendments. In that study, the amendments that resulted in lower break points maintained the turfgrass at higher level, with a corresponding higher daily ET. Amendments that had a higher breaking point had lower visual quality but more restricted ET rates. This suggests that genotypes with lower K_s values may be able to restrict ET more effectively while genotypes with higher K_s values may be able to avoid showing signs of visible stress longer and fail to restrict their ET when quality first begins to dip to minimum levels. This would indicate that species with lower K_s values are able to maintain a higher quality while still effectively restricting ET, compared to the genotypes with higher K_s value.

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Table 1. Partial analysis of Variance table used to evaluate crop coefficients (K_c) values and stress coefficients (K_s). Contrasts statements were utilized to compare genotypes within species. The P-values are considered significant at an alpha level of 0.05 or lower.

Source of Variation	K_c Degrees of Freedom	K_c P value	K_s Degrees of Freedom	K_s P Value
Week (W)	10	<0.0001	4	<0.0001
Genotype (G)	12	<0.0001	12	<0.0001
G*W	120	0.1404	48	0.0012
St. Aug[a] vs Bermuda	1	0.0002	1	0.6426
St. Aug vs Zoysia	1	<0.0001	1	0.0396
Bermuda vs Zoysia	1	<0.0001	1	0.1169
St. Aug vs Paspalum	1	0.0214	1	0.0024
Zoysia vs Paspalum	1	<0.0001	1	<0.0001
Bermuda vs Paspalum	1	0.9458	1	0.0010
St. Aug Checks vs Expt[b]	1	0.0085	1	0.0953
Bermuda Checks vs Expt	1	0.1357	1	0.1941
Zoysia Checks vs Expt	1	0.1055	1	0.3934
All Checks vs Expt	1	0.0065	1	0.0003

[a] St. Aug, St. Augustine

[b] Expt, Experimental Germplasm

Table 2. Mean K_c and K_s values and interquartile (IQ) range for each entry evaluated in the study.

Entry	Mean K_c	K_c IQ Range	Mean K_s	K_s IQ Range
Tahoma 31	0.771	0.161	0.812	0.235
TIFB16117	0.789	0.123	1.030	0.278
TifTuf	0.885	0.224	1.001	0.317
Tifway	0.781	0.159	0.890	0.169
Empire	0.985	0.236	0.948	0.109
FAES1319	1.020	0.216	1.010	0.185
DALZ1606	0.975	0.190	1.170	0.301
DALZ1613	0.938	0.215	1.030	0.173
CitraBlue	0.852	0.226	0.906	0.211
Floratam	0.812	0.168	0.861	0.240
DALSA1404	0.801	0.185	0.743	0.168
DALSA1618	0.882	0.224	0.924	0.326
SeaStar	0.808	0.243	0.786	0.303

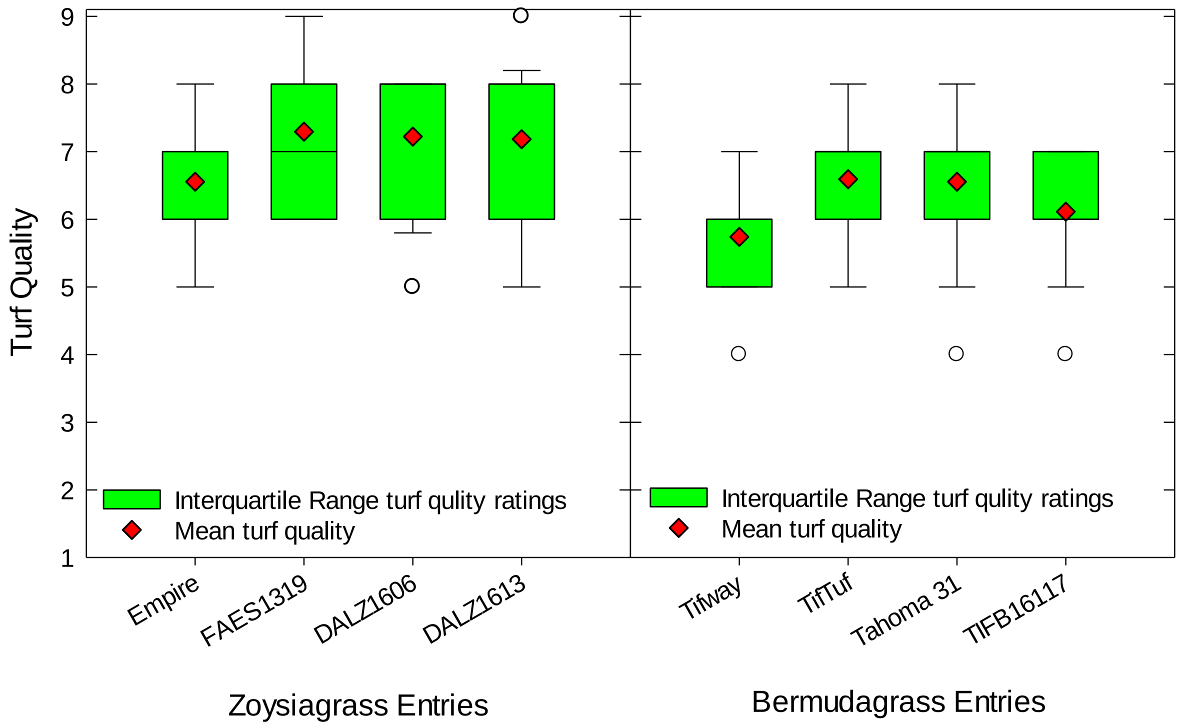

Figure 1. Turfgrass quality rating interquartile range, mean values, and outliers measured for turfgrass quality ratings for genotypes in zoysiagrass and bermudagrass species.

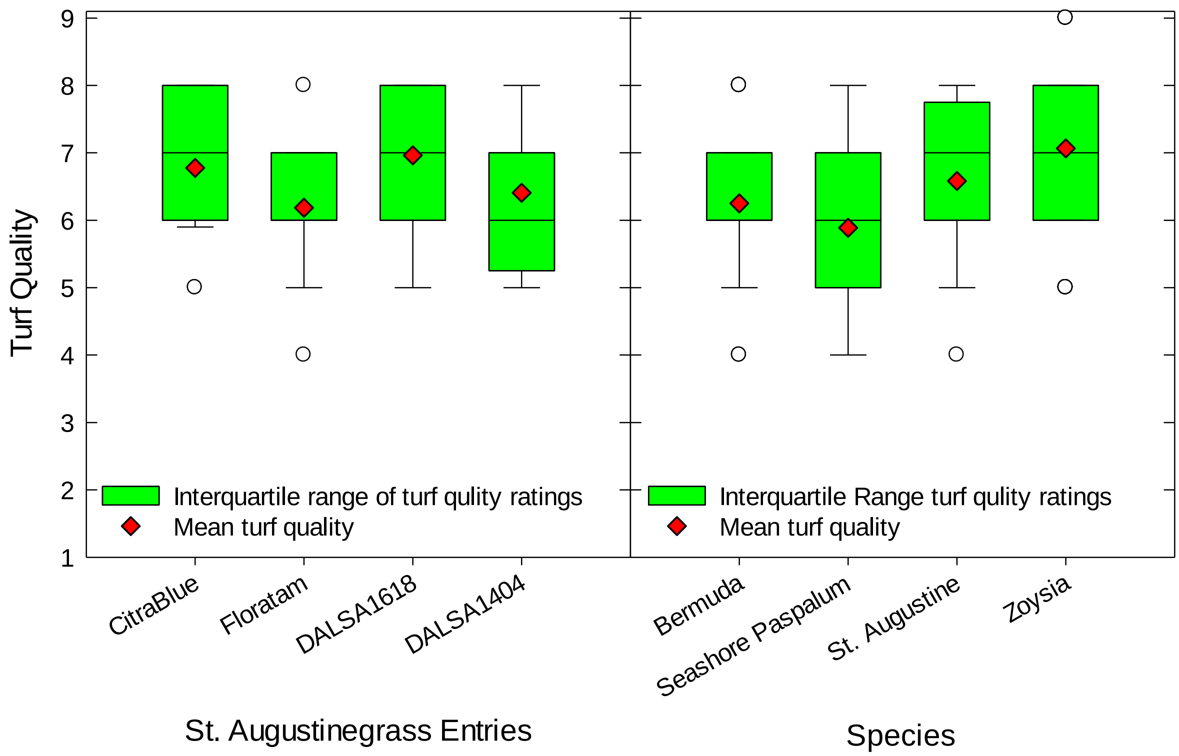

Figure 2. Turfgrass quality interquartile range, mean values, and outliers for genotypes within St. Augustine species on left side of figure and species means on right side of figure.

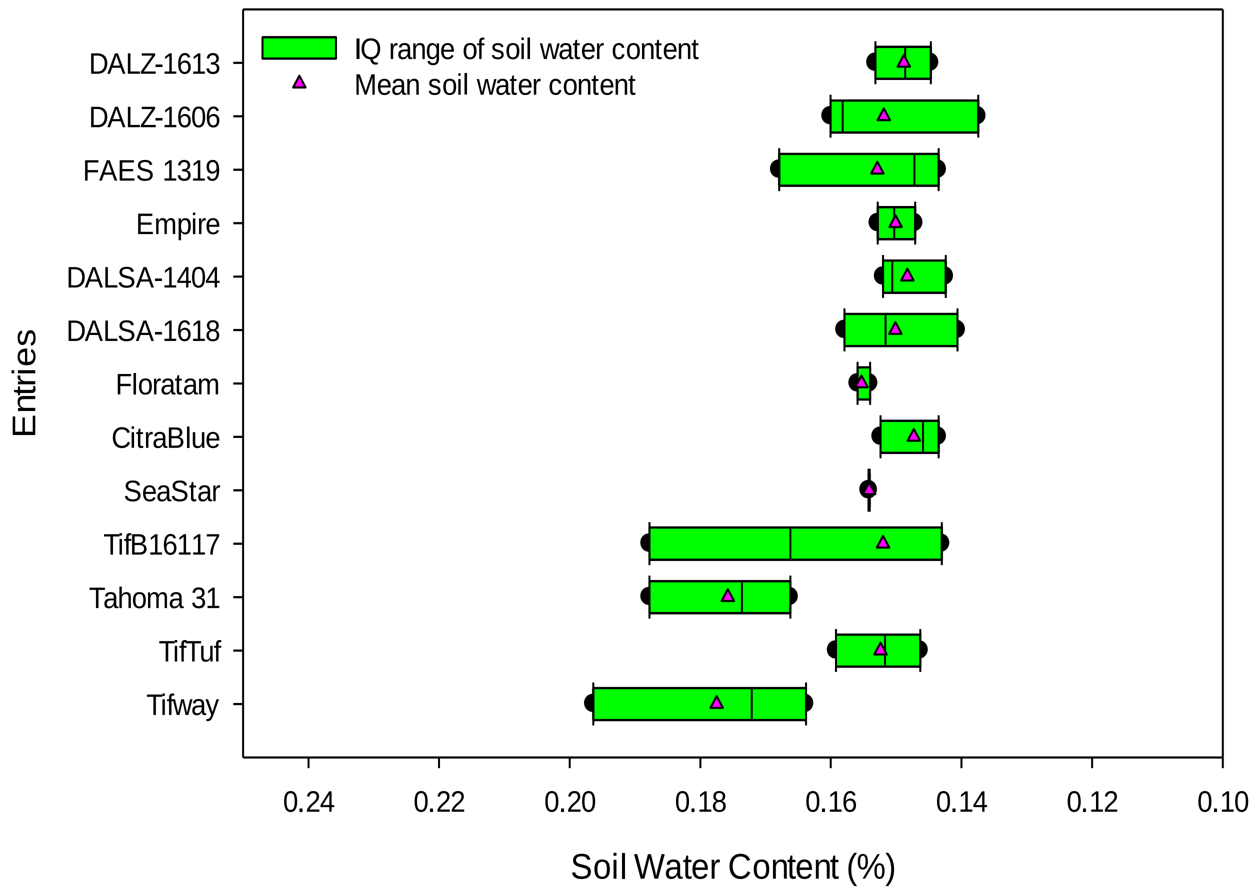

Figure 3. Interquartile range (5% to 95%) of soil water content at the point of visible drought stress. Triangles represent the mean soil water content for each genotype.

Figure 4. Box plots illustrating the crop coefficient interquartile (IQ) spread. The individual dots are the individual K_c values measured.

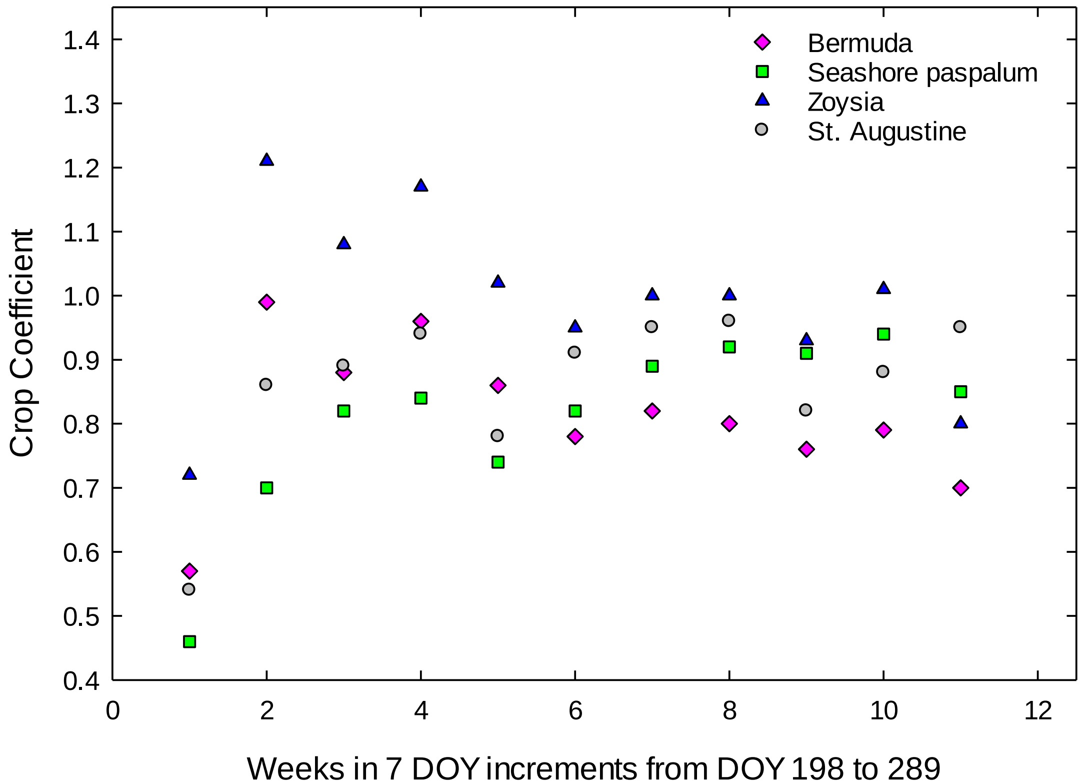

Figure 5. Crop coefficients means for the tested turfgrass species based on 7 day of year intervals through the study (DOY).

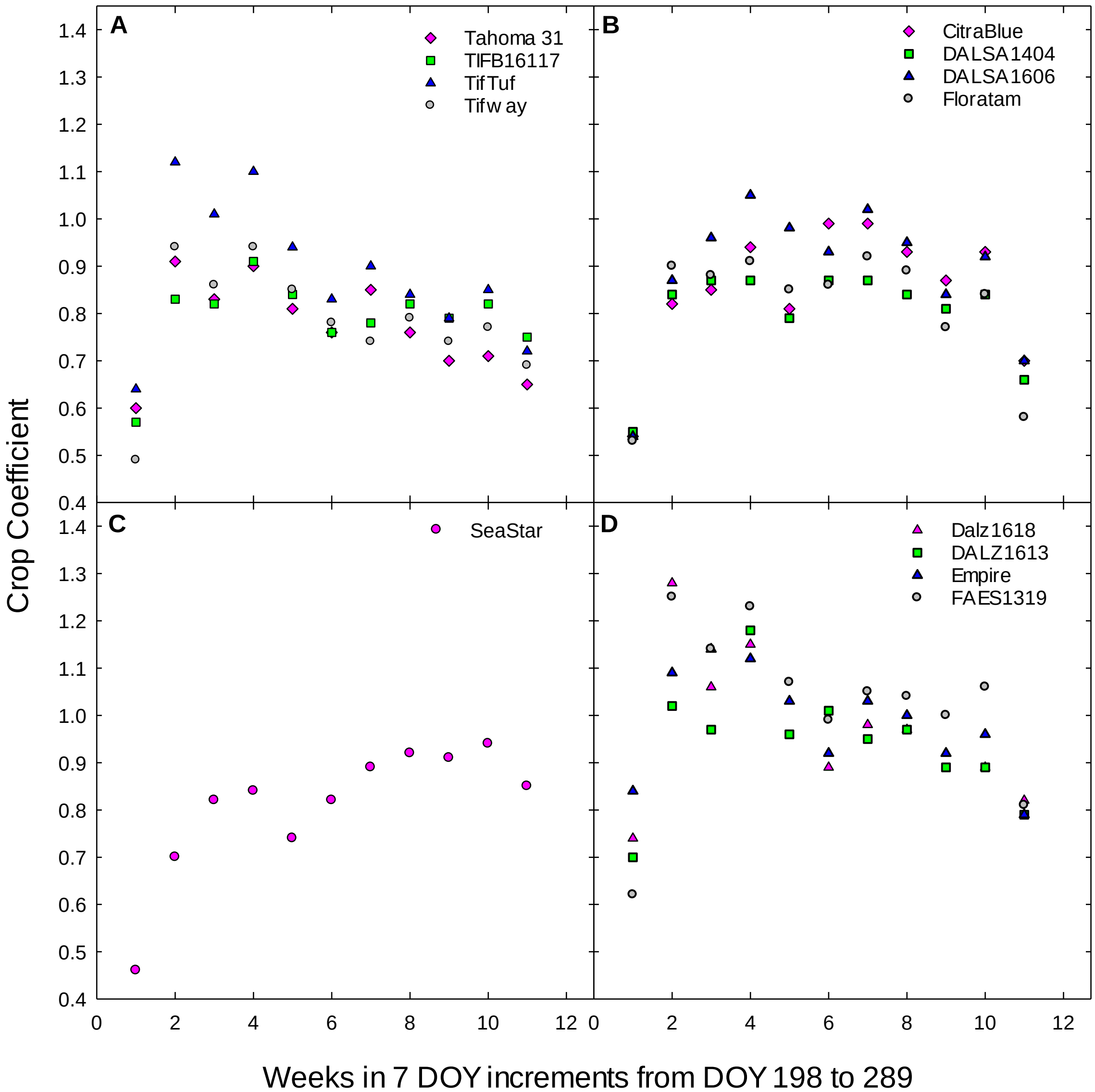

Figure 6. Crop coefficient means for bermudagrass (A), St. Augustinegrass (B), seashore paspalum (C), and zoysiagrass (D) over time based on 7 day of year (DOY) intervals throughout the study.

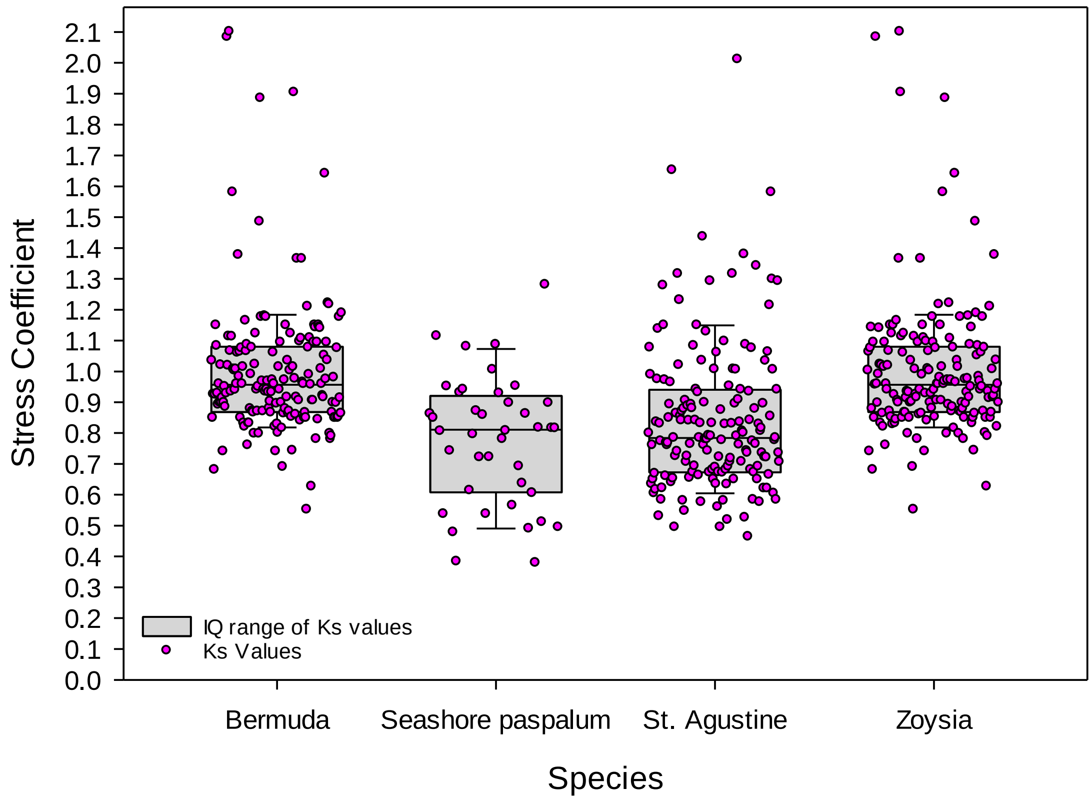

Figure 7. Interquartile (IQ) range of K_s values throughout the study. The individual points are individual K_s values.

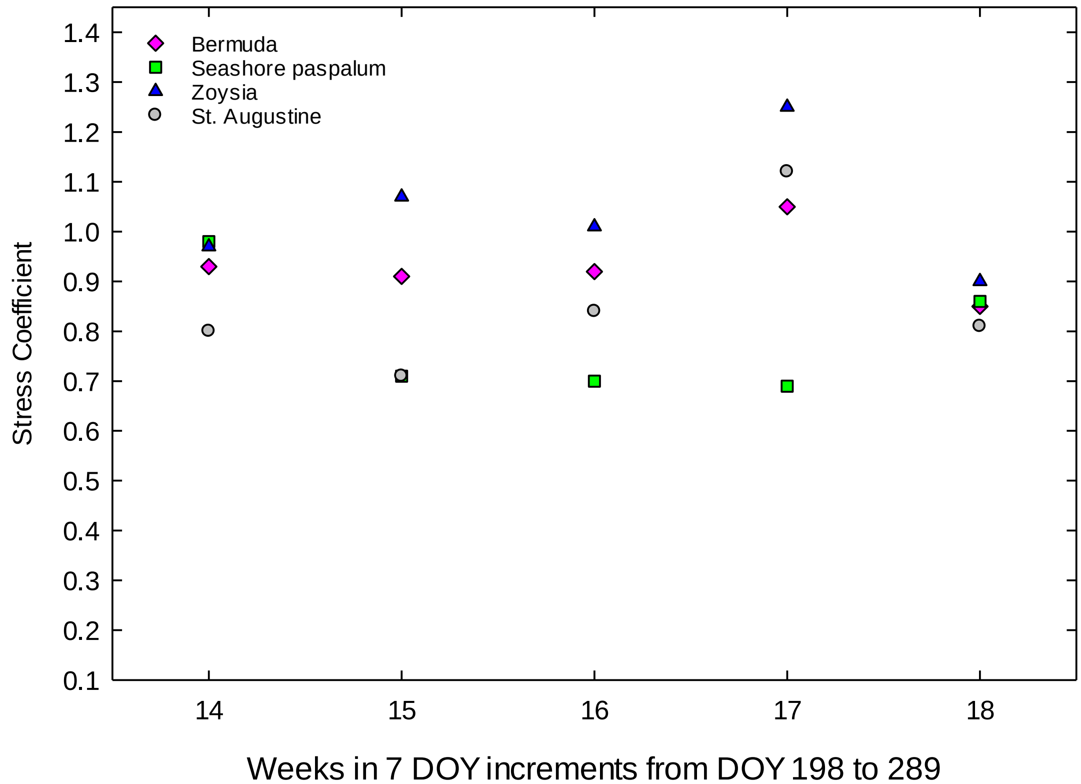

Figure 8. Stress coefficient values measured for each species based on 7 day of the year (DOY) intervals.

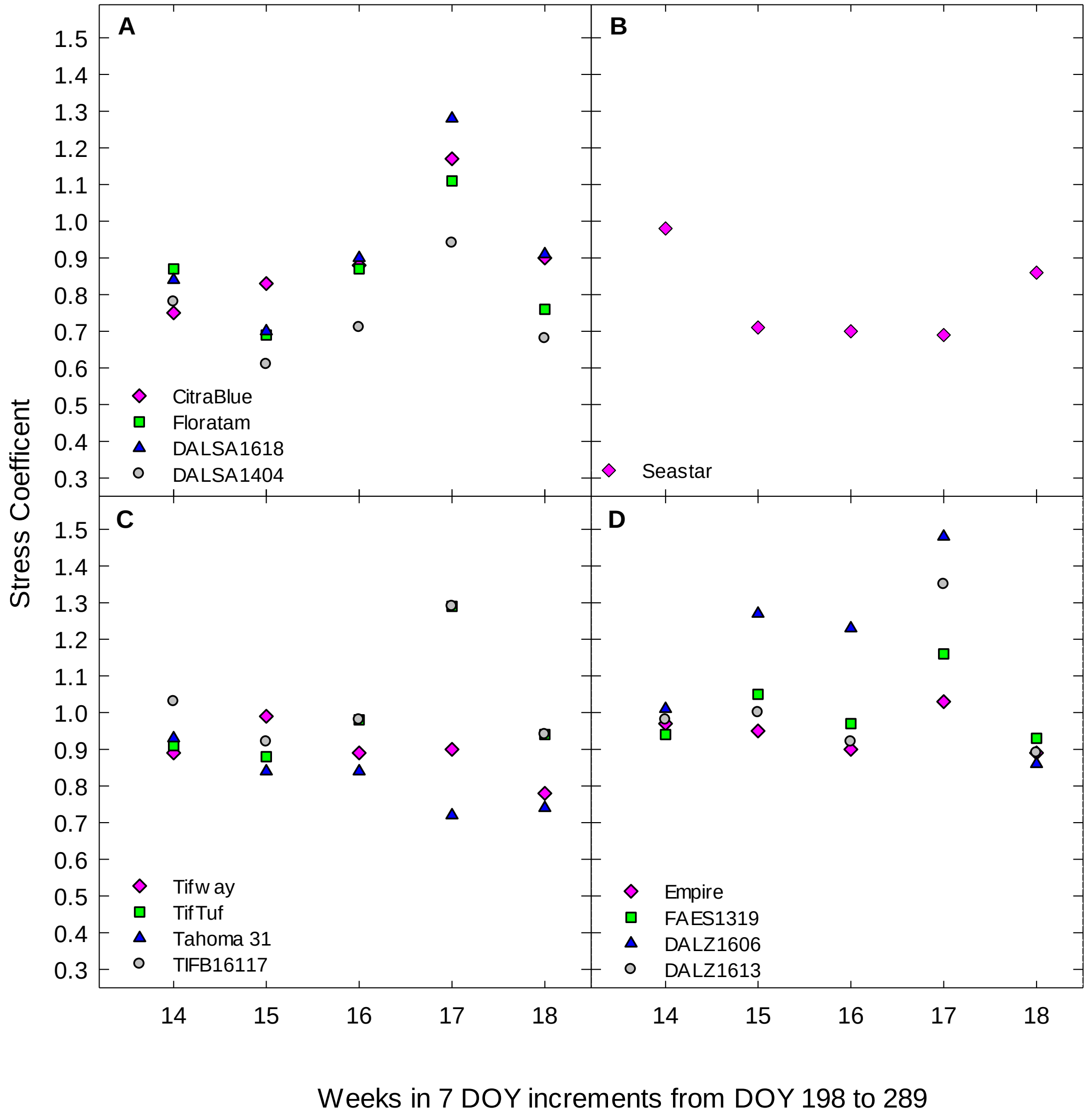

Figure 9. Stress coefficient means of bermudagrass (A), St. Augustinegrass (B), seashore paspalum (C), and zoysiagrass (D) over time based on 7 day of year (DOY) intervals throughout the study.