EVALUATING WATER USE RATES AND ROOT GROWTH CHARACTERISTICS OF TURF BERMUDAGRASS CULTIVARS UNDER NON-LIMITING SOIL MOISTURE CONDITIONS IN OKLAHOMA

By

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Bachelor of Science in Agriculture

Tribhuvan University

Kathmandu, Nepal

2010

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2014

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ACKNOWLEDGEMENTS

I would like to express my utmost appreciation to my major advisor, Dr. Justin Quetone Moss, for his excellent guidelines, patience, persistent help, and motivation. I feel proud and lucky to be his graduate student and it was a pleasure to join his team. I would like to thank Dr. Dennis Martin and Dr. Yanqi Wu for their assistance, support, guidance, comments, and suggestions as committee members.

I would like to personally thank Mr. Santanu Bikram Thapa, a former MS student, for establishing the field plots and lysimeter construction. I especially thank Dr. Kemin Su. Dr. Su put in many hours assisting with data collection. This project would not have been completed without the assistance of Zan Wang, Rachana Poudel, Chrissie Segars, and Mingying Xiang who help me in the greenhouse and field and with data collection.

I would also like to thank Mr. Bart Frie for managing my field research plots and Mr. Stephen Stanphill for managing the research greenhouse. My sincere thanks go to all the members of the Oklahoma State University Turfgrass Research Center and the Department of Horticulture and Landscape Architecture.

Finally, I would like to thank my friends and family for their unending support. I could not have completed my MS degree and had such a good time at Oklahoma State University without their support.

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Date of Degree: DECEMBER, 2014

Title of Study: EVALUATING WATER USE RATES AND ROOT GROWTH
CHARACTERISTICS OF TURF BERMUDAGRASS CULTIVARS
UNDER NON-LIMITING SOIL MOISTURE CONDITIONS IN
OKLAHOMA

Major Field: HORTICULTURE

Abstract: Evapotranspiration (ET) rates of ten bermudagrasses (*Cynodon* spp.) were evaluated in the field using weighing mini-lysimeters with calcined clay as the rooting media. Similarly, root growth characteristics were evaluated in a greenhouse using 120 cm growth tubes. The purpose of this research was to identify experimental genotypes as well as commercially available bermudagrass cultivars with low water use rates, longer root length, and greater root surface area. A total of six commercial (‘Tifway’, ‘Celebration’, ‘Premier’, ‘TGS_U3’, ‘Latitude 36’ and ‘NorthBridge’) and four experimental (‘DT-1’, ‘OKC 1302’, ‘OKC 1131’, and ‘OKC 1163’) bermudagrass entries were evaluated. Before dawn, mini-lysimeters were saturated, drained to field capacity, and the initial weight was recorded. After 24 and 48 hours, mini-lysimeters were weighed again to obtain an estimate of the daily ET rate. Significant genotype and date effects were found within each year, whereas year and genotype x year effect were found significant in the overall analysis. The genotype x date effect was not significant for 2013 but significant in 2014. Data were analyzed separately for 2013 and 2014. In 2013 TGS_U3, DT-1, Premier, and NorthBridge used more water than OKC 1163, Tifway, and OKC 1131. In 2014 DT-1, Celebration, and OKC 1302 used more water than Premier, TGS-U3, Latitude 36, NorthBridge, OKC 1163, and OKC 1131. In 2013 the ET rates ranged from 4.14 mm d^{-1} to 4.74 mm d^{-1} whereas in 2014 ET rates ranged from 4.93 mm d^{-1} to 6.19 mm d^{-1}. The root study showed that 65 to 90% of total root length and 65 to 96% of root surface area were located in the upper 30 cm profile. The entries TGS_U3, OKC 1302, OKC 1131 and NorthBridge were the only entries that had root growth into the 90-120 cm profile. The entry OKC 1163 had roots no deeper than the 60 cm profile while Premier, Latitude 36, Celebration, DT-1, and Tifway had roots no deeper than the 90 cm profile. The results from this study show the potential for irrigation water conservation by adopting bermudagrass cultivars with lower ET rates and longer and extensive root systems with greater surface area.

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CHAPTER I

LITERATURE REVIEW

Bermudagrasses (*Cynodon* spp.) are perennial, sod-forming warm season grasses adapted for use as turfgrasses on recreational areas, lawns, athletic fields, and industrial sites throughout the humid and semi-arid region of the southern and western United States. Common bermudagrass [*C. dactylon* (L.) Pers.] has its center of origin in East Africa. In the late 1700s, it was introduced to the warmer regions of the United States likely from Africa and India (Deputy et al., 1998). *Cynodon dactylon* is commonly called bermudagrass or common bermudagrass but it is also known as kweekgrass in South Africa, couch grass in Australia and Africa, devil's grass in India, gramillia in Argentina, and tooth grass in China (Duble, 1996). Bermudagrass propagates by seed and vegetatively by rhizomes (underground stems), tillers, and stolons (above ground stems). Bermudagrasses are popular in the southern United States due to their low water use rate, resistance to heat and drought, dense sod formation, good traffic tolerance, and relative ease of establishment.

Bermudagrass Growth Habit and General Adaptation Features

Bermudagrass is found throughout warm, humid, tropical and subtropical areas of the world (Beard, 1973). Duble (1996) described the ideal condition for bermudagrass growth as high sunlight and temperatures, mild winters, and moderate to high rainfall. Bermudagrass can be grown in soil types ranging from heavy clays to deep sands (Duble, 1996). The preferred soil textures for bermudagrass growth are loamy sand, coarse sandy loam, and loam (Beard, 1973). The granular and crumb soil structure are preferred for bermudagrass growth because of improved infiltration, percolation, and aeration (Beard, 1973). Bermudagrasses can tolerate acidic and alkaline soil conditions but performs best between soil pH 6.5 and 8.0. Limestone should be added at pH below 6.5 on the basis of soil test recommendations (Duble, 1996). Bermudagrass requires a medium to high intensity of culture and its prostrate growth habit makes it very tolerable of low mowing heights (Beard, 1973). Bermudagrass mowing requirements depend upon variety, physiological conditions of the turf, uses of the turf, and growth habit of the specific cultivar (Beard, 1973). Most common bermudagrass used for general purpose can be mowed as low as 1.3 cm (0.5 in.) to 2.6 cm (1 in.) (Duble, 1996). To maintain good quality and to avoid scalping, frequent mowing of turf is necessary (Beard, 1973). With the onset of cool, freezing temperatures and shortened day lengths, bermudagrass discolors and typically remains in a state of dormancy throughout the winter (Beard, 1973). According to Duble (1996), bermudagrass remains dormant until average daily temperatures rise above 10 ^{o} C (50 ^{o} F) for several days. The growth of bermudagrass begins at temperatures above 10^{o} C (50^{o} F) and the optimum temperature for growth ranges between 24-37^{o} C (75-99^{o} F).

The genus *Cynodon* contains 9 species (Harlan et al., 1970). *Cynodon dactylon* contains diploid, triploid, tetraploid, pentaploid and hexaploid plants with broad genetic variability while African bermudagrass [*C. transvaalensis* (Burtt Davy)] is a diploid species which rarely produce viable seeds (Duble, 1996). Common bermudagrass, African bermudagrass, and crosses between these two species (C. *dactylon* x *C. transvaalensis*) are economically important in the turfgrass industry (Beard, 1973).

Turfgrass Water Use

Water is one of the unique, mobile, and abundant compounds on earth. It is the vital constituent of all living plants. Approximately 80% of usable fresh water is used in agriculture (Muthena, 2011). In the United States, approximately 50 million acres of lands are estimated to be managed as turfgrass in the form of home lawns, golf courses, athletic fields, highway roadsides, cemeteries, parks and playgrounds with an economic value estimated at $40 billion per year (Beard and Kenna, 2008). Each year, 476 billion gallons of water are estimated to be used for golf course irrigation in the United States (Zoldoske, 2003). In the United States, 2.9% of all irrigation water is used in landscape and 1.5% is used on golf courses (Zoldoske, 2003). Although 1.5% is relatively small compared to agricultural uses, most of the golf courses are located in urban areas which need large amounts of potable water. In order to reduce the cost of water treatment and seasonal scarcity of water, it is needed to adopt improved irrigation and water conservation practices and grow low water using plant species.

The turfgrass production and maintenance industry is a major employer and economic industry in Oklahoma. In Oklahoma, up to 50% of municipal and city water is used to irrigate lawns during summer months. Assuming 50% of water use is outdoor, a 10%

reduction in landscape water use would save 9.5 million gallons of water per day during the growing season in Tulsa and Oklahoma City area (Oklahoma Water Resources board, 2011). With urban and suburban population increases, previously non-irrigated range, pasture/crop lands are being converted to home lawns and landscapes which have increased the urban outdoor water use. Outdoor water use can be reduced simply by using plant materials that are best adapted to the particular climate and by managing irrigation based on climate data and on-site weather station information.

The water requirements of turfgrass vary with turfgrass species and within cultivars of the same species. The water requirement of bermudagrass is also affected by environmental factors such as solar radiation, temperature, humidity, and wind speed. Water requirements increase with increasing levels of maintenance (golf green> bowling green> fairway> sports field> lawn> roadside) (Duble, 1996). A typical turfgrass plant has a water content ranging from 75 to 85% by weight (Beard, 1973). A reduction of 10% of the water content by weight within a short time may be lethal to the grass (Kim, 1983). The turfgrasses cannot utilize for purposes of growth and development all of the water that is taken up by the plant. Only 1 to 3% of the absorbed water is utilized in plant metabolic processes. Most of the water is transported to shoots where it is transpired. Turfgrass water requirement is the total amount of water needed for plant growth plus water lost through evapotranspiration (ET) (Jensen, 1968).

Water availability is becoming gradually limited in recent years. Continuous population increase and drought has made water conservation a major concern. Increased water use rates will likely pose a problem in the near future due to increased ET rates. To address this problem it is necessary to quantify how much water is used in urban landscaping.

The first choice will be turfgrass as it is one of the important components of urban landscaping. There are grasses best adapted to the wet and dry climates. Though bermudagrasses are tolerant to drought relative to other turfgrass species, a sufficient amount of water is required to maintain high quality (Christians, 2004). Selecting drought resistant species and cultivars is the best strategy to overcome drought and to reduce water requirement (Carrow, 1996a and 1996b).

Drought Resistance

Drought is a prolonged period of moisture stress conditions. Drought resistance refers to the ability of the plant to survive under water deficit conditions. Plants survive drought through physiological and structural mechanisms (Fry and Huang, 2004). Dehydration avoidance, dehydration tolerance, and drought escape are drought resistance mechanisms that turfgrasses employ (Fry and Huang, 2004). During the period of drought, both drought avoidance and drought tolerance mechanisms operate to ensure turfgrass survival. Drought tolerance involves maintaining adequate cell turgor and desiccation tolerance. Some grasses tolerate drought by osmotic adjustment (OA) related to solute accumulation, increased elasticity, and decreased cell size (Beard, 1989). Desiccation tolerance is influenced by protoplasmic resistance (Beard, 1989).

Drought avoidance mechanisms allow plants to escape tissue injury during drought by reducing water loss via decreased transpiration and increasing water uptake through development of a deep and extensive root system. Water loss can be reduced by increased canopy, stomatal, and cuticular resistance to ET, reduced leaf area, and decreased radiation absorption (Beard, 1989). High root density, deep rooting, and extensive root hair development make bermudagrass superior in drought resistance via dehydration avoidance (Casnoff and Beard, 1985; Kim, 1987).

Under moist soil conditions, the canopy resistance is a major component in reducing water loss compared to stomatal and cuticular resistance (Beard, 1989). Studies conducted by Johns (1980) and Johns et al. (1983) shows higher external canopy resistance than the internal stomatal and cuticular resistance in St. Augustinegrass [*Stenotaphrum secundataun* (Walter) Kuntze]. Casnoff et al., (1985) also found that under well watered conditions, stomatal density had minimal effects on the ET rate. High verdure, high shoot density, high leaf number, and more horizontal leaf orientation are the main morphological factors contributing to high canopy resistance (Kim 1983; Kim and Beard, 1988; Shearman, 1986; Sifers et al., 1987). Plants reduce water loss by decreasing leaf area from where ET occurs. The morphology behind this is slow vertical leaf extension, narrow leaf area, and a short leaf length (Beard 1989).

A study conducted by Zhao et al. (1994) in commercially available cultivars of cool-season turfgrass using 30 cm diameter x 22 cm deep pots demonstrated that grasses having lower ET during water stress conditions resulted in greener turf, thus showing superior drought resistance. Zhou et al. (2009) conducted a lysimeter study of eight bermudagrass genotypes and found that the genotypes having lower ET remained green for longer periods after a drought treatment. They also found that the genotypes having lower ET rates had more available soil water at later stages of the drought treatment. Generally, bermudagrass have superior drought resistance as compared to other warm season turfgrass species (Carrow, 1995 and Qian et al., 1997). Zhou et al. (2012) reported dehydration avoidance as the main mechanism of bermudagrass drought resistance in a drought resistance study of different bermudagrass ecotypes collected from different climates in Australia.

Evapotranspiration

Evapotranspiration is the combination of two separate processes: evaporation and transpiration. In evaporation, water is lost in the vapor form from soil and plant surfaces whereas transpiration is water that is used and lost to the atmosphere through the plant canopy. Evapotranspiration data are presented similar to that of precipitation i.e. the depth of water loss over particular time period. ET is measured in millimeters per day (mm d^{-1}) (Beard, 1985). ET rates of turfgrasses range from 3 to 8 mm d^{-1} and can be as high as 12 mm d^{-1} (Beard, 1973). According to Duble (1996), typical water use rates may range from 2 to 10 mm d^{-1}, depending upon specific environmental conditions. Since only 1-3% of water absorbed by plant is actually utilized in metabolic process, water use rates are generally considered equal to ET rates.

Plant transpiration occurs through cuticles, lenticels, and stomata. Plant transpiration is regulated by the physiological activity of the protoplast. The rate of transpiration is different for different plant species. About 95% of leaf transpiration occurs through stomata. Stomata are small pores present in the leaf surface (Mereu et al., 2012). Most of the plants have a large number of stomata on the underside of the leaf. Stomata regulates CO_2 uptake for photosynthesis and water loss by transpiration. The stomata are bounded by guard cells. The opening and closing of stomata is controlled by turgor pressure differences between the guard cells and bulk leaf epidermis. Environmental factors such as solar radiation, temperature, wind speed, drought, and sub-stomatal CO_2 concentration influence the opening and closing of stomatal aperture (Mereu et al., 2012). Stomatal opening is also affected by soil water supply, soil temperature, and amount of water absorb by roots. Stomata close partially or even totally when evaporative demand exceeds the water replenishment capacity. Higher evaporative demand can be due to higher temperature, intense wind, and high leaf to air vapor pressure deficit.

The ET rates of vegetation is a function of soil moisture, plant type, stage of plant development, and weather (Brown, 2014). Soil moisture is the most critical factor that affects ET rates. Adequate available soil moisture is needed for evaporation to take place. Simply there will be no evaporation if there is no water in the soil. Kneebone and Pepper (1984) reported that the availability of adequate soil moisture exhibits luxury water consumption which results in increased water use rate. The crop types, variety, and development stage also plays a critical role in determining the ET rates.

Evapotranspiration rates vary depending upon the species or cultivars of a species grown (Kim, 1983). According to Carrow (1991) the ranking of cool season and warm season turfgrass species on the basis of drought resistance and ET are: ‘Tifway’ bermudagrass [*C. dactylon* (L.) Pers. x *C. transvaalensis* (Burtt Davy)]> common bermudagrass> ‘Raleigh’ St. Augustine> ‘Rebel II’ tall fescue [*Schedonorus arundinaceus* (Schreb.)]> common centipedegrass [*Eremochloa ophiuroids* (Munro) Hack.]> ‘Kentucky 31’ tall fescue. Plant morphological and growth characteristics such as shoot and leaf density, leaf extension rates, leaf width, leaf, and shoot orientation also affect ET rates (Ebdon and Petrovic, 1998; Ebdon et al., 1998). Crop height, roughness, reflection, and rooting characteristics results in different ET rates under identical environmental conditions. The amount of water required for plant growth is determined by the plant size and activity of the plant. Dormant plants use very little water as compared to actively growing plants.

Large plants with dense plant canopies will require considerably more water than small plants with sparse canopies.

Weather is another critical factor that affects the ET rate. Weather parameters affecting ET rates are solar radiation, air temperature, humidity, and wind speed. Solar radiation contributes energy available for ET processes. Solar radiation is the main source of energy that converts water to vapor for ET. The air temperature is affected by solar radiation absorbed by the atmosphere and heat radiated by the earth. The vapor pressure difference between an evaporating surface and atmospheric air is a crucial factor for ET. Due to excessive energy and a dry atmosphere, crops grown in arid regions require large quantities of water. However, crops grown in humid regions require less water due to reduced ET due to high humidity. Wind is another critical factor affecting the ET rates. A wind transport saturated air and replaces it with dryer air. Less saturated air absorbs water vapor from plants which results in increased ET rates. As temperature increases, transpiration also increases. When the air temperature is high, stomata open resulting in increased ET rates. However, if the temperature is low, stomata close releasing less water. Temperature also affects the effectiveness of radiant energy and wind on evaporating water. In addition, temperature affects vapor pressure deficit. The vapor pressure deficit estimates the difference in vapor pressure between moist vegetation and drier atmosphere above. The relative humidity is also an important consideration in ET. As relative humidity increases ET rates decreases. Under a high relative humidity air is more saturated, hence, less water is evaporated from plant.

Evapotranspiration can be classified into potential ET and actual ET. Potential ET is the measure of the ability of the atmosphere to remove water from the plant and soil surface through the process of evaporation and transpiration. Actual ET is the measure of an actual amount of water that is removed from surface through the process of evaporation and transpiration.

Method of Estimating Evapotranspiration

Evapotranspiration can be estimated by direct and indirect measurement methods. Direct measurement methods include hydrological balance, lysimeters, and portable chambers. Indirect methods include energy balance, eddy correlation, and Bowen ratio-energy balance. The most common method for estimating ET are weighing lysimeters, Bowen ratio- energy balance, and energy covariance system (Gavilan and Castillo-Llanque, 2009). Most of the empirical methods require accurate measurement of meteorological variables such as solar radiation, temperature, relative humidity and wind speed. However, meteorological stations having accurate climatic variables are limited. The maintenance and installation cost of these weather station instruments are expensive and complicated.

Reference Evapotranspiration

Reference ET is the ET rate of ideal reference surface. This ideal reference surface resembles an extensive green surface of uniform height, actively growing, completely shading the surface, having minimal resistance and adequately watered (Allen et al., 1998). A reference crop is a hypothetical crop having height of 0.12 m, surface resistance of 70 s m^{-1} and an albedo of 0.23.

Estimated Evapotranspiration

Estimated evapotranspiration (ET_c) can be calculated by multiplying reference ET (ET_o) by a crop coefficient (K_c).

$ET_c = K_c \times ETo$

Where,

ET_c crop evapotranspiration [mm d^{-1}],

K_c crop coefficient [dimensionless],

ET_o reference crop evapotranspiration [mm d^{-1}].

Crop coefficient (K_c) is the ratio of crop ET (ET_c) to reference ET (ET_o). The value of K_c depends on crop types, crop growth stages, climate, and soil evaporation. Carrow (1991) reported K_c of warm season grasses ranges from 0.63 to 0.78 whereas K_c of cool season grasses ranges from 0.79 to 0.82 in May and October in the Southern United States.

Annandale and Stockle (1994) descried K_c variations due to differences in location. Their assumption was K_c values would be universally valid if reference ET variation was able to describe the weather variation. The energy balance method was used to test the sensitivity of a crop coefficient to variation in solar radiation, air temperature, air vapor density, and wind speed. Universal validity of crop coefficient was not fulfilled with decreasing crop canopy resistance and increasing crop height. Crop coefficient values were found to be different with changes in weather for taller crops and /or with lower canopy resistance than the reference crop. Crop coefficients derived from crops having similar height and canopy resistance to that of a reference crop are typically stable across environments.

Seasonal error could occur when a K_c is developed under a single climatic condition or environment (Jagtap and Jones, 1989). Jagtap and Jones (1989) found large seasonal errors in ET values when there were differences in wind speed, radiation, irrigation interval, temperature, planting dates, and vapor pressure. Depending on season, climate, and management variable K_c needs to be adjusted by correction factor ranging from 0.73 to 1.30 (Jagtap and Jones, 1989). They divide a crop coefficient into plant specific and soil specific coefficient and found plant coefficients were more stable than soil coefficients.

FAO Penman-Monteith method to estimate ET_o

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

where

ET_o-- reference evapotranspiration [mm day^{-1}],

R_n-- net radiation at the crop surface [MJ m^{-2} day^{-1}],

G-- soil heat flux density [MJ m^{-2} day^{-1}],

T-- mean daily air temperature at 2 m height [°C],

u_2-- wind speed at 2 m height [m s^{-1}],

e_s-- saturation vapor pressure [kPa],

e_a-- actual vapor pressure [kPa],

e_s -- e_a- saturation vapor pressure deficit [kPa],

Δ -- slope of saturation vapor pressure curve [kPa °C^{-1}],

γ -- psychrometric constant [kPa °C^{-1}].

This equation uses standard climatological parameters such as solar radiation, temperature, humidity, and wind speed. The FAO Penman- Monteith method take into account many factors affecting ET_o, hence it is the most suitable formula for calculating reference ET (Allen et al., 1998).

Atmometers and Pan Evaporation

Atmometers, including the Bellani plate and class A evaporation pan, or empirical equations, such as the Penman-Monteith model have been used to estimate the ET rates of plants (Rosenberg et al., 1983). The Class A pan evaporimeter is used because of low cost and its application in determining irrigation requirements of crop. To keep Class A pan evaporimeter free of algae and other organic matter it must be maintained daily renewing water to avoid turbidity. It should be fenced so that animals cannot drink water from it. Heat gain or loss depends on amount of water in the pan so the water level should be maintained between 5 and 7.5 cm from top of the pan (Doorenbos and Pruitt, 1977). A pan evaporimeter estimates higher multi-day average evaporation rate than true daily evaporation (Irmak et al., 2005).

An atmometer has several advantages compared to pan evaporimeter and meteorological stations. It is simple, inexpensive and useful in large irrigated agricultural areas. An atmometer is a device that measures the water evaporated from a wet and porous surface. A good correlation between water loss from a black Bellani cup atmometer and alfalfa ET measured by lysimeters was found by Wilcox (1963). Feldhake and Boyer (1988) reported there was a good correlation between both atmometers and class A pan evaporation and concluded that the Bellani cup atmometer could be used for potential ET estimation.

Qian et al. (1996) estimated turfgrass evapotranspiration using atmometers, class A pan evaporimeter and the Penman-Monteith model. They tested the precision of ET calculated using weighing lysimeter and the water balance method. The black Bellani plate atmometer was found to correlate most closely with actual turf ET followed by the class A evaporimeter and the Penman-Monteith model. The Penman-Monteith model found to overestimate ET rates when atmospheric water demand was low and under estimated ET rates when atmospheric demand was high.

Lysimeters

A lysimeter is a container containing soil or other rooting media through which water infiltrates in such a way that the quantity of water can be measured. Lysimeters are valuable in transpiration and ET study (Ben-Gal and Shani, 2002). Lysimeters have been used to estimate the vegetative water use rate since late 19th century (Young et al., 1996). According to van Bavel (1961), precise measurement of ET can be achieved by measuring moisture change in a confined body of soil. Evapotranspiration measurements in the field are difficult due to variation in soil physical properties, soil moisture, and vegetation types. Lysimeters have made it easy to estimate the ET rates more accurately (Rogowski and Jacoby, 1977; van Bavel, 1961; Kopec et al., 1988). However, for accurate ET measurement, certain requirements of lysimeter construction and operation most be considered.

In recent years, the use of lysimeters to evaluate ET has been common. The University of Arizona, Karsten Turfgrass Research Facility, used two monolith lysimeters in order to estimate ET of ‘Tifway’ hybrid bermudagrass in the summer and overseeded ‘Froghair’ intermediate ryegrass (*Lolium multiflorum* x *L. perenne*) during the winter (Brown et al., 2001). They found bermudagrass had lower K_c values compared to intermediate ryegrass. The K_c values of bermudagrass ranged from 0.78 during June to 0.83 in September whereas K_c values for ryegrass ranges from 0.78 in January to 0.90 in April. The summer K_c was found to vary in relation to turf growth rate while winter K_c was found to varied in relation to mean air temperature. Beard et al. (1992) used mini-lysimeters to measure the ET and leaf extension rates of 24 *Cynodon* genotypes under well watered conditions. Significant differences in ET rates among cultivars were observed. Overall, ET rates ranges in between 4.2 mm d^{-1} to 5.2 mm d^{-1}. The ET rates were closely related with wind speed and solar radiation (Beard, Green, et al., 1992). Significant ET differences among cultivars were found in the mini-lysimeter study conducted by Kopec et. al, (1988). Bowman and Macaulay (1991) used mini-lysimeters to measure the ET of 20 tall fescue cultivars over 7 days in a greenhouse. There were significant differences in ET among cultivars grown in non-limiting water and nutrient conditions. ‘Shortstop’ was the low water use cultivars with ET 10 mm d^{-1} whereas ‘Alta’ was the high water use cultivars with ET 13.5 mm d^{-1}. To determine the constancy of ET over time, six out of 20 tall fescue cultivars were selected in second year. The ranking was nearly identical ‘Alta’ using high water and ‘Shortstop’ using less water.

Kim and Beard (1988) conducted research on ET rates of warm and cool-season turfgrasses from 1982 to 1984. Turfgrass were evaluated in black plastic mini lysimeter containing fritted clay as rooting media using the water balance method. Six morphological characters were evaluated along with ET rates under well watered conditions. Significant ET differences were observed between and within the genera. Differences in ET rates were related with morphological characters such as shoot density, number of leaves per unit area, leaf orientation, leaf width, and vertical leaf extension rate. ‘Texas Common’ St. Augustine showed an ET rate of 5.8 mm d^{-1}. It was related with low canopy resistance. ‘Argentine’ Bahiagrass [*Paspalum notatum* (Fluegge)] exhibited a medium ET rate of 6.3 mm d^{-1}. It was due to high leaf area, low shoot density, and intermediate leaf orientation contributing to low canopy resistance. ‘Adalayd’ seashore paspalum [*Paspalum vaginatum* (Sw.)] showed a low ET rate of 5.4 mm d^{-1} it was due to vertical leaf extension rate, medium leaf width, horizontal leaf orientation, high shoot density, and the number of leaves per unit area. Significant differences in ET rates were found within zoysiagrass [*Zoysia* sp.]. It was due to difference in morphological characteristics. ‘Arizona common’, ‘Tifgreen’ and ‘Tifway’ bermudagrass showed ET rates of 5.1 mm d^{-1}, 5.2 mm d^{-1}, and 5.3 mm d^{-1} respectively. These were associated with morphological characters such as narrow leaf, high shoot density, and horizontal leaf orientation. ‘Texas Common’ Buffalograss [*Bouteloua dactyloides* (Nutt.) J.T. Columbus] exhibited an ET rate of 4.8 mm day^{-1}. A low ET rate of buffalograss might be due to pubescence on the leaf blade surface and the low leaf area. ‘Kentucky 31’ tall fescue had higher ET rates than all warm season grasses. Tall fescue had erect leaf orientation, low shoot density, intermediate vertical leaf extension rate, and medium wide leaf. It showed an ET rate of 6.1 mm d^{-1}.

Atkins et al. (1991) evaluated ET rates and growth characteristics of 10 St. Augustinegrass genotypes in the field and in a controlled chamber with high evaporative potential. The experiment was carried out using black plastic mini-lysimeter pots in Sept. 1985, July and Aug. 1986, and Sept. 1987 in field. A controlled environment chamber study was conducted during the summer of 1988. In field study, no significant differences in ET rate were found among genotypes while there were significant differences under a controlled environment chamber with high evaporative demand. In the controlled environment chamber, ‘Texas common’ and ‘PI 410356’ ranked lowest for ET rate at 6.7 and 7.3 mm d^{-1} respectively, while ‘TX 106’ and ‘TXSA 8218’ ranked highest for ET rate at 8.1 mm d^{-1}. There was no correlation between ET rates measured under field conditions and those found under controlled environment chamber conditions. Green et al. (1991) performed a similar study using mini-lysimeters under both field and controlled environment conditions for 11 zoysiagrass in Texas. The mean ET rates for three years were not significantly different among the genotypes in the field conditions, whereas the ET rates among genotypes differ significantly in the controlled environment chamber. A field study was conducted from 1985 to 1987 and results indicates that genotype ‘KLS-11’ had the highest ET rate with 4.7 mm d^{-1} while genotype ‘Belair’ and ‘FC-13521’ had the lowest ET rate with 3.8 mm d^{-1}. The genotype ‘Emerald’ had highest ET rate with 10.3 mm d^{-1} and genotype ‘KLS-11’ had the lowest ET rate with 8.4 mm d^{-1} in the controlled environment chamber. Higher ET rates for zoysiagrass under controlled environment chamber conditions were due to high evaporative demand.

Feldhake et al. (1983) used small lysimeters to evaluate the relative effects of mowing height, N fertilizer, shading, grass species, and soil composition on ET from 1979 to 1981 in Colorado. Kentucky bluegrass ‘Merion’ (*Poa pratensis* L.) mowed at 5 cm height used 15% more water than grasses mowed at 2 cm height. The N deficient treatment used 13% less water than adequately fertilized water. Grasses receiving 4 kg N 1000 m^{-2} each month during spring and summer were compared with grasses receiving a single application of fertilizer during spring. During 1979 and 1980 Kentucky bluegrass used

24% more water than bermudagrass. There was no significant difference in ET rate among the grasses grown on a clay soil or on a sand-peat mixture during 1979. However, in 1980 grasses grown on soil used 6% less water than grasses grown on sand-peat mixture.

Kopec et al. (1988) estimated the ET rates of six tall fescue cultivars using min-lysimeters. There were significant differences in ET rates among cultivars. Forage turf type was found to have 9% higher ET rates as compared to turf type. Similarly Kopec et al. (2006) used lysimeter to compare the consumptive water use rates of inland saltgrass [*Distichlis spicata* (L.) Greene], seashore paspalum, and Tifway bermudagrass in semi-arid climate of Arizona. Seashore paspalum had highest ET rate and consumptive water use rate as compared to other cultivars.

Drought Avoidance and Root System

Drought avoidance is the ability of the plant to maintain normal physiological function in water deficit stress conditions by postponing tissue dehydration, through increasing water uptake from root systems, and reducing water loss from transpiration (Pessarakli, 2007). Deep root systems, increased root branching, and increased surface area are characteristics that plants have developed for absorbing water from deep in the soil profile to avoid injury from drought. According to Leinauer et al. (1997), the shallow rooted turf species *Poa supina* (Schard) had lower drought tolerance than deep rooted species *Agrostis stolonifera* (L.) and *Festuca rubra* (L.). Drought resistant tall fescue cultivars are found to have deeper root system than sensitive cultivars (Huang and Gao, 2000). A study conducted by Burton et al (1954) on forage grasses indicates drought susceptible carpetgrass [*Axonopus affinis* (Chase)] had 94% of roots in the upper 60 cm of soil whereas ‘Coastal’ bermudagrass had 65% of roots in the upper 60 cm of soil. A greenhouse study by Hays et al. (1991) showed that the turf quality of 10 bermudagrass genotypes during drought were correlated with root mass depth at 30-60, 60-90, 90-120, and 120-150 cm for r=0.75, 0.86, 0.80, and 0.81 respectively. During drought, the root mass at lower depth plays an important role to maintain the turf quality (Hays et al., 1991). Qian et al. (1997) reported that deep and extensive rooting of tall fescue and intermediate rooting of buffalograss and bermudagrass result is drought avoidance whereas shallow rooting in zoysiagrass result is poor drought avoidance. Various studies on tall fescue cultivars show that the extensive root system of tall fescue helps to avoid desiccation and wilting by absorbing more water deeper in the soil profile (Carrow, 1996b and Sheffer et al., 1987). When rainfall or irrigation water is not adequate, turfgrass reduces transpiration water loss, defer any shoot growth, and enhance deeper root growth in search of water (Trenholm, 1991).

Goal and Objectives

The ultimate goal of this project is to conserve water used in the turf industry by testing and selecting turf bermudagrass cultivars that are adapted for use in Oklahoma and that have lower water use rates. The objectives of this research were:

1. To evaluate and explain differences in water use rates of selected commercial and experimental bermudagrass entries under non-limiting soil moisture conditions in Oklahoma.
2. To evaluate and explain differences in root growth characteristics of selected commercial and experimental bermudagrass entries.

Research hypothesis:

Hypothesis I: There are significant differences in water use rates among bermudagrass entries.

Hypothesis II: There are significant differences in root growth characteristics among bermudagrass entries.

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CHAPTER II

EVALUATING WATER USE RATES OF TURF BERMUDAGRASS CULTIVARS UNDER NON-LIMITING SOIL MOISTURE CONDITIONS IN OKLAHOMA

Water is a limited non-renewable resource. In recent years, water availability for human consumption and irrigation is becoming limited, making water conservation a prime concern. A continuous increase in water demand has reduced the water available for non-food commodities (Hanks, 1983). Urban landscaping, especially turfgrasses, are the first casualty to suffer from supplemental irrigation rationing when rainfall is inadequate and water resources are insufficient. Although turfgrasses have numerous functional, environmental, and economic benefits, it has been criticized for its excessive water requirement (Beard and Green, 1994). It is crucial to identify turf species that survive with reduced water inputs. Water requirement for turfgrasses are based on water use rates. The water use rate of turfgrass is quantified through measurement of evapotranspiration (ET) rates. Turfgrass with reduced ET rates play an important role in water conservation. Selection of turfgrass species having low water use rates together with proper turfgrass management practices is needed for water conservation (Beard, 1985).

Evapotranspiration is the combination of two separate processes: evaporation and transpiration. Evaporation refers to the process where water is lost in vapor form from the soil surface or vegetation. Transpiration refers to the process where water is lost through the plant canopy. Hence, ET is the sum of water loss through evaporation from soil and plant water loss through transpiration. Evapotranspiration rates are affected by several factors such as grass cultivars, soil moisture, humidity, solar radiation, temperature, and wind speed. Grass species is one of the most important factors that affect ET rates. Water use rates vary with turfgrass species (Youngner et al., 1981; Aronson et al., 1987; Kim and Bread, 1988; Fry and Butler, 1989; Fu et al., 2004) and among cultivars of the same species (Shearman, 1986; Salaiz et al., 1991; Ebdon and Petrovic, 1998). Warm season turfgrasses have lower ET rates than cool season grasses (Casnoff et al., 1989).

Evapotranspiration rates are affected by changes in climatic condition, soil moisture, cultural practices, and insects and diseases damage. Mowing, fertilization, and irrigation have a direct influence on turfgrass growth rates, leaf extension, canopy resistance, and root depth and extension, all of which influence ET rates. Evapotranspiration rates vary by species, region and season. A study conducted by Dacosta and Huang (2006a) on the irrigation requirements of bentgrass in New Jersey, reported that during the summer 60-80% of actual ET rate was sufficient to maintain acceptable turf quality while 40% of actual ET rate was sufficient in fall of the same year. Kneebone and Pepper (1984) reported that availability of excess soil moisture than evaporative demand increases water use rates.

Carrow (1995) reported water use by various turfgrass as; common bermudagrass [*Cynodon dactylon* (L.) Pers.] (3.03 mm day^{-1}), ‘Tifway’ bermudagrass [*C.dactylon* (L.)

Pers. x *C. transvaalensis* (Burtt Davy)] (3.11 mm d^{-1}), 'Raleigh' St. Augustine [*Stenotaphrum secundataun* (Walter) Kuntze] (3.28 mm d^{1}), 'Meyer' zoysiagrass [*Zoysia japonica* (Stued.)] (3.54 mm d^{1}), 'Rebel II' tall fescue [*Schedonorus arundinaceus* (Schreb.)] (3.57 mm d^{1}), 'Kentucky 31' tall fescue (3.69 mm d^{-1}), and common centipedegrass [*Eremochloa ophiuroids* (Munro) Hack.] (3.80 mm d^{-1}). According to Qian and Engelke (1999) under low maintenance conditions 50-70% of evaporation from a class A pan (E_{pan}) was sufficient to maintain acceptable turf quality for tall fescue while only 10-50% of E_{pan} was required for several warm season grasses. Another study conducted by Carrow (1995) under intensive management conditions shows that irrigation at 80% of E_{pan} was required for tall fescue while 60-80% E_{pan} was sufficient for warm season grasses. Meyer and Gibeault (1986), reported irrigation at 60% ET can maintain acceptable turf quality of warm season turfgrasses in southern California.

Various research trials have been done to evaluate turfgrass ET rates under well watered conditions. The most common method for estimating ET are weighing lysimeters, Bowen ratio- energy balance and energy covariance system (Gavilan and Castillo-Llanque, 2009). Lysimeters are the standard instrument to measure turfgrass ET rates (Qian et al., 1996). Lysimeters can be weighed regularly to determine water loss by ET. Lysimeters have been used to estimate the vegetative water use rate since late 19th century (Young et al., 1996). According to van Bavel (1961), precise measurement of ET can be achieved by measuring moisture change in a confined body of soil. Evapotranspiration measurement in the field is difficult due to variation in soil physical properties, soil moisture, and vegetation types. Lysimeters have made it relatively easy to estimate the ET rate more accurately (Rogowski and Jacoby, 1977; van Bavel, 1961; Kopec et al.

1988). However, for accurate ET measurements certain requirements of lysimeter construction and operation must be considered.

Interspecific variations of water use among bermudagrass, seashore paspalum [*Paspalum vaginatum* (Sw.)] and St. Augustine have been evaluated in the field condition (Kim and Beard 1988; Carrow 1995; Carrow 1996; Kopec et al., 1988; Kopec et al., 2006). However, only a small number of bermudagrasses that are commercially grown have been characterized for water use rate.

The objective of this study was to evaluate the water use rates of different commercial and experimental bermudagrass cultivars under non-limiting soil moisture conditions in Oklahoma.

Materials and Methods

Description of Research Site

This research was conducted at the Oklahoma State University (OSU) Turfgrass Research Center in Stillwater, OK (36^{o} 07’ 06.76” N and 97^{o} 06’ 11.60” W). The site was a former 2002-2006 NTEP (National Turfgrass Evaluation Program) bermudagrass trial with 2.4 x 2.4 m plots. The soil was an Easpur silty clay loam (a fine-loamy, mixed, thermic Fluventic Haplustoll).

Plant Materials

The bermudagrasses entries evaluated were the standard entries ‘Tifway’, ‘Celebration’, ‘Premier’, ‘TGS_U3’, ‘Latitude 36’, ‘NorthBridge’ and experimental entries ‘DT-1’, ‘OKC 1302’, ‘OKC 1131’, and ‘OKC 1163’. Out of ten genotypes evaluated six were new which were not included in the original NTEP trial location. These included Latitude

36, NorthBridge, DT-1, OKC 1302, OKC 1131, and OKC 1163. The new genotypes were grown into the existing plot area by removing the former grass from randomly selected plots through the application of glyphosate on May 6, 2013 and then removing the dead sod using sod cutter.

In preparation for transplanting to the field and to the lysimeters, all materials were clonally propagated in the Turfgrass Research Center greenhouse from March 10-15, 2013. Three six inch plugs of each cultivar were collected from well-established mature turf plot in March 9, 2013. Plugs were washed to remove all the soil, separated individually, and transplanted in a flat tray containing metro-mix professional growing media. Grasses were grown in the greenhouse for two month and then transplanted in the field (May 22-24) and lysimeters (May 8-10). The lysimeters contained calcined clay (Turface Pro League) as rooting media. The calcined clay was screened so that all particles ranged from 1-2 mm diameter.

Plot Design and Field Establishment

The field design was a completely randomized block design. Each cultivar was replicated three times in 2.4 x 2.4 m plot which were separated from each other by 0.3 m soil border. Each plot had a polyvinyl chloride (PVC) sleeve in the center to hold the lysimeter beneath the soil so that each lysimeter was even with the plot surface. New plots were established by sprigging the grass grown in the greenhouse in May 22-24, 2013. Newly established plots were hand irrigated three times a day for one week using a hand-held water hose. Once the grasses were established, an automatic irrigation system was used to irrigate the field plot. Irrigation was adjusted at 100% ET based on the Oklahoma Mesonet daily reference ET calculated from date collected from an Oklahoma

Mesonet weather station located approximately 400 m from the field plot area. Plots were mowed three times a week at 2.5 cm using a riding reel mower. The soil borders were maintained by spraying glyphosate to bermudagrass stolons approximately every 14 d. The nitrogen fertilizer regime used in this trial was 244 kg ha^{-1} per growing season, which lasted from April-September in 2013 and 2014. As a weed control regime, a pre-emergence herbicide (oxadiazon) was applied at the labeled rate in February and September each year. In order to prevent insect damage to plots, an insecticide (lambda-cyhalothrin) was applied at the labeled rate in August 2014.

Mini-Lysimeter Construction and Grass Establishment in Lysimeters

Mini-lysimeters were made from PVC pipe of 15.2 cm (6 in) diameter and 35.6 cm (14 in) in length with a root zone depth of 30.48 cm (12 in) as described by Kopec et al. (2004). Mini-lysimeters had a drain valve on the bottom. A 0.635 cm (0.25 in) threaded ball valve (Grainger International Inc. 0.25 in male x female valve) was used for drainage. The bottom of each mini-lysimeter was constructed using PVC sheets of 15.2 cm (6 in) diameter. Strainer washer (1 in dia and 0.5 in high filter screen) was used to cover the upper side of drain valve. To prevent the loss of the rooting media and clogging of valve by rooting media geotextile porous sheet was used in the inner side of a mini-lysimeter.

Mini-lysimeters were filled with calcined clay (Turface Pro League). Calcined clay, also known as fritted clay, is coarsely milled, dried clay, used as a granular growth medium. Calcined has a relatively low dry bulk density, is non-cohesive, drains very rapidly, retains a large quantity of plant available water, appears to be chemically inert, and can easily be washed off the roots (van Bavel et al., 1978). Calcined clay was pre-screened to a particle size of 1-2 mm to maintain uniformity in rooting media. In total, 30 mini-lysimeters were planted making three replications of each cultivar and they were allowed to establish in the greenhouse for two months before data collection. The greenhouse was maintained at 30/24C day/night temperature. Mini-lysimeters were mowed at 2.5 cm using hand scissors. Mini-lysimeters were fertilized twice a week with a nutrient solution of 20:20:20 N-P_2O_5-K_2O (20-8.6-16.6 NPK) general purpose fertilizer (J.R Peters Inc., Allentown, PA) plus micronutrient. Mini-lysimeters were moved in the field on August 10, 2013. Field ET data were collected from August 2013 to September 2014. Mini-lysimeters were maintained in the greenhouse from December to April 2014 to avoid winter injury. In order to control diseases and insects, preventive fungicides and insecticides were applied. To prevent insects, lambda-cyhalothrin and bifenthrin were applied at labeled rates and timings. To prevent diseases, pyraclostrobin was used at labeled rates and timings.

In the field, each mini-lysimeter was placed in the sleeve (PVC casing) in such a way that min-lysimeter turf canopy was even with the canopy of surrounding turf in each field plot. The heights of the mini-lysimeters were maintained by placing pea gravel at the base of the PVC casing. Mini-Lysimeters were mowed at 2.5 cm using hand scissors. Mini-lysimeters were fertilized twice a week at 250 mg N L^{-1} of a solution of 20-20-20 N-P_2O_5-K_2O (20-8.6-16.6 NPK) general purpose fertilizer (J.R Peters Inc., Allentown, PA) plus micronutrient.

Data Collection

Data were collected before dawn from August to September in 2013 and from May to September in 2014. The mass determination process was performed before dawn to avoid transpiration water loss. Mini-lysimeters were weighed on 15 precipitation free days in 2013 and 21 precipitation free days in 2014. Weather forecasts were regularly monitored before taking data to avoid precipitation throughout data collection. Weather data such as temperature, wind speed, and humidity were recorded from the Oklahoma Mesonet weather station.

Evapotranspiration rates were determined by the water balance method (Johns et al. 1983; Rogowski et al., 1977) between 24 h and 48 h followed by mowing and saturation with water. On the day of data collection, the drain valves of all mini-lysimeters were closed and then mini-lysimeters were brought to saturation. After an estimated 60 minutes, the ball valves were opened and min-lysimeters were allowed to drain for about 30 minutes to bring them to field capacity. Mini-lysimeters were said to be in field capacity when drainage had stopped completely. After bringing mini-lysimeters to field capacity, the ball valves were closed; the mini-lysimeters were wiped completely dry, and were weighed. The change in mini-lysimeters weights in each day was recorded and the difference in the two measurements gave the 24 h ET rate. On the third day mini-lysimeters were cleaned, dried, and weighed again, and then mowed to the height of 2.5 cm. After mowing, the ball valves were opened, mini-lysimeters were watered to bring back to field capacity, and the mini-lysimeters were put in the sleeve for regular maintenance until the next data collection event.

Statistical Analysis

The experimental design was a randomized complete block with ten entries and three replications of each entry. Analysis was conducted on water use rates data using SAS 9.3 (SAS Institute, Cary, NC) software. Analysis of variance (ANOVA) was performed using

“PROC GLM”. There was a significant year by treatment interaction, thus data were analyzed separately by year. In 2014, there was a significant date by treatment interaction; therefore data were analyzed by date. When genotype means were separated, Fisher’s protected least significant difference (LSD) was applied to test at the p=0.05 significance level (95% certainty level). Pearson’s correlation coefficients were calculated using “Proc Corr”.

Results and Discussion

Results

The overall ANOVA for two year ET rates showed that there was a statistically significant year and genotype x year interaction (Table 1). Hence data were analyzed separately for each year. In 2013, the genotype x date interaction was not significant (Table 1) so data were combined and analyzed, whereas in 2014, the genotype x date interaction was significant (Table 1). Therefore in 2014, data for each date were analyzed and presented separately. A significant year effect and genotype x date effect in 2014 might be due to differing environmental conditions throughout the year (Tables 2 and 3). Pearson correlation coefficients were calculated for daily environmental measurements and average daily ET measurements over all genotypes for the two years. ET rates were closely related with average temperature (r=0.55, p=0.0056), solar radiation (r=0.57, p=0.0032), and wind speed (r=0.55, p=0.0053). In 2013, OKC 1131, Tifway, and Latitude 36 were not significantly different for ET rates and were low water use cultivars with ET rates 4.14, 4.18, and 4.26 mm d^{-1} respectively.

Due to significant genotype x date interaction in year 2014, ET rates for each day were analyzed and presented separately. ET rates were evaluated for 14 different days starting on May 23 and ending on September 26 (Tables 4, 5, and 6). On eleven days out of 14 days, ET rates were significant whereas in 3 days (July 21, Aug 13, and Sept 25) ET rates were not significant. The entry DT-1 ranked consistently at the top group for ET rates for all 11 significant ET measurement days whereas OKC 1131 and OKC 1163 ranked consistently at the bottom group for ET rates for 10 significant ET measurement days (Table 7). The ET rates of DT-1 ranged from a low of 3.47 mm d^{-1} (Sept 25) to high of 9.14 mm d^{-1} (June 16). The ET rates of Celebration ranged from a low of 3.41 mm d^{-1} (Sept 25) to high of 8.6 mm d^{-1} (June 16). The ET rates of Premier ranged from a low of 3.20 mm d^{-1}(Sept 26) to high of 7.85 mm d^{-1} (June 16). The ET rates of TGS_U3 ranged from a low of 3.20 mm d^{-1} (Sept 25) to high of 7.74 mm d^{-1} (July 7). The entry Latitude 36 ET rates ranged from a low of 3.38 mm d^{-1} (Sept 25) to high of 7.78 mm d^{-1}(July 7). The entry NorthBridge ET rates ranged from a low of 3.27 mm d^{-1} (Sept 25) to a high of 7.22 mm d^{-1} (June 16). The entry Tifway ET rates ranged from a low of 3.74 mm d^{-1} (Sept 26) to high of 8.25 mm d^{-1} (June 16). The ET rates of OKC 1302 ranged from a low of 3.49 mm d^{-1} (Sept 25) to a high of 8.91 mm d^{-1} (June 16). The ET rates of OKC 1131 ranged from 3.10 mm d^{-1} (Sept 26) to 7.49 mm d^{-1} (June 16). Lastly, the ET rates of OKC 1163 ranged from a low of 3.09 mm d^{-1} (Sept 25) to high of 6.41 mm d^{-1} (July 7).

Discussion

The overall ANOVA for two year ET rates shows that there was a statistically significant genotype x year interaction (Table 1). Significant year interaction may be due to differences in environmental conditions (Table 2 and Table 3). The 0.8 mm d^{-1} range in overall ET rates is similar to the 1.0 mm d^{-1} range in overall ET rates among 24 well-watered bermudagrass genotypes reported by Beard et al. (1992). However, the two studies were not conducted under the same environmental conditions and it was statistically not valid so caution should be taken while comparing the overall mean. The ET rates in 2014 ranged from 3.09 mm d^{-1} to 9.14 mm d^{-1} and this compares similarly to Beard (1989) where turfgrass ET rates ranged from 4.5 mm d^{-1} to 8.5 mm d^{-1}. In 2014, the ET rates were relatively high in June and July whereas the ET rates were relatively low in September. This difference in ET rates is most likely due to differences in environmental conditions (Table 3) where air temperatures, solar radiation and wind speed were higher in June and July compared to September.

In this study, we observed the variation in water use rates among ten different bermudagrass cultivars. The variation in ET rates may be associated with grass morphological characteristics such as shoot density, number of leaves per unit area, leaf orientation, leaf width and vertical leaf extension rate. Shoot density, number of leaves per unit area, and leaf orientation contribute to high canopy resistance while leaf width and vertical leaf extension affect the area of ET. A study was conducted by Kim and Beard (1988) to measure the ET rates and morphological characters of 11 warm season and one cool season grasses. They found that grasses with lower ET rates have high canopy resistance, high shoot density, horizontal leaf orientation, reduced leaf area, narrow leaf texture, and slow vertical leaf extension.

Variability in ET rates among cultivars indicates a strong potential for water savings by selecting and developing improved bermudagrass cultivars with reduce ET rates. Celebration and Tifway are popular bermudagrass cultivars in the United States and they had shown good performance under drought in a study conducted by Chalmers (2008). Similarly in a study conducted by Poudel (2010) Celebration had shown good drought performance in the field at the Oklahoma State University (OSU) Turfgrass Research center. A greenhouse study by Poudel (2010) showed that Celebration and OKC 1302 had phenotypic potential for drought resistance through deep and extensive root systems. However, Celebration and OKC 1302 had shown relatively high water use rates as compared to NorthBridge, OKC 1131 and OKC 1163 in this study. In our root study OKC 1131 had shown good potential for drought resistance as it had a deep and extensive root system. In 2014 difference in ET rates between OKC 1131 and DT-1 is 1.01 mm d^{-1}, OKC 1131 and Celebration is 0.9 mm d^{-1}, and between OKC 1131 and OKC 1302 is 0.89 mm d^{-1} (Table 7). These differences in ET rates among bermudagrass show the potential water conservation that may occur by target breeding and selection of bermudagrass with reduced water use rates. Although OKC 1131 has shown genetic potential for drought resistance and had significantly low water use rates than Celebration, DT-1, and OKC 1302, its drought resistance and recovery phase from drought has not been measured nor its utilitarian features such as divot recovery or traffic tolerance on sport fields. High water use cultivars describe in our study may not be susceptible to injury from drought in the field where the soil profile is deep and extensive rooting may help certain varieties avoid internal plant water deficit. In the field, high ET rates may lead to production of high root biomass and therefore, plant may access soil moisture deeper in the soil profile and escape drought. Since low water use rates and phenotypic potential for drought resistance were observed, selecting and breeding additional bermudagrass for improved drought resistance appears feasible.

The opening and closing of stomata influence grass carbon and water balances. Carbon is an essential substrate for growth which can only be acquired at the expense of losing water. At a particular time a particular leaf has a certain rate of CO_2 assimilation and certain rate of transpiration. These fluxes are determined by the opening and closing of stomata. If stomata are more widely open, CO_2 assimilation and transpiration would be high and vice-versa (Cowan et al., 1982). Increased stomatal conductance of leaves causes an increase in CO_2 assimilation and greater rate of transpiration loss (Farguhar et al., 1989). Hence, cultivars which have high ET rates in this study might have high CO_2 assimilation. According to DaCosta and Huang (2006b) increased carbon portioning and carbohydrate accumulation during drought could help plant for better recovery upon re-watering. Future research should be focused on the ET rates, CO_2 assimilation, carbon partitioning, and regrowth and recovery of grasses.

Conclusions

This experiment was conducted in a shallow calcined clay soil profile with non-limiting soil moisture conditions. Our experiments have demonstrated substantial variation in water use rates among different bermudagrass cultivars/genotypes. Developing, selecting and using water-saving bermudagrass cultivars could lead to reduced water use in various turf applications. Future research should focus on developing/selecting drought resistance cultivars with low water use rates that provide aesthetic and utilitarian benefit for their specific areas of intended use.

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Table 1. Evapotranspiration rates of ten bermudagrass entries under non-limiting soil moisture conditions during selected months in 2013 and 2014.

Entries[z]	Year 2013	Year 2014	Overall
DT-1	4.69 ab[y]	6.19 a	5.56 a
Celebration	4.55 bc	6.08 ab	5.44 ab
OKC 1302	4.49 c	6.07 ab	5.41 abc
Premier	4.69 ab	5.71 c	5.29 abc
TGS_U3	4.74 a	5.51 d	5.19 bcd
Tifway	4.18 d	6.00 b	5.24 abcd
Latitude 36	4.29 d	5.70 c	5.11 dc
NorthBridge	4.59 abc	5.17 e	4.93 de
OKC 1163	4.47 c	4.93 f	4.76 e
OKC 1131	4.14 d	5.18 e	4.75 e
CV (%)	7.19	6.30	19.4
Genotype	*	***	**
Date	***	***	-
Genotype x Date	NS	***	-
Year	-	-	***
Genotype x Year	-	-	***

[z] ET rates were collected on 10 dates and 14 dates during 2013 (Aug-Sept) and 2014 (May-Sept) respectively.

[y] Means followed by same letters within each column are not significantly different at P = 0.05 significance level.

*, **, *** indicate significant at the P = 0.05, 0.01, and 0.001 levels, respectively, and NS = not significant at p=0.05.

Table 2. Average daily environmental parameter taken during the field evapotranspiration (ET) study for August and September, 2013.

	Air temp (°C)[y]				Wind speed[x]		Solar radiation[w]		Pan evaporation		Reference ET	
	Max		Min		$(\mathrm{ms^{-1}})$		$(\mathrm{MJm^{-2}})$		$(\mathrm{mm\ d^{-1}})$		$(\mathrm{mm\ d^{-1}})$	
Month[z]	X	SE	X	SE	X	SE	X	SE	X	SE	X	SE
August	33.7[v]	0.6	20.7	0.8	2.3	0.2	23.5[v]	0.9	6.8[v]	0.3	5.5[v]	0.2
September	33.5	0.5	15.9	1.5	2.1	0.4	21.7	1.2	6.2	0.6	4.9	0.7

[Z] ET rates were collected on 4 dates and 6 dates during August and September, respectively.

[y] Maximum and minimum air temperature measured at 1.5 m above the soil surface.

[x] Wind speed measured at 2 m above soil surface.

[w] Solar radiation measured at 1.8 m above the soil surface.

[v] Means are the average of 4 days in August and 6 days in September measured from the Stillwater Mesonet weather station located approximately 400 m from the field plot area.

Table 3. Average daily environmental parameters[z] during the field evapotranspiration study May to September, 2014.

	Air temp (°C)[y]		Wind speed[x]	Solar radiation[w]	Pan evaporation	Reference ET
Date	Max	Min	(ms^{-1})	($MJ\ m^{-2}$)	($mm\ d^{-1}$)	($mm\ d^{-1}$)
23 May	29.4	19.4	1.9	13.4	4.3	3.6
24 May	31.1	18.9	2.6	19.1	5.8	4.6
16 June	32.2	23.9	5.7	28.5	10.4	7.4
17 June	32.8	24.4	5.5	25.6	9.9	7.1
7 July	37.8	23.9	3.8	29.4	11.4	8.4
8 July	33.3	21.7	3.3	26.1	9.1	6.7
21 July	33.9	21.7	3.2	26.8	7.9	6.2
22 July	35.5	23.9	1.9	27.3	7.9	6.4
3 Aug.	31.7	17.2	1.0	27.8	6.3	5.3
4 Aug.	32.8	18.9	1.7	27.3	7.1	5.6
13 Aug.	31.1	16.1	1.9	26.9	6.8	5.6
14 Aug.	32.8	18.3	2.9	24.0	7.6	5.8
25 Sept.	30	13.9	1.9	19.7	4.8	3.8
26 Sept.	28.8	14.4	2.0	20.5	4.8	3.8

[z] Environmental parameters were measured from the Stillwater Mesonet weather station located approximately 400 m from the field plot area.

[y] Maximum and minimum air temperature measured at 1.5 m above the soil surface.

[x] Wind speed measured at 2 m above soil surface.

[w] Solar radiation measured at 1.8 m above the soil surface.

Table 4. Mean daily ET rate (mm d^{-1})[z] of ten bermudagrass entries under non-limiting soil moisture conditions May to June, 2014.

Bermudagrass entries	23-May	24-May	16-June	17-June
DT-1	6.10 ab[y]	7.09 a	9.14 a	6.59 ab
Celebration	6.44 a	6.78 ab	8.6 abc	7.15 a
OKC 1302	5.47 bcd	6.24 abc	8.91 ab	6.39 b
Premier	5.54 bcd	6.00 bcd	7.85 cde	6.64 ab
TGS_U3	5.65 abcd	5.49 cde	7.30 e	5.34 de
Tifway	5.84 abc	6.39 abc	8.25 bcd	6.16 bc
Latitude 36	5.11 dce	5.88 bcde	7.18 e	5.59 cd
NorthBridge	5.57 bcd	5.20 ed	7.22 e	5.48 d
OKC 1163	4.55 e	5.03 e	6.22 f	4.82 e
OKC 1131	4.88 de	5.27 ed	7.49 ed	5.30 ed
Significance Level	**	**	***	***

[z] Water use in mm d^{-1} . Values are the mean of three replications.

[y] Treatments within column with same letters are not significantly different at p=0.05.

*, **, *** indicate significant at the P = 0.05, 0.01, and 0.001 levels, respectively, and NS = not significant at p=0.05.

Table 5. Mean daily ET rate (mm d^{-1})^{z} of ten bermudagrass entries under non-limiting soil moisture conditions July, 2014.

Bermudagrass entries	7-July	8-July	21-July	22-July
DT-1	7.74 abc^{y}	6.13 a	6.33 a	6.89 a
Celebration	7.06 cde	5.99 ab	6.42 a	5.88 bc
OKC 1302	7.95 ab	6.22 a	6.50 a	6.22 ab
Premier	7.34 bcd	5.57 abc	6.31 a	5.88 bc
TGS_U3	7.74 abc	5.45 bc	6.30 a	5.64 bcd
Tifway	8.34 a	5.77 abc	6.50 a	6.16 ab
Latitude 36	7.78 abc	5.84 ab	6.72 a	6.08 ab
NorthBridge	6.37 e	5.12 cd	5.94 a	4.72 e
OKC 1163	6.41 e	4.41 e	5.88 a	4.87 cde
OKC 1131	6.67 de	4.72 ed	5.94 a	5.19 ed
Significance Level	***	***	NS	**

^{z}Water use in mm d^{-1}. Values are the mean of three replications.

^{y}Treatments within column with same letters are not significantly different at p=0.05.

*, **, *** indicate significant at the P = 0.05, 0.01, and 0.001 levels, respectively, and NS = not significant at p=0.05.

Table 6. Mean daily ET rate (mm d^{-1})^{z} of ten bermudagrass entries under non-limiting soil moisture conditions August-September, 2014.

Bermudagrass entries	3-Aug	4-Aug	13-Aug	14-Aug	25-Sept	26-Sept
DT-1	5.73 abc^{y}	6.28 ab	5.68 a	5.79 ab	3.47 a	3.74 a
Celebration	6.08 a	6.44 a	5.80 a	5.61 abc	3.41 a	3.50 abc
OKC 1302	5.85 ab	6.39 a	5.76 a	5.93 a	3.49 a	3.69 a
Premier	5.74 abc	5.87 abc	5.49 a	5.28 bcd	3.26 a	3.20 b
TGS_U3	5.45 abc	5.67 bcd	5.81 a	5.19 dc	3.20 a	3.23 bc
Tifway	5.70 abc	5.96 abc	5.79 a	5.53 abc	3.86 a	3.74 a
Latitude 36	5.59 bcd	5.91 abc	5.56 a	5.67 abc	3.38 a	3.55 ab
NorthBridge	4.90 bcd	5.13 d	5.11 a	4.92 ed	3.27 a	3.36 abc
OKC 1163	5.11 d	5.00 cd	5.76 a	4.55 ed	3.09 a	3.39 c
OKC 1131	5.39 cd	5.29 d	5.11 a	4.83 e	3.32 a	3.10 abc
Significance Level	*	**	NS	**	NS	*

[z] Water use in mm d^{-1}. Values are the mean of three replications.

[y] Treatments within column with same letters are not significantly different at p=0.05.

*, **, *** indicate significance at the P = 0.05, 0.01, and 0.001 levels, respectively, and NS = not significant at p=0.05.

Table 7. Number of measurement dates in which bermudagrass entries were in the top and bottom statistical group for evapotranspiration rate. Original comparisons based on the least significant difference test at p=0.05.

Bermudagrass Entries	Top LSD Group	Bottom LSD Group	Avg. Daily ET (mm d^{-1})
DT-1	11[z]	0	6.19
Celebration	9	0	6.08
OKC 1302	9	0	6.07
Premier	6	0	5.71
TGS_U3	2	4	5.51
Tifway	9	0	6.00
Latitude 36	7	2	5.70
NorthBridge	0	6	5.17
OKC 1163	0	10	4.93
OKC 1131	0	10	5.18

[z] There were 11 of 14 dates with a significant genotype effect.

CHAPTER III

DIFFERENCES IN ROOT GROWTH CHARACTERISTICS OF BERMUDAGRASS CULTIVARS

Drought stress is common during the summer month in the U.S transition zone (Dunn and Diesburg, 2004). Drought is a prolonged period of moisture deficit stress conditions. Drought resistance refers to the ability of plant to survive under water deficit conditions. Plants survive drought through physiological and structural mechanisms (Fry and Huang, 2004). Plants survive water stress with the mechanisms of drought avoidance or drought tolerance. Plants avoid tissue injury during drought by reducing water loss via evapotranspiration (ET) and increasing water uptake through development of deep and extensive root systems. Water loss can be reduced by increased canopy, stomatal and cuticular resistance to ET, reduced leaf area, and decreased radiation absorption (Beard, 1989). High root density, deep rooting, and extensive root hair development makes bermudagrass superior in terms of drought resistance via dehydration avoidance (Casnoff and Beard, 1985; Kim, 1987). An extensive root system allows a turfgrass to extract water from the deeper soil profile during moisture stress (Hurd, 1975). Several research studies have been conducted to study the rooting characteristics of turfgrass in response to drought avoidance and turf quality (Carrow and Duncan 2003; Su et al., 2007).

Tall fescue [*Schedonorus arundinaceus* (Schreb.)] was found to have higher root length density and better visual quality than Kentucky bluegrass (*Poa pratensis* L.) under soil water deficit conditions (Su et al., 2008). A field study was conducted by Sheffer et al. (1987) at Missouri to study the interspecific differences in turfgrass rooting. They found Kentucky bluegrass had higher root mass than tall fescue at 0-12 cm depth in late August. However, tall fescue had higher root mass than Kentucky bluegrass at soil depths of 30-48 cm. In a Georgia study, Carrow (1991) showed a ranking for root length density (RLD) for various turfgrasses was ‘Tifway’ hybrid bermudagrass [*Cynodon dactylon* (L.)Pers. x *C. transvaalensis* (Burtt Davy)]> common bermudagrass [*C. dactylon* (L.) Pers.] =‘Rebel’ tall fescue> ‘Kentucky 31’ tall fescue> ‘Raleigh’ St. Augustinegrass [*Stenotaphrum secundataun* (Walter) Kuntze]> ‘Meyer’ zoysiagrass [*Zoysia japonica* (Stued.)] at 20-60 cm depth in late August. Rooting depth and activity can be determined by the soil water depletion (SWD) pattern (Qian et al., 1997). Soil water depletion was found to be positively correlated with vertical root distribution in a study conducted by Sheffer et al. (1987). Tall fescue had higher soil water content than Kentucky bluegrass at 6 cm depth whereas at 54 and 78 cm depth Kentucky bluegrass had higher soil water content than tall fescue. Deep extensive and viable root systems are major components of drought avoidance (Beard, 1989). Hays et al. (1991) used long polyvinylchloride (PVC) tubes with fritted clay to study the intraspecific diversity in rooting depth. Full expression of genetic rooting potential is affected by soil physical and chemical stress such as high soil strength, acid soil complex, low soil oxygen, high soil temperature, and salt toxicities (Foy, 1992; Duncan and Shuman, 1993).

Greater root length, root surface area, and root size are desirable traits for selecting grasses in areas having irregular rainfall. Rooting characteristics and root:shoot ratio is important for selecting drought resistance cultivars (Bonos et al., 2004). In a drought performance analysis, selected tall fescue cultivars for high root:shoot ratios show improved drought performance compared to their parental lines under field drought conditions (Karcher et al., 2008). Qian et al. (1997), reported leaf wilting resistance during drought was due to deep and extensive rooting of ‘Mustang’ tall fescue and intermediate rooting of ‘Prairie’ buffalograss [*Bouteloua dactyloides* (Nutt) J.T.Columbus] and ‘Midlawn’ hybrid Bermudagrass. Meyer zoysiagrass shows poor drought avoidance due to shallow rooting.

The objective of this research was to evaluate and explain differences in root growth characteristics of selected commercial and experimental bermudagrass entries.

Materials and Methods

A greenhouse study was conducted at Oklahoma State University (OSU) at the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) greenhouse facility located in Stillwater, OK. The bermudagrasses that were evaluated were the standard entries ‘Tifway’, ‘Celebration’, ‘Premier’, ‘TGS_U3’, ‘Latitude 36’, ‘NorthBridge’ and the experimental entries ‘DT-1’, ‘OKC 1302’, ‘OKC 1131’, and ‘OKC 1163’. Six inch diameter sod plugs were collected from the field during November 2013. Plugs were washed to remove all the soil, separated individually and transplanted in a flat tray using metro-mix professional growing media. Grasses were grown in the greenhouse. Mature grasses were grown in clear polyethylene tube of 3.5 cm diameter and 120 cm deep. Polyvinylchloride (PVC) pipe of 5.08 cm diameter and 120 cm deep were used to hold polyethylene tubes. Holding tubes were capped with PVC plugs at the bottom and a small hole was drilled to facilitate drainage. Holding tubes were prepared and positioned as described by Qian et al. (1997). Calcined clay was used as growing media. Calcined clay has relatively low dry bulk density, is non-cohesive, infiltrate easily, good water holding capacity, chemically inert and can be easily washed from roots (van Bavel et al., 1978). Calcined clay was sieved using a 2 mm and 1 mm sieve. Particles size greater than 2 mm diameter were removed in the first screening whereas particles smaller than 1 mm were removed in the second screening. Growing tubes were filled with 100% calcined clay of 1-2 mm particle size and saturated before planting. Ten bermudagrass sprigs with 4-5 nodes were planted in each growing tube in July 17, 2014. Growth tubes were set under mist system which had an automatic irrigation timer control setting. For the first two weeks, the mist system was set to water 15 sec every 20 min. After a two week establishment period, the mist system was set to water 6 minute every 4 h. Fertilizer was applied twice a week at 250 mg N L^{-1} using a solution of 20-20-20 N-P_2O_5-K_2O (20-8.6-16.6 NPK) general purpose fertilizer (J.R Peters Inc., Allentown, PA) plus micronutrient. The average greenhouse condition for study was 34/26°C day/night air temperature. A 14 h photoperiod was stimulated by supplemental light suspended above growing tube set to turn on/off at 7:00 AM/21:00 PM. Grasses were clipped at 5 cm height every week. Clippings were collected in paper envelop and dried at 80^oC for 48 h and shoot dry weight (SWD) was recorded throughout the study period. Maximum root extension (MRE) in each growth tube was determined by measuring the deepest root visible from polyethylene tube in every two weeks. The study was halted once MRE of one of the tubes reached 120 cm depth. Clear polyethylene tubes were cut into six sections: 0-7.5 cm, 7.5-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, 90-120 cm. Above ground shoots were collected separately, dried at 80^{o}C for 48 h and final SWD was recorded. After calcined clay was removed from the roots, roots were collected in plastic bags and refrigerated at 4^{o}C until further analysis. Roots were washed to remove calcined clay and then methyl blue (5 g L^{-1} water) was used to stain roots for proper image of finer roots. Roots were scanned and analyzed using WinRHIZO (Regent Instruments Nepean, ON, Canada) to calculate total root length (TDR), average root diameter (ARD), root surface are (RSA), and root volume (RV). After analyzing roots were dried at 80^{o}C for 48 h, weighed separately and root dry weight (RDW) were recorded. Finally root to shoot ratio (R:S) was calculated based on RWD and SWD.

To prevent insects, lambda-cyhalothrin and bifenthrin were applied at labeled rates and timings. To prevent diseases, pyraclostrobin was used at labeled rates and timings.

Data Analysis

The experimental design was a randomized complete block with ten genotypes and four replications. Analysis were conducted on total root length (TRL), average root diameter (ARD), root surface are (RSA), root volume (RV), shoot dry weight(SDW), root dry weight (RDW), and root to shoot ratio (R:S) data using Statistical Analysis System (SAS) 9.3 software (SAS Institute, Inc., Cary, NC). Analysis of variance (ANOVA) was performed using “PROC GLM”. When ANOVA criteria were meet at P=0.05 level, mean separation test were performed using Duncan’s multiple range test at P= 0.05 significant level.

Results and Discussion

Results

In the entire 120 cm soil profile, there were significant differences in TRL, RSA, ARD, RV, SDW, RDW, and R:S ratio (Tables 8 and 9). Similarly in the sub profile (0-7.5, 7.5-15, 15-30, 30-60, 60-90, and 90-120 cm), there were significant differences in TRL, RSA, ARD, RV, and RDW (Table 10-15). TGS-U3 had consistently higher TRL, RSA, RV, and RDW in the entire profile and sub profile whereas OKC 1163 had consistently lower TRL, RSA, ARD, RV, SDW, RDW and R:S ratio in the entire profile and sub profiles. However, there was variability in rankings of other cultivars. Latitude 36 had significantly higher R:S ratio than TGS_U3, Premier, OKC 1131, Celebration, DT-1, NorthBridge, Tifway, and OKC 1163. However, it was not significantly different in R:S ratio than OKC 1302. In the entire 120 cm profile 65% to 90% of TRL was located in upper 30 cm profile (Table 16). Similarly, in the entire 120 cm profile 65% to 96% of RSA was located in upper 30 cm profile (Table 16). TGS_U3, OKC 1302, OKC 1131 and NorthBridge were the only cultivars which have roots in the 90-120 cm profile (Table 15). OKC 1163 had roots up to 60 cm profile while Premier, Latitude 36, Celebration, DT-1, and Tifway had roots up to 90 cm profile (Table 14).

Discussion

In the entire 120 cm profile 65% to 90% of TRL and 65 to 96% of RSA was located in upper 30 cm (Table 16). Greater roots in the upper 30 cm profile results in a greater soil moisture extraction during irrigation and adequate rain fall. Deep extensive root systems are the most important mechanism by which turfgrass avoid drought by increase water absorption. TGS_U3, OKC 1302, OKC 1131, and NorthBridge had roots at 90-120 cm profile which suggests that it can absorb water form deep soil profile during drought. Cultivars having greater TRL at lower soil profile can absorb water from deep soil profile. According to Duncan (1994) for selecting cultivars in a drought stressed environment, an extensive root system is desirable character. Water extraction in soil is related to root characteristics (Carrow, 1996b; Fry and Huang, 2004). For selecting drought resistant cultivars root distribution within the profile is more important than total root production. Higher root surface area is also a desirable characteristic for selecting cultivars in drought sensitive areas. Cultivars with higher root surface area can absorb water form larger soil area. The R:S ratio may be an important characteristic for selecting drought resistance cultivars. In turfgrass, high R:S ratio is desirable (Beard, 1973). High R:S ratio is very effective means for plant to adapt dry conditions. Plants having high R:S ratio transpiration surface is reduced while root systems can absorb water from large volumes of soil. Karcher et al. (2008) reported, that tall fescues selected for higher root:shoot ratios performed better in the field and were first to recover from drought stress after re-watering as compared to lower root:shoot ratio selections.

Based on the TRL and RSA TGS_U3, OKC 1302, and OKC 1131 had good genetic potential for drought resistance. OKC 1163 had relatively shallow roots as compared to other bermudagrass entries studied which suggest it may have inferior drought avoidance compared to other cultivars. According to Casnoff and Beard (1985) and Kim (1987) deep rooting and extensive root hair development are major factors contributing to superior drought resistance.

Conclusions

This experiment has demonstrated differences in root growth characteristics among different bermudagrass cultivars. Ten bermudagrass cultivars differed in TRL, RSA, RV, RD, RDW, SDW, and R:S ratio. These root characteristics are important in selecting drought avoiding cultivars. These root characteristics could be used as selection criteria in turfgrass breeding programs for improved drought resistance. However, our experiment was carried out in non-limiting soil moisture conditions. We did not observe the root growth characteristics under soil and plant water deficit stress conditions. Further research is needed to learn more about root characteristics and performance of these bermudagrass entries under drought conditions. In order to select drought resistance turfgrass cultivars, it is essential to identify the drought tolerance mechanism along with drought avoidance mechanism. Future work should focus on physiological and whole plant attributes that contribute to drought tolerance which ultimately lead to drought resistance cultivars.

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Table 8. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from 0-120 cm depth[z] as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Root Diameter (mm)	Root Volume (cm^3)
0-120	TGS_U3	15762 a[x]	1027.7 a	0.200 abc	5.413 ab
	Premier	14725 ab	873.4 ab	0.180 c	4.176 ab
	OKC 1131	14457 ab	921.9 ab	0.190 bc	4.737 ab
	OKC 1302	14341 ab	969.6 a	0.205 ab	5.277 ab
	Latitude 36	13050 abc	936.8 ab	0.219 a	5.481 a
	Celebration	12904 abc	917.0 ab	0.216 a	5.293 ab
	DT-1	11780 bc	786.7 ab	0.207 ab	4.224 ab
	NorthBridge	10867 c	706.1 b	0.202 abc	3.715 b
	Tifway	10552 c	694.7 b	0.196 abc	3.717 b
	OKC 1163	6258 d	390.95 c	0.192 bc	1.962 c

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 9. Total shoot and root dry weight and root to shoot ratio of ten bermudagrass entries from 0-120 cm depth[z] as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total shoot dry weight[y] (g)	Total root dry weight (g)	Root:Shoot Ratio
0-120	TGS_U3	10.109 ab[x]	0.885 ab	0.087 c
	Premier	7.502 cde	0.780 bc	0.109 b
	OKC 1131	8.831 abc	0.765 bcd	0.086 c
	OKC 1302	8.857 abc	0.988 a	0.112 ab
	Latitude 36	8.303 bcd	1.001 a	0.121 a
	Celebration	10.391 a	0.883 ab	0.084 c
	DT-1	8.99 abc	0.689 cd	0.076 c
	NorthBridge	7.341 cde	0.787 bc	0.107 b
	Tifway	6.739 de	0.589 d	0.087 c
	OKC 1163	6.002 e	0.351 e	0.058 d

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80°C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 10. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from 0-7.5 cm depth[z] as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	Root Dry Weight[y] (g)
0-7.5	TGS_U3	3482.2 ab[x]	266.75 a	0..243 ab	1.631 a	0.362 ab
	Premier	3388.2 ab	229.46 a	0.215 e	1.240 b	0.313 bc
	OKC 1131	3462.7 ab	242.79 a	0.224 cde	1.368a b	0.283 c
	OKC 1302	3574.9 ab	264.84 a	0.235 bcd	1.563 a	0.362 ab
	Latitude 36	3428.5 ab	265.44 a	0.246 ab	1.638 a	0.390 a
	Celebration	3112.2 b	253.94 a	0.260 a	1.662 a	0.375 a
	DT-1	3378.9 ab	252.51 a	0.237 bc	1.508 ab	0.302 c
	NorthBridge	3055.8 b	234.92 a	0.244 ab	1.442 ab	0.367 a
	Tifway	3742.5 a	256.77 a	0.216 e	1.421 ab	0.280 c
	OKC 1163	2442.1 c	167.07 b	0.217 de	0.913 c	0.193 d

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80°C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 11. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from 7.5-15 cm depth[z] as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	Root Dry Weight[y] (g)
7.5-15	TGS_U3	3187.3 a[x]	197.61 a	0.196 ab	0.981 a	0.174 ab
	Premier	2778.0 abc	155.04 ab	0.176 b	0.690 ab	0.143abc
	OKC 1131	2608.9 abc	149.88 ab	0.182 ab	0.688 ab	0.124 bc
	OKC 1302	2382.3 bc	153.50 ab	0.205 ab	0.791 ab	0.155 ab
	Latitude 36	2542.1 bc	171.46 ab	0.212 a	0.933 a	0.186 ab
	Celebration	2419.1 abc	164.26 ab	0.213 a	0.905 a	0.166 ab
	DT-1	2880.5 ab	184.51 ab	0.204 ab	0.943 a	0.152 ab
	NorthBridge	2151.0 c	130.23 bc	0.192 ab	0.627 ab	0.204 a
	Tifway	2812.0 ab	189.52 ab	0.205 ab	1.048 a	0.149 ab
	OKC 1163	1487.1 d	84.95 c	0.108 b	0.387 b	0.074 c

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80°C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 12. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from 15-30 cm depth[z] as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	Root Dry Weight[y] (g)
15-30	TGS_U3	3979.6 a[x]	249.28 a	0.198 ab	1.244 ab	0.179 ab
	Premier	3853.5 ab	228.5 ab	0.186 b	1.086 ab	0.175 ab
	OKC 1131	3391.8 abc	205.84 ab	0.193 b	0.994 abc	0.153 ab
	OKC 1302	3327.2 abc	220.28 ab	0.209 ab	1.168 ab	0.201 ab
	Latitude 36	3166.9 abc	227.71 ab	0.227 a	1.315 a	0.220 a
	Celebration	3350.1 abc	228.22 ab	0.214 ab	1.262 ab	0.178 ab
	DT-1	3056.7 bc	200.17 ab	0.209 ab	1.048 ab	0.143 abc
	NorthBridge	2591.7 c	185.64 ab	0.194 b	0.776 bc	0.202 ab
	Tifway	2823.4 c	158.68 bc	0.207 ab	0.982 abc	0.124 b
	OKC 1163	1730.8 d	105.57 c	0.191b	0.514 c	0.069 c

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80°C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 13. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from 30-60 cm depth^{z} as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	Root Dry Weight^{y} (g)
30-60	TGS_U3	3739.3 a^{x}	243.51 a	0.207 abcd	1.266 ab	0.142 ab
	Premier	3742.1 a	216.66 ab	0.182 bcd	1.001 abc	0.128 ab
	OKC 1131	3801.3 a	256.14 a	0.213 abc	1.380 a	0.167 ab
	OKC 1302	3048.7 abc	214.62 ab	0.223 ab	1.216 ab	0.190 a
	Latitude 36	3141.1 abc	228.35 a	0.235 a	1.393 a	0.180 a
	Celebration	3422.8 ab	237.74 a	0.219 abc	1.320 a	0.148 ab
	DT-1	2205.2 c	134.28 c	0.194 abcd	0.651 cde	0.082 bc
	NorthBridge	2514.7 bc	150.97 bc	0.191 bcd	0.723 bcd	0.197 a
	Tifway	1129.5 d	60.14 d	0.166 d	0.257 de	0.034 c
	OKC 1163	598.4 d	33.36 d	0.178 d	0.147 e	0.013 c

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80°C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 14. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from the 60-90 cm depth[z] as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	Root Dry Weight[y] (g)
60-90	TGS_U3	1114.9 ab[x]	59.54 abc	0.168a	0.254 abc	0.025ab
	Premier	963.1 abc	43.75 abcd	0.139 a	0.159 bc	0.019 b
	OKC 1131	1172.5 ab	66.38 ab	0.171 a	0.302 ab	0.034 ab
	OKC 1302	1699.5 a	99.60 a	0.185 a	0.465 a	0.068 ab
	Latitude 36	771.2 abc	43.81 abcd	0.176 a	0.201 b	0.023 ab
	Celebration	599.7 bc	32.88 bcd	0.171 a	0.143 bc	0.014 b
	DT-1	258.9 bc	15.27 bcd	0.140 a	0.071 bc	0.008 b
	NorthBridge	536.6 bc	29.87 bcd	0.157 a	0.133 bc	0.120 a
	Tifway	44.4 c	2.11 cd	0.037 b	0.008 c	0.001 b
	OKC 1163	0.0 d	0.00 d	0.00 c	0.00 d	0.00 c

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80° C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 15. Total root length, root surface area, average root diameter and root volume of ten bermudagrass entries from 90-120 cm, depth[z], as calculated using Win-Rhizo scanning software.

Depth (cm)	Bermudagrass Entries	Total Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	Root Dry Weight[y] (g)
90-120	TGS_U3	285.5 ab[x]	10.944 ab	0.033 b	0.036 ab	0.002 a
	Premier	0.00 c	0.00 c	0.00 c	0.00 c	0.00 b
	OKC 1131	19.4 b	0.895 b	0.074 b	0.003 b	0.001 a
	OKC 1302	308.9 a	16.71 a	0.173 a	0.0722 a	0.008 a
	Latitude 36	0.00 c	0.00 c	0.00 c	0.00 c	0.00 b
	Celebration	0.00 c	0.00 c	0.00 c	0.00 c	0.00 b
	DT-1	0.00 c	0.00 c	0.00 c	0.00 c	0.00 b
	NorthBridge	17.2 b	1.47 b	0.133 ab	0.010 b	0.010 a
	Tifway	0.00 c	0.00 c	0.00 c	0.00 c	0.00 b
	OKC 1163	0.00 c	0.00 c	0.00 c	0.00 c	0.00 b

[z] Growth tubes were made from clear polyethylene tubing (3.5 cm diameter x 120 cm length).

[y] Dry weights were determined after drying at 80°C for 48 hours.

[x] Means followed by same letters within each column are not significantly different at the P = 0.05 significance level.

Table 16. Percentage of total root length and root surface area in the 0-30 cm profile.

Depth (cm)	Bermudagrass Entries	Total Root length %	Root surface Area %
0-30	TGS_U3	68	69
	Premier	68	70
	OKC 1131	65	65
	OKC 1302	65	66
	Latitude 36	70	71
	Celebration	69	70
	DT-1	79	81
	NorthBridge	72	78
	Tifway	86	87
	OKC 1163	90	96

APPENDIX

Protocol for lysimeter study

Day 1

- Pull out the mini-lysimeter using locking pliers early in the morning (4 AM).
- Water the field plot on the basis of ET rate for warm season grass from Mesonet.
- Mow the mini-lysimeter at the height of 2.5 cm using good sharp scissors.
- Close the valve of all mini-lysimeter by hand.
- Saturate the lysimeter by putting water slowly until water start to flow from top of the mini-lysimeter being careful not to lose calcined clay.
- Leave the mini-lysimeter for 45-60 minute.
- Open the valve and let water drain for about 30 minutes to bring them to field capacity.
- Close the valve once the drainage completely stops. Watch carefully, sometime there may be drop of water coming out so make sure no water is coming out before closing the valve.
- Wipe the mini-lysimeter completely dry including underneath but canopy was not wiped.
- Measure the weight of mini-lysimeter using balance and record the beginning weight.

- Put the mini-lysimeter back into the sleeve in the filed plot.

*Maintain the height of lysimeter in such a way that top canopy of mini-lysimeter matches with the grasses on the field.

*Close the irrigation valve so that irrigation will not turn on during data collection.

Day 2

- Pull the mini-lysimeter from sleeve around 5:30 AM.
- Wipe the mini-lysimeter completely dry including underneath.
- Measure the weight, keep record and put back the mini-lysimeter in the respective sleeves in the field plot.

Day 3

- Pull out the mini-lysimeter from sleeve around 5:30 AM.
- Wipe the mini-lysimeter completely dry including underneath.
- Measure the weight and keep record.
- Mows the mini-lysimeter if needed and put back them in their respective sleeve in the field plot.
- Enter the data, analyze and compare with reference ET rate and ET rate for warm season grass with mesonet data.

*Turn on the irrigation valve before leaving the field.

Fig 1. Washing and planting of grasses in mini-lysimeters.

Fig 2. Mini-lysimeter filled with calcined clay as a growing medium.

Fig 3. Mini-lysimetry field plots.

Fig 4. A mini-lysimeter in a field plot.

Fig 5. Data collection early in the morning.

Fig 6. Mowing of mini-lysimeter.

Fig 7. Saturation of a mini-lysimeter.

Fig 8. Opening of valve to bring a mini-lysimeter in field capacity.

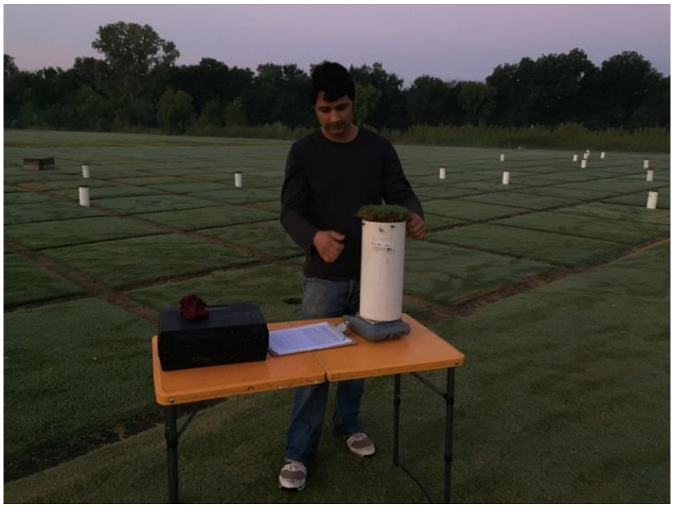

Fig 9. Weighing of mini-lysimeter.

Fig 10. Grasses in PVC tubes for root growth study.

VITA

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