STRATEGIES FOR REDUCING SUPPLEMENTAL IRRIGATION OF COOL-SEASON LAWNS THROUGH SPECIES SELECTION, MOWING PRACTICES, AND IRRIGATION SCHEDULING

by

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Water resources for outdoor areas, such as lawns and landscapes, continues to become limited in many urban areas, especially in times of acute drought stress. Lawn species selection and cultural practices, such as mowing height, can strongly influence overall seasonal water needs. While previous research has reported various lawn species water use rates and differences in the ability of some cultivars to maintain green coverage during acute drought stress, little is known regarding the irrigation requirements of cool-season lawn species when using a deficit irrigation strategy based on a green coverage target threshold (e.g. 60-80% green) approach. Two greenhouse studies were conducted to screen various candidate species and seed mixtures in a sandy media. The highest water use and worst appearance/green coverage was associated with an inexpensive commercial lawn mixture; and the lowest water use and best appearance was generally associated with improved Kentucky bluegrass (*Poa pratensis* L.: KBG) cultivars. Field studies were conducted to quantify the irrigation requirements of drought susceptible (DS) and improved, drought tolerant (DT) KBG and tall fescue [*Schedonorus arundinaceus* (Schreb.): TF] cultivars, blends and mixtures at two mowing heights (5.1 or 8.9 cm). Results from a 74-day field study using a deficit irrigation replacement approach with a 70% green coverage threshold (GCT_{70}) irrigation trigger, demonstrated water savings of approximately 73 to 78% when using a DT TF (60.3 mm) as compared to 100% evapotranspiration (ET_o) replacement (223.4 mm) and a conventional lawn irrigation approach (268.5 mm), respectively. The time to reach the GCT_{70}

generally ranked: TF=TF:KBG mixture>KBG and ranged from 18.0 days for DS ‘Right’ KBG and 52.5 days for DT ‘RainDance’ TF. Among TF and KBG cultivars using the GCT_{70} irrigation approach, DT TF required 35 to 68% less supplemental irrigation compared to DT and DS KBG cultivars (92.1 vs. 187.3 mm), respectively. Within KBG cultivars, the DT ‘Desert Moon’ required one-half the irrigation of DS Right (92.1 vs. 187.3 mm), while there were no differences among TF cultivars for irrigation needs. Mowing height did not affect KBG irrigation needs, but TF at 5.1 cm showed increased visual quality and green coverage, and significantly reduced irrigation requirements. Field research also compared species mixtures and blends using DS and DT KBG and TF to determine the amount of a DT species/cultivar that would enhance drought performance with ratios ranging from 25-100% DT as well as 90:10 TF:KBG mixtures. The quantity of a DT KBG in a blend, and DT TF in a TF:KBG mixture reduced irrigation needs, whereas the drought rating of the KBG cultivar in a TF:KBG mixture had no significant effect. In summary, these studies continue to demonstrate that significant supplemental lawn irrigation savings can be achieved by the selection of superior DT species and cultivars combined with a deficit irrigation replacement approach compared to other cool-season species and conventional irrigation practices.

CHAPTER 1. LITERATURE REVIEW

Introduction

Turfgrass species have been used for centuries as a functional aspect of domesticated animal grazing, residential and commercial landscape designs, and recreational and professional sports. Turfgrass managed for residential and commercial lawns, golf courses, athletic fields, and public parks is estimated to account for 1.9% of the surface of the United States (16 to 20 million hectares), making turfgrass the fourth largest crop in the US (Milesi et al., 2005; Morris, 2006; USDA, 2018). For many states in the cool-humid region, such as Maryland, the total turfgrass acreage (459,000 ha) is largely (82.5%) comprised of single-family homes lawns (379,000 ha) (USDA, 2006).

Turfgrass systems provide many functional, recreational, and aesthetic benefits to the ecosystem and overall population (Beard and Green, 1994). Turfgrass increases infiltration of water and reduces sediment transportation and soil erosion. The thick canopy of turfgrass provides hydraulic resistance, reducing sediment and nutrient loss in established turfgrass systems (Gross et al., 1990). Managed turfgrass areas can be defined as a source and sink of methane, carbon dioxide, nitrogen oxides, nitrous oxides, as well as other non-greenhouse gas pollutants (Stier et al., 2013). Turfgrass around buildings can reduce energy consumption by 20-30% during summer months from a cooling effect as compared to hardscapes (McPherson et al., 1989).

A well-maintained landscape increases property value of residential areas, provides a place for gathering, and an area for children and pets to play outside. Mowing a lawn once a week for thirty minutes provides the adequate daily exercise for a person between the ages of eighteen and sixty-five (Haskell et al., 2007). Recreational activities and outdoor sports played on turfgrass provides a place for physical activity, and turfgrass is a safe, low-cost surface that provides a cushioning effect to reduce injuries (Beard and Green, 1994).

Cool-Season Turfgrass Species in the Midwest

Turfgrass species are physiologically classified as either cool- or warm-season grasses based on their photosynthetic pathway, with the primary difference in the carbon compound initially produced in carbohydrate production; three-carbon or four-carbon compounds are produced for cool and warm-season grasses respectively. Cool-season grasses utilize the C_3 photosynthetic pathway with ribulose 1,5-bisphosphate (RuBP) enzyme as the carbon dioxide acceptor during the first reaction in the process of photosynthesis. These grasses thrive in temperatures between 16 and 24°C and maintain some green color through the winter (Beard, 1973). Warm-season species prefer temperatures between 27 and 35°C and lose chlorophyll as they go into dormancy at soil temperatures below 10°C (Beard, 1973). These grasses use the C_4 photosynthetic pathway, with phosphoenolpyruvate (PEP) carboxylase as the carbon dioxide acceptor during the first reaction of photosynthesis, decreasing photorespiration and increasing the efficiency of photosynthesis as compared to C_3 plants.

Regardless of the photosynthetic pathway, water is essential for maximum productivity, vigor, and health, while water excess or deficits decrease overall turf health. Under high temperatures, RuBP has difficulty differentiating between CO_2 and O_2, increasing photorespiration, decreasing photosynthetic efficiency of C_3 grasses, and increasing the overall water use rate in comparison to warm season grasses, reducing overall drought tolerance. Warm-season grasses have root systems up to 90 cm or greater in depth as compared to C_3 grasses which maintain roots primarily in the upper 30 to 45 cm, increasing total water availability in the soil profile for warm-season grasses (Christians et al., 2016).

The United States can be divided into five climatic regions based on geographical locations. These regions can be defined as the cool-humid, warm-humid, cool-arid, warm-arid, and the transition zone. The cool-humid region includes several Midwest states with environmental conditions favoring cool-season turfgrass species. Two of the primary species grown in the cool-humid region and transition zones of Indiana are Kentucky bluegrass (*Poa pratensis* L.) and tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh. = *Schedonorus arundinaceus* (Schreb.) Durmort., formerly *Festuca arundinacea* Schreb. var. *arundinacea*].

Kentucky bluegrass

Kentucky bluegrass is a popular grass for lawns in Midwestern states like Indiana and is the most widely used turfgrass species in the United States (Christians et al., 2016). This species was introduced to the United States from areas of Eurasia and is used today in residential and commercial properties, athletic fields, and golf courses. Kentucky bluegrass has medium to fine leaf texture and high shoot density (Huff, 2003). The leaf has a boat-shaped tip, folded vernation, and lacks a visible ligule. Kentucky bluegrass has excellent color, mows cleanly, and has improved cold hardiness as compared to other cool-season lawn turfgrass species; however, it can become weak and thin in high shade environments (Christians et al., 2016). This species grows best in fertile, moist, well-drained soil conditions, which are a rare occurrence in many disturbed soils associated with the urban-built environment (Beard, 1973; Bigelow and Soldat; 2013; Christians et al., 2016).

Kentucky bluegrass seed is primarily produced through apomictic reproduction, allowing genetic purity to be maintained among generations (Huff, 2003; Bonos and Huff, 2013).

Germination of seeds typically takes 10 to 21 days, which is relatively slow compared to other cool-season species. Delayed germination of Kentucky bluegrass seedlings allows a competition with broadleaf and grassy weed species for access to light, water, nutrients, and space. The development of rhizomes as Kentucky bluegrass matures increases density, reduces weed encroachment, and increases recuperation from stress and traffic. Rhizomes create a sod-forming sward of turfgrass, making Kentucky bluegrass a desired species for commercial companies growing and installing sod for lawns and athletic fields. However, the knitting of rhizomes in the upper layer of the soil profile over time can contribute to the production of a thatch layer.

Kentucky bluegrass cultivars are divided into two general categories, common and improved types (Christians et al., 2016). Common types consist of many forage and older cultivars with high susceptibility to some diseases and upright growth habits, but increased tolerance to some environmental stress conditions. Improved "turf-type" cultivars have been developed from these common cultivars; 'Merion' was released in the 1930s as the first improved cultivar (Bonos and Huff, 2013). Major advancements have been made in the improvement of Kentucky bluegrass cultivars since the release of Merion. Kentucky bluegrass reproduces by apomixis, so there is high phenotypic and genotypic variation among improved Kentucky bluegrass cultivars, more than other cool-season species (Huff, 2003). This variability has led to a classification system for Kentucky bluegrass cultivars based on growth characteristics, desired environment, and stress tolerance (Bonos et al., 2000; Honig et al., 2018). The proper Kentucky bluegrass cultivar selection in consideration of environment and expectations is important for turf managers due to the high variability in aggressiveness, disease susceptibility, drought tolerance, and other traits.

Tall fescue

Tall fescue is a bunch-type, cool-season turfgrass that is native to Eurasia and was introduced into the United States in the 1800s (Hopkins et al., 2009). Tall fescue leaves have a rolled vernation, pointed leaf tip, prominent venation, and lacks a prominent midrib, auricle, and ligule (Christians et al., 2016). Reproduction of tall fescue occurs through cross-pollination and the species is largely self-incompatible. Germination of tall fescue occurs on average in seven days and helps stabilize bare soil conditions and decrease initial weed competition. The species was predominately used as a forage species until the 1940s, when ‘Kentucky-31’ was released (Meyer and Funk, 1989). This cultivar has a deep root system, heat tolerance, persistence in low-fertility soils, and tolerance to insects (Murray and Powell, 1979). Coarse texture, light green color, poor mowing quality, and non-uniform stands when combined with other turfgrasses make Kentucky-31 undesirable in high-value lawns today.

Major improvements through breeding and selection have produced “turf-type” tall fescue cultivars with lower growth habits, finer leaves, increased tiller density, darker-green color, improved disease resistance, and improved mowing quality (Meyer and Watkins, 2003; Bonos and Huff, 2013). Turf-type tall fescue tolerates warm, dry climates, but is not as cold hardy as many of the cool-season species, such as Kentucky bluegrass. Turf-type tall fescue is used in many home lawns, commercial properties, athletic fields, and parks throughout the southern cool-humid region and transition zone.

Established turf-type tall fescue has a deep root system (60-80 cm), three times the length of Kentucky bluegrass (Su et al., 2008). Even though tall fescue is classified as a bunch-type turfgrass, short rhizomes occur in some cultivars. Breeders have made efforts to increase rhizomes in turf-type tall fescue to improve recovery from damage caused by diseases and traffic. St. John et al. (2009) concluded that tall fescue marketed as rhizome-forming did not improve recoverability and lateral spread compared to other tall fescue cultivars after injury, however, Macolino et al. (2014) described rhizomatous tall fescue as more competitive, even outperforming non-rhizomatous tall fescue when mixed with Kentucky bluegrass. Continued improvements of turf-type tall fescue could increase the overall popularity and uses of the species, especially for low-input lawns.

Turfgrass Population Dynamics

Cool-season turfgrass systems are normally planted as a single cultivar, a blend of several cultivars of a species, or as a mixture of several turfgrass species. Monostands of one species are used under high intensity and highly maintained environments, such as golf courses and stadium athletic fields, because they provide a highly uniform turfgrass surface. Warm-season turfgrass species are planted as a monostand due to differences in texture, color, and tendency to segregate between cultivars and species as well as difficulties in establishing warm-season grasses by seed and the sterility of some hybrids (Steinke and Ervin, 2013). Planting a single cultivar, however, can be risky because of the reduction of genetic diversity, which increases the vulnerability to biotic and abiotic stresses.

Turf is recommended to be planted as a blends or mixtures for cool-season turfgrass stands to increase genetic diversity and adapt to varying micro-environments (Steinke and Ervin, 2013). Cultivars in blends are selected based on complimentary growth habit, leaf texture, color, shoot density, vertical growth rate, environmental adaptation, and pest resistance (Madison, 1971; Beard, 1973; Vargas and Turgeon, 1980). Careful selection of cultivars for a blend composition is critical to ensure persistence of desired cultivars in a sward over time. Composition of a blended sward can change over time, because of the aggressiveness of particular cultivars over others in a blend composition (Lickfeldt et al., 2002). Combining disease susceptible cultivars with tolerant or resistant cultivars may result in thinning and loss of susceptible cultivars, outweighing the benefits of the blend composition (Steinke and Ervin, 2013). The addition of a low or mid-performing cultivar to a high performing cultivar in a blend can reduce the overall seed cost, but will likely reduce the overall quality of the turf (Brede, 2004; Vargas and Turgeon, 1980).

Mixtures of turfgrass species are comprised of multiple species and cultivars to complement the strengths and weaknesses of the other, while being complimentary in overall color and texture. A mixture provides the greatest genetic diversity and tolerance to abiotic and biotic stresses. According to Donald (1963), mixtures potentially have higher overall turf quality as compared to a monostand. A potential risk of mixtures is that one species may become dominant over another, reducing the benefit of that species provides in the sward (Dunn et al., 2002).

Kentucky bluegrass is a popular component in many commercial mixtures in the Midwestern US due to its uniformity when combined with other cool-season turfgrass species. Fine fescue (*Festuca* spp.) is mixed with Kentucky bluegrass to increase turfgrass density in shaded areas. Rose-Fricker et al. (1997) reported Kentucky bluegrass mixed with hard or strong creeping red fescues [*Festuca brevipila* (Tracey.) and *Festuca rubra* L. ssp. *rubra*, respectively] maintained higher turf quality and disease resistance, compared to the mixture of Kentucky bluegrass with chewings fescue (*Festuca rubra* L. ssp. *commutata*) in a field study under low and high fertility maintenance. Perennial ryegrass (*Lolium perenne* L.) is also mixed with these two species to provide quick germination. Kentucky bluegrass, at a rate of 5 to 10%, by seed weight, has been effectively mixed with tall fescue (Meyer and Watkins, 2003). A 90:10 ratio of tall fescue and Kentucky bluegrass contains a seed ratio of approximately 1:1, due to the relatively smaller seed size of Kentucky bluegrass (Turgeon, 2008). The mixture of Kentucky-31 tall fescue and Kentucky bluegrass resulted in clumping of tall fescue, however, improved turf-type tall fescues were found to not segregate over time (Juska et al., 1969; Brede, 1993). The influence of seeding rate, overall turf quality, brown patch (*Rhizoctonia solani*) severity/tolerance, wear tolerance, and plant population composition over time and at different mowing heights have been previously evaluated using mixtures comprised of tall fescue and Kentucky bluegrass (Brede, 1993; Hunt and Dunn, 1993; Dunn et al., 2002; Reynolds et al., 2005; Macolino et al., 2014; Park et al., 2017). Information regarding drought performance and irrigation requirements of these mixtures is limited.

Cultural Inputs: Mowing

Turfgrass areas, such as lawns, parks, golf courses, or athletic fields, are consistently mowed to maintain overall aesthetics and functionality. Mowing originally occurred through the grazing of animals, but today numerous motorized devices, such as reel or rotary mowers, are used to efficiently mow and maintain turfgrass. There are less than 50 grass species that possess a subapical meristem to tolerate mowing and produce new tillers from the crown and nodes of lateral stems (Christians et al., 2016). Mowing is a stress to the turf, removing photosynthesizing plant tissue that could be used to produce carbohydrates for the plant. The plant compensates by increasing in density to produce enough carbohydrates.

Mowing heights for lawns are generally based on aesthetics and homeowner preference, ranging from 3.2 to 10.0 cm (Christians et al., 2016). A recommendation of removing no more than 30 to 40% of the turfgrass leaf tissue during one mowing event (Crider, 1955), was adopted as the “one-third rule” (Madison, 1971; Beard, 1973; Christians et al., 2016) to prevent unnecessary mowing events and the removal of too much leaf tissue. A mowing height that is gradually reduced can respond to stress events, unlike turfgrass that is scalped. Following the one-third rule has been shown to reduce mowing events by 31% as compared to mowing on a weekly basis (Law et al., 2016). As mowing height is lowered, the frequency of mowing increases, resulting in increased equipment emissions, labor, and financial costs.

Turf-type tall fescues have been shown to tolerate mowing heights as low as 1.0 cm while maintaining an acceptable turf quality, increasing in shoot density and decreasing leaf blade width (Grossi et al., 2004). Accordingly, tall fescue was found to remain competitive at a mowing height of 2.5 and 5.0 cm when combined with Kentucky bluegrass over several years (Hall, 1980; Hunt and Dunn, 1993). However, monostands of tall fescue were shown to have an increase in weed pressure at a mowing height of 1.6 and 2.2 cm, as compared to tall fescue mixed with Kentucky bluegrass or perennial ryegrass (Hunt and Dunn, 1993).

Water extraction by roots is related to mowing height, while research on the overall drought tolerance of turf at different mowing heights has shown conflicted results. Mowing heights have been shown to influence root mass, length, depth, mortality, and turnover rate (Juska and Hanson, 1961; Beard and Daniel, 1965; Yelverton, 1999; Liu and Huang, 2002). Mowing heights greater than 5 cm were shown to influence Kentucky bluegrass rooting depth and improve the plants response to drought stress by favoring rhizome and root growth, in a greenhouse study (Juska and Hanson, 1961). Madison and Hagan (1962) demonstrated soil water extraction per Merion Kentucky bluegrass plant was directly proportional to the height of mowing. Carrow (1996) described that an increase in rooting depth in tall fescue correlates with reduction in leaf firing and wilt, while a highly dense root system at the soil surface enhanced wilt. Chabon et al. (2017) observed in a field study that tall fescue maintained at 5.1 cm had an increase of 9 to 17% in frequency of mowing, compared to 8.9 cm, but reported no differences in irrigation requirements between the two mowing heights using a soil moisture sensor-based irrigation regime. However, a 10% increase in crop coefficient was demonstrated in Kentucky bluegrass and perennial ryegrass maintained at 6.3 cm, as compared to 3.1 cm, and creeping bentgrass (*Agrostis stolonifera* L.) maintained at 9.4 mm, as compared to 3.1 mm (Poro et al., 2017). Biran et. al (1981) demonstrated an increase in mowing height of tall fescue from 3 to 6 cm increased water consumption by 29%. Further, a field study in California found tall fescue maintained at 3.8 cm had higher overall visual quality than at 6.4 cm during year one of their experiment with 80% ET supplemental irrigation, however, differences were not seen during year two among the two mowing heights (Richie et al., 2002).

Water Use in Turfgrass Systems

As the human population continues to increase, land use patterns are changing, and the conversion of rural agricultural land to developed, urbanized areas in the US is increasing. This growth has resulted in an increase in the total land used as lawns in urban areas. Irrigation systems are installed in many of these urban lawns to maintain dense, green lawns throughout the growing season. The increase in supplemental irrigation for turfgrass in the US has resulted in the citation of turfgrass as the highest irrigated crop (12 million hectares), receiving three times the irrigation of any other irrigated crop (Milesi et al., 2005; Morris, 2006). In certain regions of the US, supplemental irrigation provided to the outdoor landscape is estimated to account for 50-75% of total water consumption for some residential households (Milesi et al., 2005; DeOreo et al., 2016). In a typical residential system with an irrigation system, there is a tendency to apply excess irrigation to a lawn, with 30-40% more water applied than outdoor plants require (Adhikari et al., 2006). This excess irrigation could be attributed to automated irrigation systems, which apply 47% more irrigation than non-automated, and/or failure to adjust irrigation systems during the fall season (mid-September through late October) when the plant requires less water due to decreased temperatures and reduced day length (Mayer et al., 1999; Nautiyal et al., 2014).

As development increases in many areas of the US, water resources have become limited or depleted, causing the implementation of irrigation restrictions and/or bans to conserve water resources. The majority of these restrictions are during times of acute drought stress and can be voluntary or mandatory (Hill and Polsky, 2005). Restrictions may attempt to reduce the number of irrigation events by implementing an odd-even irrigation schedule based on street address or total irrigation bans until rainfall returns. Different communities within an urban area can draw from different water sources, which varies restriction polices based on the municipality’s water resources (Sisser et al., 2016). A survey showed the general public favoring restrictions during short-term acute drought events as long as agriculture or the environment is not negatively impacted (Stoutenborough and Vedlitz, 2014). The potential for future acute drought events in every climate, not just arid, will result in irrigation restrictions and/or bans and creates the need to have turfgrass systems that can tolerate extended periods of acute drought stress and require less supplemental irrigation to reduce overall water consumption.

Water Use and Drought Mechanisms

Turfgrass water use is reported as evapotranspiration (ET) in inches or millimeters per day, and includes the total water required for growth and transpiration, along with losses from the soil (Beard, 1973; Huang, 2008). Climatic factors (temperature, relative humidity, wind, solar radiation, length of growing season), soil type, turfgrass species, and cultural management influence turfgrass water use. ET rates are influenced by soil texture and structure because these features influence the soil water content (Leinauer and Devitt, 2013). Coarser textured soils have increased hydraulic conductivity, moving water and air more freely in the soil compared to finer soils, such as those with high clay content. Soils with coarser textures, containing an increased percentage of sand and increased pore space, promote deeper rooting, while finer textured soils have been shown to reduce rooting depth (Kopp and Jiang, 2013). The reduction in rooting depth limits the plant-available water in the lower portion of the soil profile and the ability to efficiently utilize precipitation events.

Turfgrass species and cultivars inherently utilize different mechanisms to conserve plant water and ultimately reduce overall irrigation requirements during acute drought stress. These mechanisms include drought tolerance, avoidance, and escape. Drought tolerance is when a plant can maintain the overall physiological functions with little to no water. Adjustments in osmotic potential, cell wall elasticity, and defense mechanisms against reactive oxygen species are examples of drought tolerance mechanisms deployed in turfgrasses. Osmotic adjustment (OA) is the accumulation of compatible inorganic and organic solutes that decrease osmotic potential and water potential to prevent the loss of water to the intercellular spaces when moving water into cells. OA positively correlates with drought tolerance. Pre-conditioning plants prior to drought exposure increases total OA, improving drought tolerance (Jiang and Huang, 2001). DaCosta and Huang (2006b) found that velvet bentgrass (*Agrostis canina* L.) with 50 to 60% more OA had increased drought tolerance as compared to creeping bentgrass. Under limited water availability, reactive oxygen species are produced by the accumulation of excessive energy from light absorption during limitation of water. These reactive oxygen species interact with lipids, nucleic acids, and proteins to cause cellular damage in the plant. Increasing enzyme activity of the antioxidants; superoxide dismutase (SOD), peroxidase (POD), ascorbate peroxidase (APX), glutathione reductase (GR), and dehydroascorbate reductase (DHAR) uses the free oxygen species, reducing damage to cells (Sharma et al., 2012).

Drought avoidance is the physiological function of a plant to delay tissue dehydration through increasing water uptake by increasing root depth, root branching, and overall surface area of the root system, or reducing water loss from transpiring leaves. In tall fescue, cultivars with deeper root systems had increased drought tolerance, compared to cultivars with shallow root systems (Huang and Gao, 2000). '2^{nd} Millennium' tall fescue was found to have increased rooting when compared to two other tall fescue cultivars, without differences in volumetric water content, after irrigation was withheld for 11 days in a growth chamber study (Pan et al., 2013). However, Huang et al. (1997) found drought resistance of tall fescue was due to root plasticity and viability instead of rootmass or length. Among tall fescue, Kentucky bluegrass, and hybrid bluegrass (*Poa arachnifera* Torr. x *P. pratensis*), overall root length, 60-80 cm deep in the soil profile, was 3 to 12 times greater for 'Dynasty' tall fescue in a greenhouse study (Su et al., 2008). The same study found Dynasty to have the greatest total dry root mass of 1.638 g as compared to 1.141, 1.240, and 0.965 g for Kentucky bluegrass and two hybrid bluegrasses, respectively. Ervin and Koski (1998) found tall fescue had 65% more root dry weight from 31 to 90 cm than Kentucky bluegrass, increasing tall fescue's ability to extract more deep soil moisture for continued transpiration under limited water availability.

Turfgrasses can reduce water loss by leaf rolling or stomatal closure to prevent water loss through transpiring leaves (Frank and Berdahl, 2001). Extended stomatal closure, however, can have a negative impact on the turf through decreased transpirational cooling and from reduced carbon fixation (Throssell et al., 1987). Narrower leaves, increased cuticle thickness, and greater epicuticular wax reduce water loss through transpiring leaves, positively correlating with drought avoidance and improved turf quality (Fu and Huang, 2004).

Drought escape refers to the process of plants going into dormancy during long periods of drought. Rhizomes are an escape method for turfgrasses, such as Kentucky bluegrass, surviving in dry soils until moisture becomes sufficient to support regrowth (Youngner, 1985). Species such as annual bluegrass (*Poa annua* L.) can escape water stress by setting seed in the spring during adequate moisture, surviving as dormant seeds during dry periods, and germinating in the fall after rainfall events (Youngner, 1985). Escape mechanisms to combat acute drought are not a preferred survival strategy, since most turf managers desire a persistent green turf throughout the growing season from year to year, and desire not to replant each year.

In situations where summer survival is more important than a persistent green turf under non-irrigated extended drought conditions, Kentucky bluegrass is the preferred species, when compared to other cool-season species, such as tall fescue. This due to its ability to generate new roots and shoots from its rhizomes after drought induced dormancy, whereas tall fescue is slow to recover upon re-watering under a long-term drought after the turf canopy has become desiccated (Huang, 2008).

Supplemental Irrigation Requirements and Programming Strategy

Regardless of the plant's natural drought stress response, supplemental irrigation is commonly used for golf and sports turf, and for commercial and residential properties to maintain healthy turfgrass during low rainfall periods. A general rule of thumb is to provide 25.4 to 38.1 mm of irrigation minus rainfall per week to maintain a dense, healthy cool-season turf (Christians et al., 2016). An irrigation cycle, determined by an operator, can be on a set schedule or a response-based system. A programmatic approach to irrigation scheduling, applying irrigation on given dates (i.e. Monday, Wednesday, Friday), regardless of precipitation events, is rather common. In a survey of Olathe and Wichita, KS homeowners, 40% of residents with a high-value home applied irrigation at least three to four times per week (Bremer et al., 2015). This information revealed that homeowners typically apply irrigation regardless of environmental conditions and likely waste a great deal of water resources. Research is continuing to be conducted to provide information about supplemental irrigation scheduling based on the turf's water use as compared to a pre-set irrigation regime.

Several research methods are acceptable to estimate the water needs and irrigation requirements for turfgrass species. Replacement based on visual percent wilt and leaf firing, ET replacement using gravimetric loss or reference ET replacement, and percent green coverage using digital image analysis are all acceptable methods. Visual observation of wilt (leaf fold and rolling) and leaf firing (yellow/brown color leaves) has been historically used to quantify drought, since wilt is the first sign of drought stress in turf, however, this method can result in inconsistencies among dates of observations and various observers. Thus more quantitative approaches are desired.

Evapotranspiration (ET) rate

Irrigation amounts and timing can be applied to turfgrass based on the calculated ET rates to significantly reduce irrigation amounts in comparison to a "set and forget" irrigation schedule. Haley et al. (2007) reported a 30% reduction in landscape irrigation needs when water was applied based on ET rates. The actual turf water use (ET_t) can be directly measured by gravimetric water loss using lysimeters or estimated by multiplying a crop coefficient (K_c) by the estimate reference evapotranspiration (ET_o). The estimated K_c values change throughout a growing season, with typical K_c values for warm-season species ranging from 0.6 to 0.8, while cool-season species range from 0.7 to 0.95; varying with species, climate, time of year, turf quality, and turf height (Brown and Kopec, 2014). ET_o refers to the ET rate from a reference surface that is described as a hypothetical grass reference crop with an assumed height of 0.12 m, fixed surface resistance of 70 s m^{-1} and albedo of 0.23 (Allen et al., 1998). ET_o can be calculated using the Penman-Monteith method, or the Priestley-Taylor method (Peterson et al., 2017). The Penman-Monteith equation is the standard ET_o estimation method and is calculated using vapor pressure, air temperature, solar radiation, soil heat flux, air density, wind speed, psychrometric constant, and surface and aerodynamic resistance measurements. The Priestley-Taylor approach requires only net or solar radiation, air temperature, and soil heat flux measurements. Peterson et al. (2017) found the Penman-Monteith method to be equivalent to measuring ET using the gravimetric mass balance method using lysimeters, however, the Priestley-Taylor method had rates 5 to 9% lower than using lysimeters.

To measure ET_t using the gravimetric mass balance method, turfgrass is grown in lysimeters, brought to field capacity for initial weight, and the subsequent weights measure water loss over time (g d^{-1}) (Kneebone et al., 1992; Young et al., 1996; Young et al., 1997). Differences in ET rates have been shown among cool-season species. Bowman and Macaulay (1991) found ET rates of 20 tall fescue cultivars to range from 10.0 to 13.5 mm day^{-1} in a greenhouse study over seven days. ET values of Kentucky bluegrass cultivars under well-watered conditions ranged from 3.9 to 6.4 mm day^{-1} using the water balance method under greenhouse conditions (Shearman, 1986). A field study located in Fort Collins, CO, evaluated ET rates of Kentucky bluegrass and hybrid bluegrass, finding ET values of 5.0 and 6.1 mm day^{-1} for hybrid and Kentucky bluegrass, respectively (Suplick-Ploense and Qian, 2005).

Weather stations can calculate ET_o using the Penman-Monteith equation or the Priestley-Taylor method to assist in irrigation management. Applying irrigation based on ET_o rates in Las Vegas, NV, showed a 20% reduction in water applied to tall fescue lawns without loss in quality (Devitt et al., 2008). ET_o based irrigation replacement below 100% ET_o has not shown significant loss in turfgrass quality and function (Shearman, 2008). Cool-season turfgrass species maintain acceptable quality with 80% ET_o replacement, while warm-season species maintain acceptable quality at 60% ET_o replacement (Meyer and Gibeault, 1987). According to DaCosta and Huang (2006a), velvet bentgrass and creeping bentgrass could maintain quality at an ET_o replacement of 60 to 80%, while colonial bentgrass (*Agrostis capillaris* L.) maintained quality at 80 to 100% ET_o replacement. Irrigation replacement of 80% ET_o in hybrid bluegrass and Kentucky bluegrass maintained an acceptable turf quality, but Kentucky-31 and Dynasty tall fescue sustained a higher visual turf quality, with reduced leaf wilt and firing over a two-year period at 80% ET_o as compared to the bluegrasses (Baird et al., 2009). Ervin et al. (2009) reported similar findings, showing that Kentucky bluegrass could be irrigated at 85% ET_o rate without loss of turfgrass quality.

Green coverage threshold

Supplemental irrigation scheduling can be based on a simple conventional, programmatic approach of a set volume at dates, or a plant response-based approach on visual wilt rating or change in the turf appearance as green coverage declines during drought stress. The use of 50% leaf wilt as a trigger for supplemental irrigation was studied by Lewis et al. (2012), finding supplemental irrigation requirements among 28 Kentucky bluegrass cultivars and two hybrid cultivars to range between 233 and 449 mm for a prolonged (≈105 days) drought event in a field study located in Manhattan, KS. Once firing in the leaf blades begins, a decline in overall canopy green coverage can be monitored to evaluate drought tolerance.

Advancements in technology and software analysis have generated a reliable digital image method to estimate green coverage that is more accurate and reproducible, compared to visual ratings or line-intersect analysis (Richardson et al., 2001). Digital image analysis can be performed by various evaluators without bias or variability and can provide consistency across various geographical sites (Karcher and Richardson, 2013). Digital images of turfgrass plots are taken using an enclosed light box to quantify data such as percentage green coverage of the image and turfgrass color. The light box system is intended to exclude all surrounding ambient light, only providing light supplied from a battery-powered artificial light source, which provides consistency among images. Digital images of plots are uploaded to a software program to analyze every pixel for RGB light intensity, with 16.7 million possible colors for each pixel (Karcher and Richardson, 2013). Various software programs have been used to quantify green turf coverage such as: SigmaScan Pro (Systat Software, Chicago, IL), ImageJ [National Institutes of Health (USA)], Assess (Am. Phytopath. Soc., St. Paul, MN), and more recently Turf Analyzer (Karcher et al., 2017). Hue, saturation, and brightness ranges are set to create a threshold based on the (green) color of interest. After the threshold is determined for green pixels, the image is processed to output percent green coverage based on the number of green pixels represented in the total number pixels in the image. Images can be batch processed with each image analyzed in approximately five seconds to one minute, depending upon the computer processing speed and resolution of images (Karcher and Richardson, 2005).

Evaluation of decline in green coverage using digital image analysis has been previously used to quantify drought tolerance of turfgrass species and cultivars. Significant differences in the number of days to reach 25, 50, or 75% green coverage among tall fescue and Kentucky bluegrass cultivars have been reported using digital image analysis, indicating differences in overall drought tolerance among cultivars (Karcher et al., 2008; Richardson et al., 2008; Richardson et al., 2012; Goldsby et al., 2015). A field study in Albany, OR, demonstrated a difference of over 20 days for 49 Kentucky bluegrass cultivars and one hybrid bluegrass to reach 50% green coverage (Richardson et al., 2008), while differences of 13-14 days was demonstrated among 12 tall fescue cultivars (Karcher et al., 2008). Goldsby et al. (2015) found 28 Kentucky bluegrass cultivars and two hybrid bluegrasses to reach 75% green coverage between 21 and 41 days in a field study in KS. Using a green coverage threshold as a drought tolerance indicator has shown tall fescue decline to 50% green coverage in 37.8 to 56.0 days after irrigation is withheld, while Kentucky bluegrass and hybrid bluegrasses decline to 50% green coverage in only 20.3 to 34.0 days (Richardson et al., 2012).

Turfgrass irrigation scheduling based on a green coverage threshold could demonstrate significant water savings, especially using cultivars that remain green longer during periods of acute drought (Goldsby et al., 2015). A threshold of 40% green coverage to trigger irrigation has been shown to simulate a condition where the turf would not experience summer dormancy and ensure recovery (Richardson et al., 2012). The amount of irrigation applied after reaching the green coverage threshold could be based on ET rates or through simulating the amount of water applied during a routine irrigation cycle, typically 12.7 mm of water (Richardson et al., 2012). In a field study, tall fescue cultivars required between 56.9 and 98.8 mm of supplemental irrigation and Kentucky bluegrass required 63.5 to 139.7 mm during an acute drought event (≈90 days) with 40% green coverage as a trigger to supply 12.7 mm of irrigation (Richardson et al., 2012). Limited data are available for the total supplemental irrigation required to maintain lawn turf at an acceptable quality when using a higher greenness threshold as an irrigation trigger (e.g. 60-80% green coverage).

Research Goal and Objectives

Throughout the cool-humid region, seasonal rainfall amounts are generally sufficient for turf persistence, and supplemental irrigation for survival reasons is not essential. However, prolonged (e.g. > 14 days) acute drought events are not uncommon in the cool-humid region, especially in the summer. For residential or commercial properties where the highest visual appearance, green color, and/or vigor are desired, periodic supplemental irrigation may be warranted. Water availability for irrigation in the cool-humid region is generally not a concern, and many homeowners utilize a programmatic (e.g. Mon.-Wed.-Fri., etc.) irrigation schedule. Future restrictions, however, could limit the amount of water available for use during acute drought events. Further, the actual supplemental irrigation needs of various lawn grasses in the Midwest are not well documented. The overall goal of this research was to develop best management strategies to conserve water in the urban-built environment. This was done by exploring various factors that may affect supplemental lawn irrigation needs such as the turf species or cultivar grown and the effect of cultural management inputs, specifically mowing height.

The specific objectives of this research were to:

1. Screen various cool-season lawn species, cultivars and blends/mixtures for water use and acute drought tolerance on a sandy media under greenhouse conditions.

2. Determine supplemental irrigation requirements of drought susceptible and tolerant Kentucky bluegrass and tall fescue cultivars subject to deficit irrigation, using a 70% green coverage threshold at two mowing heights (5.1 vs. 8.9 cm) in the field.
3. Determine the minimum percentage of a drought tolerant cultivar required to make a practical difference in reducing the supplemental water needs in lawn species blends or 90% tall fescue:10% Kentucky bluegrass (90:10) mixtures when tested under field conditions.

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CHAPTER 2. SCREENING COOL-SEASON LAWN SPECIES AND MIXTURES FOR WATER USE AND ACUTE DROUGHT PERFORMANCE

Abstract

Supplemental lawn irrigation accounts for a large portion of total water use in urban and suburban areas. One method to conserve water used for irrigation is to plant lawns with turf species or mixtures that require less water, perhaps due to lower evapotranspiration (ET) needs, but still maintain an acceptable green appearance. Two greenhouse studies were conducted to screen candidate lawn grasses for their water use characteristics. The objective was to compare the acute drought tolerance of commonly planted commercial lawn species/mixtures for the Midwestern US and improved individual species [e.g. tall fescue (TF) and Kentucky bluegrass (KBG)]. Turf was grown to maturity (≈60 d) from seed in PVC cylinders (10 cm diam. x 20 cm deep) containing a high sand content rootzone. In experiment 1, water losses ranged from 3.8 to 4.3 mm d^{-1} for 'Midnight' KBG and Vigoro Lawn Mix, respectively, and 3.0 to 3.3 mm d^{-1} for 90:10 TF:KBG mixture and 'Barvette HGT' KBG, respectively, in experiment 2. Rootmass was determined at the termination of each study and values in experiment 1 ranged from 0.84 to 2.08 g for 'Mallard' KBG and 'Shenandoah Elite' TF, respectively, and 0.385 to 1.727 g for 'Right' KBG and a TF blend, respectively in experiment 2. The highest water use and worst appearance/green coverage was associated with an inexpensive commercial lawn mixture; and the lowest water use and best quality was generally associated with improved KBG cultivars. In summary, these short-term greenhouse studies emphasized the importance of lawn turf species selection for urban water conservation efforts. These results also provided information and guidance for candidates to be used in field trials.

Introduction

As the population continues to increase, the amount of land used for lawns in urban areas has subsequently grown. Many urban lawns have irrigation systems installed to maintain a dense, healthy lawn throughout the growing season. In some regions of the US, supplemental irrigation provided to the outdoor landscape is estimated to account for 50-75% of total water consumption for some residential households, with a tendency to over-irrigate 30-40% more than a lawn requires (Milesi et al., 2005; Adhikari et al., 2006; DeOreo et al., 2016). Excess supplemental irrigation can be attributed to a culture of employing a programmatic approach to irrigation scheduling, applying consistent amounts on set dates (i.e. Monday, Wednesday, Friday) regardless of plant need or recent precipitation events. Due to the large amount of water being used for supplemental lawn irrigation, community limitations regarding water use, especially during acute drought events, have been increasing, even in temperate climates such as the Midwestern US. These restrictions create a need to irrigate based on water used by the turfgrass instead of a programmatic approach.

Turfgrass water use is reported as evapotranspiration (ET) in inches or millimeters per day, and includes the total water required for growth and transpiration, along with losses from the soil (Beard, 1973; Huang, 2008). Climate, soil type, turfgrass species, cultivar, and cultural management practices influence turfgrass water use. Differences in ET rates have been shown among cool-season species (Kopec et al., 1988; Bowman and Macaulay, 1991; Shearman, 1986; Suplick-Ploense and Qian, 2005). Two cool-season species predominately grown in the cool-humid region and transition zones of the Midwestern US are Kentucky bluegrass (*Poa pratensis* L.: KBG) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF]. Kentucky bluegrass is a popular grass for lawns in the Midwest and has excellent color, improved cold hardiness, and determinate rhizomes, which increases density to reduce weed encroachment, improves recuperation from stress and traffic, and improves recovery time after extended drought conditions (Christians et al., 2016). Tall fescue has higher heat and acute drought tolerance, compared to KBG, and improved "turf-types" have lower growth habits, finer leaves, darker-green color, improved disease resistance, and improved mowing quality compared to forage types (Meyer and Watkins, 2003; Bonos and Huff, 2013). Many cool-season lawns in the cool-humid region are planted as a blend of cultivars or a mixture of species, which increases genetic diversity and adaptation to varying micro-environments (Steinke and Ervin, 2013).

Species and cultivar differences in daily total water use have previously been reported for KBG and TF. In 1988, six TF cultivars grown in mini-lysimeters differed in ET ranges by 18%, with values of 6.6 to 7.2 mm day^{-1} (Kopec et al., 1988). Bowman and Macaulay (1991) found ET rates of 20 TF cultivars to range from 10.0 to 13.5 mm day^{-1} in a greenhouse study in Nevada over seven days. Evapotranspiration values of KBG cultivars under well-watered conditions ranged from 3.86 to 6.43 mm day^{-1} using the water balance method under greenhouse conditions in Nebraska (Shearman, 1986). In a field study in Fort Collins, CO, Suplick-Ploense and Qian (2005) evaluated ET rates of KBG and hybrid bluegrass (*Poa arachnifera* Torr. x *P. pratensis*), finding ET values of 5.0 to 6.1 mm day^{-1} for hybrid bluegrass and KBG, respectively. Information on daily water use of recently released and commercially available cultivars, blends, and mixtures is limited and deserves further study.

Turfgrass with an overall increased root system has been shown to delay tissue dehydration and drought stress. Among TF, KBG, and hybrid bluegrass, 'Dynasty' TF had the greatest total dry root mass of 1.638 g, compared to 1.141, 1.240, and 0.965 g for KBG and two hybrid bluegrasses, respectively, in a Kansas greenhouse study (Su et al., 2008). Further, overall root length at 60-80 cm deep in the soil profile was 3 to 12 times greater for Dynasty TF in the same greenhouse study. Variances in rooting characteristics have not only been demonstrated among species, but also cultivars within a species, potentially demonstrating differences in drought tolerance (Huang and Gao, 2000; Pan et al., 2013). Differences in total root depth and mass have been cited among TF cultivars, with no differences in volumetric water content after withholding irrigation for 11 days in a growth chamber study with TF grown in lysimeters using a sand and soil (1:1 v/v) root zone mixture (Pan et al., 2013). Huang and Gao (2000) found TF cultivars with deeper root systems had increased drought tolerance as compared to cultivars with shallow root systems.

If the overall goal is to conserve water in urban environments and reduce supplemental lawn irrigation, then there is a need to determine differences in irrigation requirements among lawn species, cultivars, blends, and mixtures. Thus, comparisons in total water use among these need to be evaluated to add to the limited information currently available on the total water use and visual quality of commercial mixtures compared to newer, higher quality cultivars when subjected to drought. Two greenhouse studies were conducted to evaluate the relative differences among commonly planted lawn species (e.g. TF and KBG) and/or mixtures used in the Midwestern US. The specific objectives of these studies were to 1.) evaluate total water use of commercially available cool-season lawn species and mixtures grown in a sandy media, 2.) monitor/measure changes in visual quality and canopy greenness during acute drought and 3.) determine differences in rootmass and relative leaf water content during acute drought.

Materials and Methods

Two experiments were conducted in the Purdue University Horticulture greenhouses (West Lafayette, IN) during the spring of 2017 and 2018. In the first experiment, five KBG cultivars and blends, five TF cultivars and blends, and four commercial lawn mixtures (Table 2.1) were grown from seed in PVC lysimeters (10 cm diam. x 25.5 cm depth) containing a 80:15:5 (v/v/v) sand-based rootzone consisting of medium-coarse calcareous sand, porous ceramic (Greens Grade Profile; Profile Products; Buffalo Grove, IL) and screened topsoil. Kentucky bluegrass, TF, and species mixtures were seeded at 74, 343, and 294 kg ha^{-1}, respectively, on 2 February 2017. Prior to subjecting the grasses to acute drought, turf received a total of 51.31 kg N ha^{-1}, 25.36 kg P_2O_5 ha^{-1}, and 25.36 kg K_2O ha^{-1} during establishment, rotating urea (46-0-0) with a complete fertilizer (20-20-20). A liquid fertilizer solution was delivered (7.33 kg N ha^{-1} wk^{-1}) every week, split into three applications in 12.7 mm of water per application. Turf was mowed at a 6.4 cm, with clippings removed. Propiconazole was applied to all lysimeters at a rate of 0.99 kg a.i. ha^{-1} on 21 March for suppression of powdery mildew, *Erysiphe graminis*.

On 4 April 2017, acute drought stress was initiated, and water use was determined by the gravimetric mass balance method (Kneebone et al., 1992; Young et al., 1996; Young et al., 1997). At day zero (4 April), all lysimeters received a total of 50.8 mm irrigation in split into two 25.4 mm applications within a period of one hour. Six hours after the final water application, each lysimeter was weighed, representing the lysimeter at field capacity. Each lysimeter was weighed every three to four days thereafter to determine water loss over time. Additionally, the turf was rated for visual quality during the acute drought event using a 0 to 10 scale; where 10=optimal greenness, density, and uniformity; 6=acceptable lawn turf; and 0=bare soil. Once visual quality ratings fell below a mean rating of 4.0 for a given treatment, all lysimeters were rehydrated with 50.6 mm of water wk^{-1}. Thirty-eight days after the drought event was terminated, turf was removed from the lysimeters, the sand was shaken from the roots, roots were washed, and leaf tissue/crown-thatch layer was separated. All tissue was dried in an oven at 60°C, any remaining sand was removed, and the rootmass was weighed.

A second experiment with five KBG cultivars, five TF cultivars, and five blends and mixtures (Table 2.2) were grown in lysimeters (10 cm diam. x 25.5 cm depth) containing a 75:25 (v:v) sand-based rootzone consisting of medium-coarse calcareous sand:porous ceramic (Greens Grade Profile; Profile Products; Buffalo Grove, IL) in 2018. Kentucky bluegrass, TF and mixtures were seeded on a dry weight basis (i.e. 90% TF by weight, 10% KBG by weight) on 26 February 2018 and seeding rates are described in Table 2.2. The turf was grown to maturity and water use was determined gravimetrically as described previously.

Instead of visual quality, differences in green coverage over the drought period were quantified using digital image analysis techniques (Richardson et al., 2001; Karcher and Richardson, 2013). Images were taken using a PowerShot ELPH SD630 camera (Canon U.S.A. Inc., Huntingtion, NY) and an enclosed light box with 2 LED light bulbs (685 lumens, 5000 K) to provide consistent lighting and image height. Images were cropped and analyzed using ImageJ software [National Institutes of Health (USA)] with hue, saturation, and brightness ranges of 40-135, 55-255, and 70-255, respectively. Percent green coverage was calculated: [green coverage % / (100 – background %)], x 100%. Once a treatment average fell below 10% green coverage, water was applied to all treatments with 50.8 mm wk^{-1}, and digital images were taken to evaluate recovery of green coverage.

Thirty days following the acute drought event, all lysimeters recovered to ≥ 75% green coverage. Lysimeters were subjected to another acute drought event to determine differences among percent relative leaf water content (RLWC) (Jiang et al., 2009). Fresh clippings from each lysimeter were collected on day 0, 7, and 14 of the second drought event. Clippings were weighed (to nearest 0.001 g) immediately following harvest as fresh weight (FW), and immersed in water for 24 hours to determine turgid weight (TW) (g). Clippings were then dried and weighed to determine dry weight (DW). Percent RLWC was calculated: [(FW-DW) ÷ (TW-DW)] x 100. After day 14 for RLWC evaluations, lysimeters were fully rehydrated. Twenty days following the final RLWC measurement, the turf was removed from the lysimeters, sand was shaken from the roots, and any remaining rootzone washed free. The leaf tissue/crown-thatch layer was separated and trimmed from roots, and roots were dried and weighed as previously described.

Greenhouse environmental conditions during the experiments were as follows: average daily minimum and maximum temperature in experiment 1 was 20 and 26°C, respectively, with an average relative humidity of 42.7%. The average daily minimum and maximum temperature in experiment 2 was 22 and 29°C, respectively, with an average relative humidity of 76.0%. During both experiments, plants received supplemental lighting to ensure 14/10 hr day/night periods.

Lysimeters were arranged in a randomized complete block on greenhouse benches with five blocks in experiment 1 and four blocks in experiment 2. All data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedure in SAS (SAS Institute, Cary, NC). Significant treatment means were separated using Fisher's protected least significant difference (LSD) test ($P<0.05$). Data were not combined across experiments due to different cultivars and blends/mixtures used in the two experiments.

Results and Discussion

Water Use, Turf Quality, and Green Coverage

The greatest water use occurred between five and ten days after drought initiation (DAI) in experiment 1, with an average of 5.1 mm d^{-1}, while the least water loss occurred between 11 and 14 DAI, with an average of 2.1 mm d^{-1} (Table 2.3). This is not surprising since the growing media was predominantly sand with a relatively low water holding capacity and is natural that the water use would decrease with time as the water in the media was depleted. Water use during the first four days ranged from 3.5 to 4.8 mm d^{-1}. In general, water use ranked, TF>species mixtures>KBG, with the least water used for 'Midnight' KBG, and most for the Vigoro Sun and Shade Mixture. Among the KBG cultivars, the commercial KBG sod blend had the highest water use 10 DAI, with no significant differences 11 to 14 DAI. There were no significant differences in water use among the TF cultivars during the first 10 DAI, but 'Rebel XLR' used significantly more water, compared to 'Penn RK4' 11 to 14 DAI (1.9 and 1.4 mm d^{-1}, respectively) (Table 2.3). Among the mixtures in experiment 1, Vigoro Sun and Shade Mix and Ace Sunny Grass Mix initially used the most water ten DAI, 5.1 and 4.9 mm d^{-1}, respectively. These mixtures used the least water 11 to 14 DAI [1.8 and 2.0 mm d^{-1}, respectively (Table 2.3)], suggesting these mixtures used the majority of water resources in lysimeters within the first 10 DAI.

Prior to the drought event, TF cultivars had the highest visual quality ratings (8.0), while the lowest quality value was associated with Midnight KBG (5.8) (Table 2.3). Turf quality remained consistent 7 DAI, but as available water began to be depleted, turf quality significantly dropped by 14 DAI in TF and species mixtures. At 14 DAI, individual treatments ranged from 3.2 to 6.8 for Vigoro Sun and Shade Mix and My Holiday Lawn KBG, respectively.

In the second experiment, the greatest overall water use again occurred at the beginning of measurements. Within the first 6 DAI, there was an average water loss of 4.2 mm d^{-1}. The least water loss occurring 14 to 20 DAI, with average water loss of 1.6 mm d^{-1}. At 6 DAI, ‘Blue Note’ KBG used the most water (4.7 mm d^{-1}) while ‘Dynamic II’ and ‘Summer’ TF lost the least at 3.7 mm d^{-1} (Table 2.4). When comparing only among the KBG cultivars six DAI, Blue Note was significantly different from ‘Barvette HGT’ and ‘Right’, using 4.7, 4.0, and 4.1 mm d^{-1}, respectively. Among all cultivars 14 to 20 DAI, the highest water use occurred in Barvette HGT KBG, ‘Summer’ TF, ‘Dynamic II’ TF, and 75:25 DS:DT KBG blend with 2.0 mm d^{-1}, while the least was with Blue Note KBG. Water loss among KBG, TF, and mixture means was not significant from days 0-6, 7-13, and 14-20 DAI (Table 2.4). Among KBG cultivars, Right and Barvette HGT used the least water initially, then used more water between 14 and 20 DAI. Dynamic II and Summer TF were able to use the least water among the TF cultivars in the first six DAI, using the most water 14 to 20 DAI. Among the mixtures, the two commercial mixtures, Pennington Midwest Mix (MWM) and a 50:50 KBG:PR commercial lawn care mixture, used the most water six DAI, with 4.6 and 4.5 mm d^{-1}, respectively.

Green coverage between all grasses 13 DAI ranged from 52.4% to 90.3% green for Pennington MWM and Dynamic II TF, respectively (Table 2.4). By 20 DAI, green coverage ranged from 6.1 to 34.0% for the 50:50 KBG:PR commercial lawn care mixture and Right KBG, respectively. Tall fescue cultivars had the highest green coverage compared to KBG cultivars and mixtures until 17 DAI. Kentucky bluegrass cultivars had significantly higher green coverage (59.1%) compared to TF and mixtures (51.8 and 46.4%, respectively) 17 DAI. Twenty DAI, the KBG cultivars continued to have significantly higher green coverage, 27.0%, while TF cultivars and mixtures were at 13.6 and 15.5%, respectively.

Within each species, green coverage generally reflected water loss, R^2 = 0.68 (Figure 2.1). Cultivars that had lost the most water by 6 DAI had reduced green coverage by days 13 to 17 compared to other cultivars. At 20 DAI, there were significant differences in green coverage among KBG cultivars, with Right and Barvette HGT having the highest green coverage, 34%, while Blue Note had the lowest green coverage at 11.5%. TF showed no significant differences in green coverage until 17 and 20 DAI. Summer and Dynamic II remained at 64.1% and 67.4% green coverage 17 DAI, respectively, while other TF were ≤ 45.4%. By 20 DAI, Summer and Dynamic II dropped in green coverage to 19.3 and 22.1%, respectively, while other cultivars were ≤ 11.4% green coverage (Table 2.4).

Recovery, Relative Leaf Water Content, and Rootmass

After 14 days of recovery from the drought event in experiment 2, differences in green coverage among KBG cultivars were found, with the highest green coverage in Midnight and Barvette HGT at 80.6 and 79.4%, while Blue Note KBG only improved to 60% (Table 2.4). All TF cultivars recovered to 75% green coverage by 14 days of recovery. Among the blends and mixtures, the 75:25 DS:DT TF blend had the highest overall green coverage 14 days after recovery (34 DAI), while the two commercial mixes, Pennington Midwest Mix and 50:50 KBG:PR commercial lawn care mixture, reached 70.2 and 60.4% green coverage respectively (Table 2.4).

Relative leaf water content (RLWC) was measured in all treatments except for the two commercial mixtures, Pennington Midwest Mix and 50:50 KBG:PR commercial lawn care mixture during the second experiment. At day 0, RLWC was significantly higher ($P < 0.001$) in TF cultivars, 83.5%, compared to the KBG cultivars and mixtures at 78.9% and 77.1%, respectively (Figure 2.2). By day 7, TF cultivars continued to have significantly higher RLWC compared to KBG cultivars (P=0.025), but by day 14, KBG had significantly more water with 31.6%, as compared to TF and mixes at 24.1 and 24.5% respectively (P=0.002) (Figure 2.2).

Rootmass was higher in TF and mixtures as compared to KBG in experiment 1, but there was no significant difference in rooting between TF species or mixtures (Table 2.3). Rootmass of cultivars and mixtures ranged between 0.84 to 2.08 g for Mallard KBG and Penn RK4 TF, respectively. Within KBG, significant differences in rooting were found, with Mallard and 'Apollo H_2O' having the least (0.84 and 0.96 g, respectively) and a commercial KBG sod blend having the greatest rootmass (1.38 g). There were no differences among TF cultivars or the species mixtures. In the second experiment, nine grasses were evaluated for rootmass, TF cultivars and the 90:10 TF:KBG mixture had the most rootmass compared to three KBG cultivars and one KBG blend (Figure 2.3). Root weights ranged from 0.385 to 1.727 g for Right KBG and the 75:25 DS:DT TF blend, respectively.

In summary, this screening of potential candidate lawn grasses with a lower water requirement and superior acute drought performance (e.g. ability to retain green coverage during drought stress and maintain visual quality) found that KBG cultivars generally had the lowest water use, highest visual quality, and green coverage relative to TF and the various lawn mixes. Treatments with the most water lost initially (≈ 6 d) were the least tolerant to sustained acute drought stress, resulting in lower visual turf quality and/or less green coverage by 14 to 20 DAI. The ET rates of grasses measured in these greenhouse studies during experiments 1 and 2 were different than previous studies, with KBG ET values in this study ranging from 3.1 to 4.1 mm day^{-1} compared to 3.9 to 6.1 mm day^{-1} (Shearman, 1986; Suplick-Ploense and Qian, 2005) and tall fescue ET rates ranging from 3.1 to 4.2 mm day^{-1} in this study compared to 6.6 to 13.5 mm day^{-1} (Kopec et al., 1988; Bowman and Macaulay, 1991). The variation in values could be attributed to differences in greenhouse environmental conditions and cultivar selection.

Within this screening study, there were some limitations to the interpretation of results. Most notable is the fact that these grasses were grown in a sandy media with a restricted (e.g. 20 cm deep) rootzone. Thus, the limited rootzone and limited water reservoir may have been a key factor in reduced turf quality and green coverage in these greenhouse studies for TF and the mixtures. These responses, however, provide some insight of possible field performance during acute drought where these turfgrasses may be grown under less than optimal and/or compacted soil conditions common in the urban-built environment. Field evaluations of candidate KBG, TF, and species mixtures/blends will need to be conducted to compare performance data to more typical lawn situations like turf grown on fine-textured silt-loam soils common to the Midwest, where turf rooting depth is not limited.

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Table 2.1. Kentucky bluegrass (*Poa pratensis* L.: KBG), tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF], and commercial mixtures in 2017 greenhouse study.

Category	Cultivar †	Composition	Seeding Rate
		------------------- (w/w) ------------------	-- kg ha^{-1} --
KBG	Mallard (TWCA)	100% KBG	74
	Midnight		74
	Apollo H_2O (TWCA)		74
	My Holiday Lawn		74
	Commercial Sod blend		74
TF	Falcon IV (TWCA)	100% TF	343
	Rebel XLR (TWCA)		343
	Penn RK4 (TWCA)		343
	Shenandoah Elite (TWCA)		343
	Pennington TF blend	34% Penn RK4, 34% Virtue II, 15% Rebel XLR, 15% ATF1258	343
Mix ‡	Pennington Midwest Mix	29% APR2190 PR, 28% APR2105 PR, 18% Blue Bonnet KBG, 15% Survivor CF, 7% Integra II PR	294
	Scott’s Midwest Mix	10% Jump Start KBG, 9% Shademaster III CRF, 8% Silver Dollar PR, 8% Right KBG, 7% Defender PR, 5% Treazure II CF, 3% Midnight II KBG	294
	Vigoro Sun and Shade Mix	25% Bargamma PR, 24% Bargena III CRF, 10% Panterra V AR, 10% Barduke KBG, 9% Barterra AR, 2% Barpearl CRF, 2% Hardtop HF	294
	Ace Sunny Grass Mix	Baron KBG, LS2100 PR, Envy PR, Patriot 4 PR, Gulf AR	294

† Cultivars were selected from qualified Turfgrass Water Conservation Alliance (TWCA) cultivars and local commercially available mixtures.

‡ Mixtures consisted of various ratios by weight (w/w) of Kentucky bluegrass (KBG), perennial ryegrass (*Lolium perenne* L.: PR), chewings fescue (*Festuca rubra* L. ssp. *commutata*: CF), annual ryegrass (*Lolium multiflorum* L.: AR), creeping red fescue (*Festuca rubra* L. ssp.: CRF), and hard fescue (*Fesctuca brevipila* (Tracey.): HF].

Table 2.2. Kentucky bluegrass (*Poa pratensis* L.: KBG), tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF], and commercial mixtures in 2018 greenhouse study.

Category	Cultivar †	Composition	Seeding Rate
		----------------------- (w/w) ---------------------	---kg ha^{-1} ---
KBG	Blue Note	100% KBG	123
	Midnight		123
	Barvette HGT		123
	Desert Moon (TWCA)		123
	Right		123
TF	Falcon IV (TWCA)	100% TF	392
	Penn RK4 (TWCA)		392
	Summer		392
	RainDance (TWCA)		392
	Dynamic II		392
Mix ‡	KBG blend	75:25 Right (DS), Desert Moon (DT)	123
	TF blend	75:25 Dynamic II (DS), RainDance (DT)	392
	TF:KBG Mix	90:10 Dynamic II (DS), Desert Moon (DT)	392
	Pennington Midwest Mix	29% APR2190 PR, 28% APR2105 PR, 18% Blue Bonnet KBG, 15% Survivor CF, 7% Integra II PR	392
	Commercial Lawn Care Mix	50% KBG, 50% PR	245

† Cultivars were selected from qualified Turfgrass Water Conservation Alliance (TWCA) cultivars and local commercially available mixtures.

‡ Mixtures consisted of various ratios by weight (w/w) of Kentucky bluegrass (KBG), (*Lolium perenne* L.: PR), and chewings fescue (*Festuca rubra* L. ssp. *commutata*: CF).

Table 2.3. Summary of the experiment 1 greenhouse study of Kentucky bluegrass (KBG) cultivars, tall fescue (TF) cultivars, and commercial mixtures for total water loss, visual quality, and rootmass over a 14 day acute drought event.

		Water lost †			Visual quality ‡			Rootmass §
Species	Cultivar	Day 0-4	Day 5-10	Day 11-14	Day 0	Day 7	Day 14	
		------------------ $mm\ d^{-1}$ -----------------			--------- (0-10 scale) ---------			------- g ------
KBG	Mallard	3.6 ef	4.7 e	2.5 a	6.8 bc	6.4 cd	5.6 bc	0.84 e
KBG	Midnight	3.5 f	4.6 e	2.5 a	5.8 d	5.6 d	4.6 cde	1.12 de
KBG	Apollo H_2O	3.7 def	4.6 e	2.4 a	6.4 cd	6.4 cd	5.6 bc	0.93 e
KBG	My Holiday Lawn	3.6 def	4.8 e	2.4 a	7.6 a	7.8 a	6.8 a	1.19 de
KBG	Commercial Sod blend	4.0 cde	5.1 d	2.4 a	8.0 a	7.2 abc	5.8 ab	1.38 cd
TF	Falcon IV	4.6 ab	5.4 ab	1.6 cd	8.0 a	8.0 a	4.0 ef	1.76 ab
TF	Rebel XLR	4.3 bc	5.3 bcd	1.9 b	8.0 a	7.6 ab	4.4 de	1.74 abc
TF	Penn RK4	4.7 ab	5.6 a	1.4 d	8.0 a	8.0 a	3.2 f	2.00 a
TF	Shenandoah Elite	4.4 abc	5.5 ab	1.8 bc	8.0 a	8.0 a	4.0 ef	2.08 a
TF	Pennington TF Blend	4.3 bc	5.4 ab	1.9 bc	8.0 a	7.8 a	4.2 def	1.85 ab
Mixture	Pennington MWM	3.8 def	5.1 cd	2.4 a	7.6 a	7.2 abc	5.0 b-e	2.02 a
Mixture	Scott's MWM	3.8 def	5.1 d	2.4 a	7.4 ab	6.8 bc	5.2 bcd	1.62 bc
Mixture	Vigoro Sun and Shade Mix	4.8 a	5.4 bc	1.8 bc	6.6 c	5.8 d	3.2 f	1.61 bc
Mixture	Ace Sunny Grass Mix	4.0 cd	5.4 ab	2.0 b	7.6 a	7.2 abc	4.6 cde	1.74 abc
ANOVA								
Cultivar		***	***	***	***	**	**	*

†Lysimeters brought to field capacity at the initiation of the experiment and weighed every three to four days to calculate water loss ($mm\ d^{-1}$) using the gravimetric mass balance method.

‡Visual quality determined using a 0 to 10 scale; where 10=optimal greenness, density and uniformity; 6=acceptable lawn turf.; 0=bare soil.

§Turf was removed from the lysimeters, sand was shaken from the roots, roots were washed, leaf tissue/crown-thatch layer separated, and all tissue dried and weighed to calculate rootmass.

*Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 2.4. Summary of the experiment 2 greenhouse study of Kentucky bluegrass (KBG) cultivars, tall fescue (TF) cultivars, and various blends and mixtures of water loss and green coverage over a 20-day acute drought event.

Species	Cultivar	Water lost †			Green coverage ‡				
		Day 0-6	Day 7-13	Day 14-20	Day 6	Day 13	Day 20	Day 27	Day 34
		----------------mm d^{-1} --------------			---------------------------------- % ----------------------------------				
KBG	Blue Note	4.7 a	3.6 a-e	1.1 c	86.0 de	61.1 def	11.5 e-h	37.5 e	60.0 f
	Midnight	4.4 a-d	3.6 a-e	1.5 abc	85.6 e	66.6 c-e	31.4 abc	57.1 abc	80.6 ab
	Barvette HGT	4.0 cde	3.6 ab	2.0 a	87.0 b-e	81.5 abc	33.8 a	58.3 abc	79.4 abc
	Desert Moon	4.5 abc	3.5 a-f	1.3 c	82.3 bc	67.1 c-e	24.1 a-d	44.8 cde	64.1 def
	Right	4.1 b-e	3.5 a-f	1.9 a	80.8 fg	75.0 a-e	34.0 a	57.6 abc	73.7 bcd
TF	Falcon IV	4.6 ab	3.6 abc	1.2 c	89.7 ab	65.9 c-e	7.0 h	57.7 abc	77.5 abc
	Penn RK4	4.2 a-e	3.7 a	1.4 bc	90.4 a	74.1 a-e	8.3 gh	55.0 a-d	75.8 bc
	Summer	3.7 e	3.4 b-f	2.0 a	87.7 a-e	86.0 ab	19.3 d-g	59.6 ab	81.0 ab
	RainDance	4.4 a-d	3.6 a-e	1.4 c	88.0 a-e	77.7 a-d	11.4 e-h	52.3 bcd	77.9 abc
	Dynamic II	3.7 e	3.4 def	2.0 a	89.4 abc	90.3 a	22.1 b-e	68.4 a	86.4 a
Mixture	75:25 DS:DT KBG blend	4.1 b-e	3.3 f	2.0 a	79.6 fg	76.8 a-d	32.6 ab	61.3 ab	78.5 abc
	75:25 DS:DT TF blend	3.9 de	3.4 ef	1.9 ab	88.7 a-d	89.7 a	20.4 c-f	67.6 a	86.6 a
	90:10 TF:KBG Mix	4.1 b-e	3.6 a-e	1.2 c	86.6 cde	68.4 c-e	8.7 gh	54.7 a-d	79.9 abc
	Pennington MWM	4.6 ab	3.4 c-e	1.2 c	78.9 g	52.4 f	9.9 fgh	48.6 b-e	70.2 cde
	50:50 KBG:PR LCO Mix	4.5 abc	3.6 a-d	1.3 c	81.9 fg	57.7 ef	6.1 h	41.3 de	60.4 ef
<u>ANOVA</u>									
Cultivar		**	*	***	***	**	***	**	***

†Lysimeters brought to field capacity at the initiation of the experiment and weighed every three to four days to calculate water loss (mm d^{-1}) using the gravimetric method.
‡Green coverage was determined using digital image analysis software, ImageJ to scan digital images (green pixels/total image pixels)*100, where 0%=bare soil and 100% = complete turfgrass coverage. Images were taken two to three times per week once drought initiated and during recovery. Irrigation was applied after day 20 and recovery was evaluated on day 27 and 34.
*Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

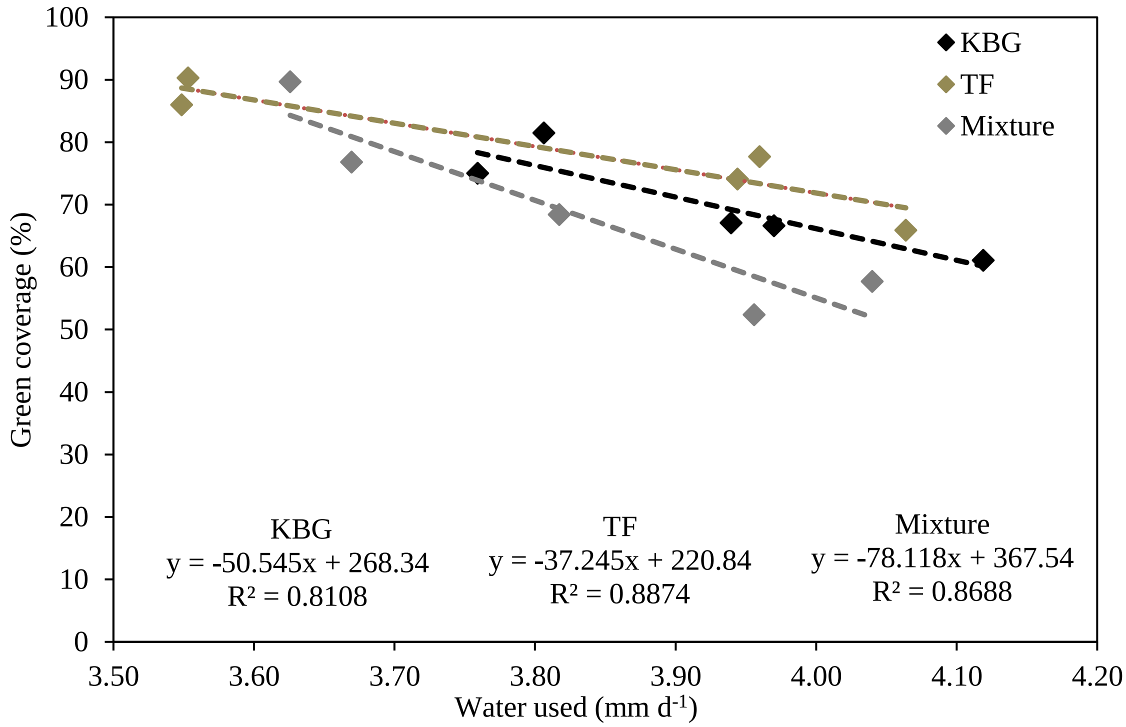

Figure 2.1. Relationship between water used per day between days 0-13, and green coverage within Kentucky bluegrass (KBG), tall fescue (TF), and mixtures 13 days after acute drought initiation in experiment 2. Each data point represents the average of four replications.

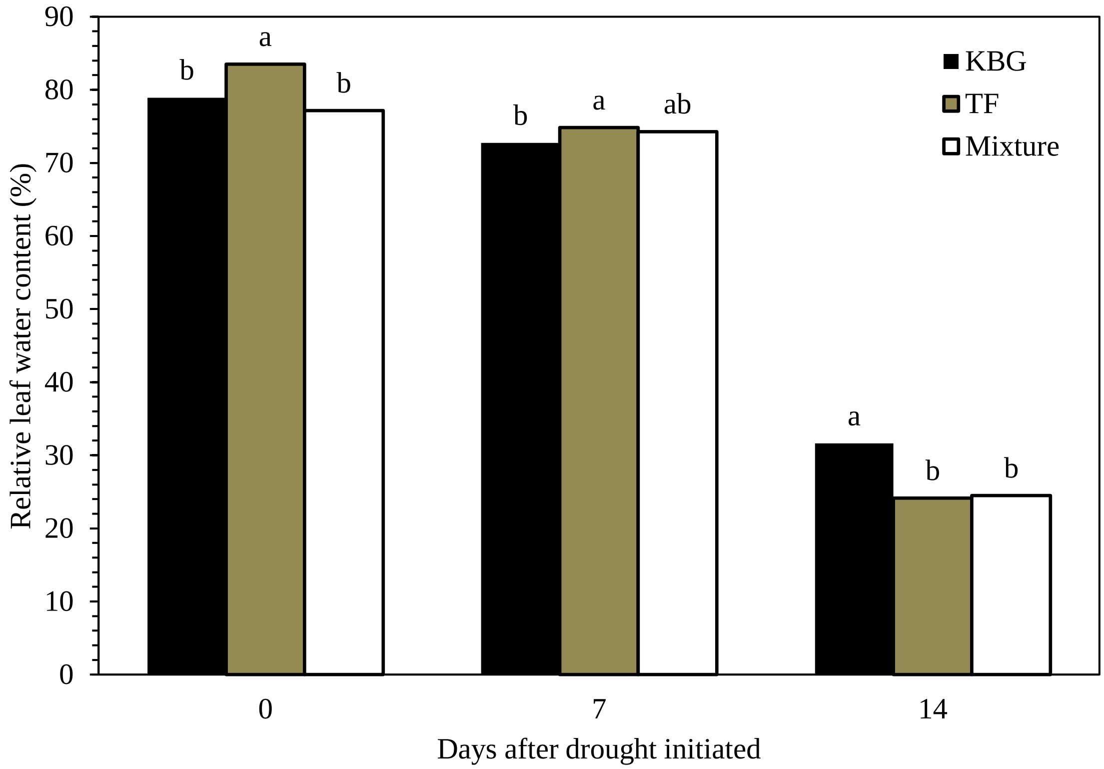

Figure 2.2. Relative leaf water content of Kentucky bluegrass (KBG), tall fescue (TF), and various blends and mixtures in the second acute drought greenhouse experiment. Each bar represents the average of four replications. Bars with the same letter are not significantly different within each date according to Fisher's protected LSD test (α=0.05).

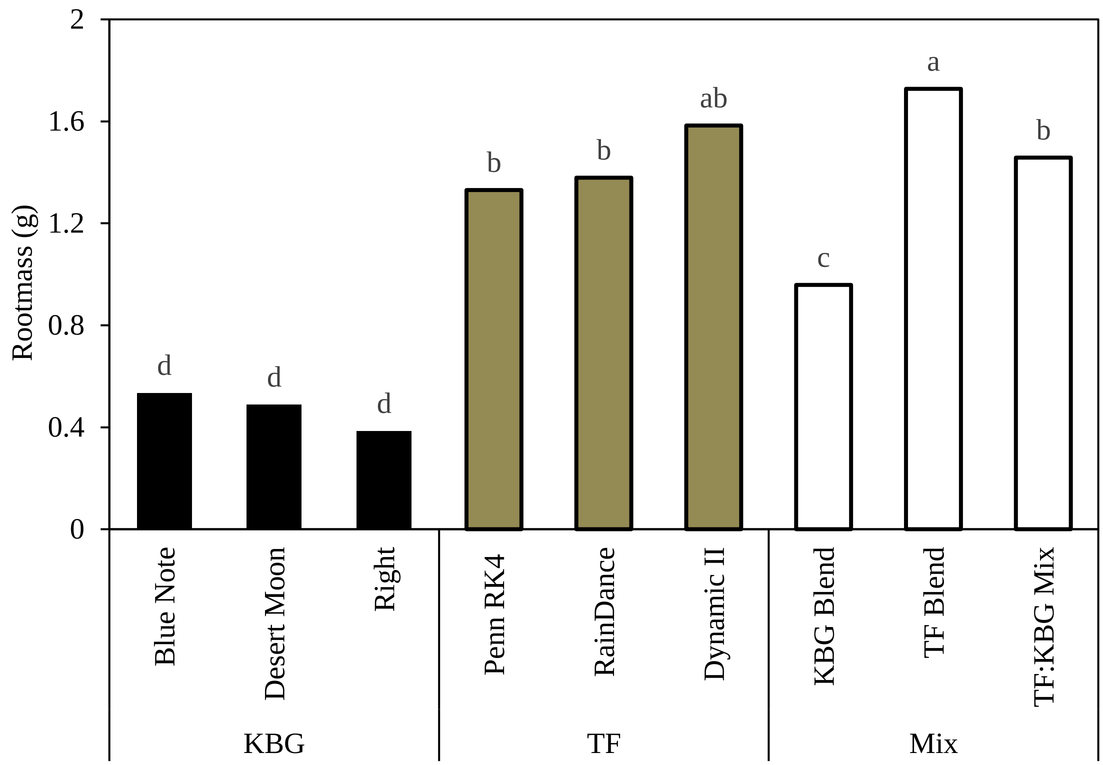

Figure 2.3. Rootmass (g) of Kentucky bluegrass (KBG), tall fescue (TF), and various blends and mixtures in the experiment 2 greenhouse evaluation. Each bar represents the average of four replications. Bars with the same letter are not significantly different according to Fisher's protected LSD test (α=0.05).

CHAPTER 3. IRRIGATION NEEDS OF DROUGHT SUSCEPTIBLE AND TOLERANT TALL FESCUE AND KENTUCKY BLUEGRASS CULTIVARS AT TWO MOWING HEIGHTS

Abstract

Water consumption and supply in the urban landscape continues to be concerns for many communities throughout the US. While much of the public prefers an aesthetically pleasing lawn with consistent green color across growing season, they are unaware of the differences among species for cultural inputs, such as supplemental irrigation, or how factors such as mowing height can affect water needs, often resulting in excessive irrigation. A field study was conducted to determine the water needs of a drought sensitive (DS) and two drought tolerant (DT) Kentucky bluegrass (*Poa pratensis* L.: KBG) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF] cultivars at two mowing heights (5.1 or 8.9 cm). Turf was subjected to a 74-day deficit irrigation event using a fixed-roof rain-out shelter. Supplemental irrigation was determined using a green coverage threshold (GCT_{70}) approach, where if an individual plot fell below 70% green coverage using digital imaging software, 12.7 mm of supplemental irrigation was applied. Time to reach GCT_{70} ranged from 18.0 to 52.5 days. Total irrigation needs ranged from 60.3 to 187.3 mm and varied by species and cultivar, with TF generally taking the longest time to reach GCT_{70}. Within KBG cultivars, the DT cultivars required 33.3 days to reach GCT_{70}, compared to 18.0 days for the DS cultivar. Total water needed for TF was 74.1 and 91.0 mm, at 5.0 and 8.9 cm, respectively, compared to 92.1 and 187.3 mm for the DT and DS KBG cultivars, respectively. Mowing height had no effect on KBG cultivar performance, but maintaining TF at 5.1 cm reduced irrigation needs and improved appearance. These data reinforces the fact that

significant supplemental irrigation can be saved by planting DT species and cultivars and the use of a deficit irrigation strategy.

Introduction

Throughout the United States, water resources are becoming limited or depleted. As more agricultural land is urbanized by an increase in human population, water scarcity will only increase. Although Midwestern states in the cool-humid region receive adequate annual rainfall, prolonged acute drought events (e.g. > 14 days) occur. During these events, water resources for the outdoor landscape often become restricted. These restrictions may attempt to reduce the number of irrigation events by implementing an odd-even schedule based on street addresses, or completely ban irrigation until rainfall returns. This creates a need to reduce irrigation inputs while still maintaining dense, healthy lawn turf, as turfgrass has been cited as the highest irrigated crop in the United States (Milesi et al., 2005).

Supplemental irrigation is used for highly maintained commercial and residential properties to sustain turfgrass quality during low rainfall periods. A general rule of thumb is to provide 25.4 to 38.1 mm of water via rainfall or irrigation per growing week to maintain a dense, healthy cool-season turfgrass (Christians et al., 2016). The irrigation cycle is typically determined by the operators and can be on a set daily schedule or on a response-based system. A programmatic approach to irrigation scheduling on given dates (i.e. Monday, Wednesday, Friday), regardless of precipitation events, is rather common and wastes water resources for lawns.

One possible way to conserve irrigation is to plant a lawn with turfgrass species or cultivars that can tolerate extended periods of acute drought stress. Further, only applying supplemental irrigation based on the turf’s needs rather than a traditional programmatic approach saves water. Turfgrass breeding has produced improved cultivars that require less supplemental irrigation, reducing overall water consumption, while still maintaining an aesthetically pleasing green color. In the cool-humid and transitional climatic zones of the United States, Kentucky bluegrass (*Poa pratensis* L.:KBG) and turf-type tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.:TF] are the predominant drought tolerant cool-season turfgrass species planted in lawns.

Due to genetic variability between KBG and TF, cultivars within each species possess variances in drought mechanisms (i.e. avoidance, tolerance, and escape) that influence the overall susceptibility to acute drought events. Within KBG cultivars, differences of ≈ 20 days have been cited for cultivars to reach 50 or 75% green coverage when subject to acute drought using digital image analysis techniques (Richardson et al., 2008; Goldsby et al., 2015; Richardson et al., 2001; Karcher and Richardson, 2013). In Kansas, Goldsby et al. (2015) found that 28 KBG cultivars and two hybrid bluegrasses (*Poa arachnifera* Torr. x *P. pratensis*) reached 75% green coverage as early as 21 and as late as 41 days after the initiation of drought stress in a field study. Richardson et al. (2008) found KBG cultivars to reach 50% green coverage between 23 and 45 days after drought initiation in year one, and 32 to 42 days year two in a field study in Albany, OR. A difference of 13 to 14 days to reach 50% green coverage among 12 TF cultivars was reported during a prolonged drought event in Albany, OR, ranging from 46 to 59 days in year one and 40 to 54 days to reach 50% green among cultivars (Karcher et al., 2008).

The use of a deficit irrigation replacement strategy that determines total irrigation requirements through digital image techniques, by triggering irrigation at a set green coverage threshold, is useful for water conservation as compared to a traditional programmatic approach. A field study conducted in Albany, OR used 40% green coverage as a trigger for irrigation (12.7

mm plot^{-1}), with total supplemental for TF cultivars ranging from 56.9 to 98.8 mm, while KBG ranged from 63.5 to 139.7 mm irrigation for the acute drought event (≈90 days) (Richardson et al., 2012). A field study in Manhattan, KS, used a 50% visual wilt rating, instead of a green coverage method, and found supplemental irrigation among 28 KBG cultivars and two hybrid bluegrass cultivars to range between 233 and 449 mm for a prolonged (≈105 days) drought event (Lewis et al., 2012).

In addition to species selection, the adjustment of cultural practices, such as mowing, is a potential method to reduce turf irrigation needs. Mowing heights for lawns are generally based on aesthetics and homeowner preference, with heights ranging from 3.2 to 10.0 cm (Christians et al., 2016). Mowing heights have been shown to influence root mass, length, depth, mortality, and turnover rate (Juska and Hanson, 1961; Beard and Daniel, 1965; Yelverton, 1999; Liu and Huang, 2002) with increased mowing heights resulting in increased rooting and improved root health. However, conflicting results have been reported on the correlation of mowing height with drought tolerance or irrigation requirement. Poro et al. (2017) found a mowing height of 3.1 cm, compared to 6.3 cm, resulted in a 10% increase in crop coefficient for KBG and perennial ryegrass (*Lolium perenne* L.), however, Chabon et al. (2017) found no differences in irrigation requirements when TF was maintained at either 5.1 or 8.9 cm. Richie et al. (2002) reported increased visual quality in TF cultivars maintained at 3.8 cm, as compared to 6.4 cm, when receiving 80% ET supplemental irrigation during year one, however, no differences in quality were seen in year two.

While previous research has shown differences in decline of green coverage and supplemental irrigation requirements among TF and KBG cultivars when subjected to an acute drought event, a majority of these studies focused on a prolonged drought event, monitoring until the turf reached 25% green coverage, or irrigation based on an acceptable greenness recovery value of 40 to 50% green or a visual wilt rating. There is limited information about the irrigation requirements of KBG and TF cultivars when irrigation is triggered at a higher green coverage value (e.g. 60-80% green coverage) that is more likely to be perceived by the average consumer as an acceptable visual quality/green coverage level. There is also limited information about irrigation requirements using digital image analysis techniques of these two species when maintained at two mowing heights. Thus, a field study was conducted to document the supplemental irrigation needs of improved drought tolerant KBG and TF cultivars compared to drought susceptible cultivars using a deficit irrigation approach. The specific objectives of this study were to 1.) determine the differences in irrigation required among KBG and TF drought tolerant (DT) and drought susceptible (DS) cultivars when using a 70% green coverage threshold (GCT_{70}) irrigation scheduling technique, and 2.) determine the effect of mowing height on the supplemental irrigation needs and overall appearance or turf quality of these grasses.

Materials and Methods

A field study was conducted at the William H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN. The soil type was a Starks-Fincastle silt loam (fine-silty, mixed, mesic, Aeric Ochraqualf) with a pH of 6.6, 61.75 kg P ha^{-1}, 292.5 kg K ha^{-1}, and 47 g kg^{-1} organic matter. The experimental area was fallow for one year prior to seeding; and 1.13 m^2 plots were seeded in July 2017 and covered with a germination blanket (Futerra EnviroNet: Profile Products; Buffalo Grove, IL). Three KBG cultivars were seeded at 98 kg ha^{-1} and three TF cultivars were seeded at 294 kg ha^{-1} (Table 3.1). Cultivars were selected based on prior documented drought performance provided by Pure-Seed Testing, Inc. (Canby, OR) and qualified cultivars from the Turfgrass Water Conservation Alliance (TWCA). Perennial ryegrass was planted as a border around the experimental area.

Once established, plots were maintained at either 5.1 cm or 8.9 cm with a rotary mower (Honda #HRR216VKA, 53-cm wide deck walk-behind self-propelled mower: American Honda Motor Co., Inc., Alpharetta, GA). Plots were mowed every five days, with clippings collected, and plots were irrigated to promote growth and maintain optimum visual quality until initiation of deficit irrigation in July 2018. During the study, the turf was fertilized according to regional cool-season lawn recommendations using Purdue University Extension's recommendations (Bigelow et al., 2013). From the time of seeding until July 2018, a total of 103.5 kg N, 24.4 kg of P_2O_5, and 42.0 kg K_2O ha^{-1} yr^{-1} were applied over six applications on 18 July, 30 August, 21 September, and 8 November in 2017, and 20 April and 25 May in 2018.

Mesotrione (Tenacity, Syngenta) applications were made on 7 September and 28 September 2017 at 0.28 kg ha^{-1} to suppress undesirable weeds in the seedling turf and amicarbazone (Xonerate 2SC, FMC) was applied at 0.12 kg ha^{-1} on 23 April and 7 May 2018 for postemergence control of *Poa annua* L. Preventative fungicide applications were applied before deficit irrigation on 14 September 2017 using a tank mix of chlorothalonil (Manicure Ultra, Lesco) at 0.36 kg ha^{-1} and fluxpyroxad (Xzemplar, BASF) at 0.20 kg ha^{-1} and again on 26 June 2018 with a tank mix of chlorothalonil (Manicure Ultra, Lesco) at 0.36 kg ha^{-1} and azoxystrobin (Heritage TL, Syngenta) at 0.31 kg ha^{-1}.

Visual turf quality was rated monthly prior to deficit irrigation, then every seven days during the study using a 0 to 10 scale, where 0=brown, dead turf; 6=minimally acceptable lawn turf; and 10=optimal uniformity, density, and color. On 19 July 2018, a fixed-roof rain-out shelter (9.1 m x 21.9 m) (Four Season Tools, Kansas City, MO) covered with 5 mil translucent plastic was placed over the study to exclude rainfall. During rainfall events, the plastic sides were rolled down to prevent lateral water intrusion.

The deficit irrigation event was initiated on 23 July 2018. Immediately prior to this, the trial area received 12.7 mm of water on 22 and 23 July to uniformly hydrate the study area. Thereafter, the center of each plot was imaged twice weekly using a digital camera and a light box. The light box was equipped with an external battery (MotoMaster Eliminator PowerBox, Toronto, ON) to power four LED light bulbs (675 lumens, 5000 K). Images were taken using a Canon PowerShot G12 camera (Canon U.S.A. Inc., Huntington, NY). Percent green coverage of each plot was calculated by digital image analysis (Richardson et al., 2001) using a Java-based software program, Turf Analyzer (Karcher et al., 2017) (hue, saturation, and brightness ranges: 70-170, 10-100, 0-100, respectively).

Once an individual plot fell below the 70% green coverage threshold (GCT_{70}) based on digital green coverage, the corresponding plot received a total of 12.7 mm of water applied in split, 6.35 mm applications measured by a GPI Electronic Water Meter (Great Plains Industries, Inc., Wichita, KS), approximately 30 minutes apart to prevent runoff into the borders. A GCT_{70} was selected to maintain turf at a minimally acceptable turf quality rating ≥ 6. An irrigation rate of 12.7 mm was selected to represent the typical lawn irrigation cycle (Richardson et al., 2012). Irrigation was applied manually using a garden hose connected to a flow meter with a Nelson shower wand. During deficit irrigation, mowing was scheduled by the one-third rule (Crider, 1955; Madison, 1971; Beard, 1973; Christians et al., 2016) to limit traffic and injury to the plots. Weather data, including reference evapotranspiration (ET_o) was gathered using an on-site weather station (Vantage Pro2, Davis Instruments, Hayward, CA).

The experiment was a 2 x 3 x 2 factorial design with two species, three cultivars, and two mowing heights. Each treatment was replicated four times (n=48) and arranged in a strip plot (by mowing) design with cultivars and species randomized within each mowing block. All data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedure in the SAS system (SAS Institute, Cary, NC). Significant treatment means were separated by Fisher's protected least significant difference (LSD) test ($P<0.05$). Due to a significant species effect, each species was analyzed separately.

Results

The time to reach GCT_{70} ranged from 18-52.5 days and varied by species and cultivar. Between KBG and TF, TF remained above the GCT_{70} for a longer period of time, resulting in less supplemental irrigation and higher turf quality during the 74-day drought event. Kentucky bluegrass cultivars fell below GCT_{70} between 18 and 34 days for a DS and DT KBG, respectively, while TF cultivars reached the GCT_{70} between 38.5 and 52.5 days after irrigation at the high and low mowing height (8.9 and 5.1 cm), respectively (Table 3.2). Differences in total irrigation were highly significant between KBG and TF cultivars, with KBG requiring 125.4 and 137.6 mm at the low and high mowing heights, while TF cultivars required 74.1 and 91.0 mm (Table 3.3 : Figure 3.1 B). The cumulative ET_o during this deficit irrigation study was 223.4 mm, as measured by the on-site weather station. Total irrigation needs using a deficit GCT_{70} approach ranged from 33.2 to 61.6% of ET_o for TF and KBG, respectively. Mowing height between KBG and TF cultivars was also significant for species supplemental irrigation needs from day 46 until the end of the study. Differences in green coverage were highly significant from day 18 to 46, and day 60 between species, and mowing height was significant on day 32, 39 and 60 (Table 3.4 : Figure 3.1 A). Initial turf quality differences were highly significant between TF and KBG, due to the increased density, color, and growth of TF (Table 3.2 : Table 3.7). Further, average visual turf quality for the deficit irrigation period was also highly significant, with TF cultivars maintaining higher visual quality throughout (Table 3.2). Representative digital images of ‘Desert Moon’ KBG, ‘Right’ KBG, ‘RainDance’ TF, and ‘Dynamic II’ TF at the two mowing heights on day 22 are presented in Figure 3.4.

Kentucky bluegrass

Differences in days to GCT_{70}, supplemental irrigation, and green coverage were highly significant among KBG cultivars during this experiment. In general, mowing height did not influence the drought response of KBG cultivars. The DT cultivars ‘Apollo H_2O’ and Desert Moon remained above the GCT_{70} for 31 and 33 days, respectively while the DS cultivar, Right, fell below the GCT_{70} by day 18 (Table 3.2). Total supplemental irrigation for KBG cultivars was significant for each date after day 18. Supplemental irrigation amounts ranged from 92.1 to 187.3 mm for Desert Moon at 5.1 cm and Right at 8.9 cm, respectively, ranging 41.2 to 83.8% of ET_o (Table 3.4 : Figure 3.2 B).

Green coverage among KBG cultivars was different during the experiment, except on days 39 and 60. Initial percent green coverage ranged from 78.8 to 95.3% for Right and Desert Moon at 5.1 cm (Table 3.6). Initial green coverage of Right KBG was slightly lower, possibly due to a slow establishment rate and some competition with early spring *Poa annua*, which was later chemically removed. By day 18, Right at both mowing heights fell below GCT_{70}, while Desert Moon green coverage was 91.8%. After falling below the GCT_{70} on day 33, Desert Moon increased in green coverage on day 53 and day 67, reaching above 81% and 77% green coverage at 5.1 and 8.9 cm, respectively. This quick, positive response to supplemental irrigation is a desirable trait (Table 3.6 : Figure 3.2 A).

Initial visual quality ratings for KBG cultivars ranged from 6.0 to 7.4 for Right at 8.9 cm and Desert Moon at 5.1 cm, respectively (Table 3.8). By day 15, Right fell below a minimally acceptable rating (6.0), while Desert Moon remained at a rating of ≈ 7.0 (Table 3.8). All cultivars fell below a minimally acceptable turf quality rating by day 36, but all were able to increase and maintain a quality rating ≥ 6.0 by day 66.

Tall fescue

In general, there were no differences among TF cultivars during this study, however, the mowing height of TF cultivars influenced green coverage and supplemental irrigation. The maintenance of TF at 5.1 cm required less supplemental irrigation from day 39 to day 67. On day 53, total irrigation ranged from 12.7 to 57.2 mm, and by day 74 irrigation totaled from 60.3 to 104.8 mm for RainDance at 5.1 cm and 'Saltillo' at 8.9 cm, respectively (Table 3.4 : Figure 3.3 B). Total irrigation ranged from 27.0 to 46.9% of ET_o. There were no differences in the number of days to reach GCT_{70} for TF cultivars within mowing heights (Table 3.2).

All TF cultivars had > 90% green coverage at the start of the study (Table 3.5). A lower mowing height resulted in significantly higher green coverage between days 9 and 39, and on day 67 (Table 3.6 : Figure 3.3 A). All visual quality ratings for TF cultivars at both mowing heights on day 0 were ≥ 7.4 (Table 3.8). For the duration of the study, turf quality values of all TF cultivars at the two mowing heights remained above the minimally acceptable (≥ 6.0) quality rating. Overall, TF mowed at 5.1 cm had higher visual quality ratings during the first two weeks of the study and between days 36 and 44.

Discussion

Irrigation restrictions and limitations on outdoor water use during prolonged drought events create the need to evaluate turfgrass species and cultivars that tolerate limited supplemental irrigation. If the goal is greater water conservation in irrigated lawns, this study demonstrated the importance of species and cultivar selection when establishing a lawn. From this 74-day field study, up to a three-fold water savings (e.g. 60 vs. 180 mm) was observed by the use of TF, compared to KBG, using a deficit irrigation replacement approach. The number of days to reach the GCT_{70} in this study was similar to the number of days for TF and KBG cultivars to reach 75% green coverage in previous studies (Karcher et al., 2008; Richardson et al., 2008; Richardson et al., 2012; Goldsby et al., 2015). Total irrigation needs for TF and KBG were higher in this study, as compared to those reported by Richardson et al. (2012), but not surprising since irrigation was triggered at a GCT_{70} versus GCT_{40}.

Mowing height was also shown to be an important factor in water needs, especially for TF. An increase in irrigation requirements of TF at a higher mowing height is consistent with results by Biran et al. (1981), showed that increasing the mowing height of TF from 3 to 6 cm increased water consumption by 29%. In a field study in Albany, OR, high root:shoot ratios of TF cultivars demonstrated improved drought tolerance of experimental entries compared to their parents, whereas the root:shoot ratio of KBG cultivars showed no correlation to drought tolerance (Karcher et al., 2008; Richardson et al., 2008). Root length between TF and KBG cultivars in this study will need to be further evaluated to correlate rooting and mowing height/shoot growth to irrigation requirements. Even though these results found a decrease in supplemental irrigation requirements of TF at 5.1 cm, reducing mowing heights is not currently recommended due to possible weed encroachment and increased mowing requirements at this low mowing height.

A conventional "set it and forget it" irrigation schedule of 25.4 mm wk^{-1} would have applied 268.5 mm during the course of this study. The selection of a DT TF cultivar could result in 78% less supplemental irrigation when maintained at 5.1 cm, while a DT KBG cultivar could use 66% less irrigation, using a GCT_{70} approach as compared to a programmatic approach. Compared to 100% ET_o (223.4 mm) replacement irrigation amounts, a water savings of up to 73% and 59% could be attained using a DT TF and DT KBG cultivar, respectively. The replacement of 2.54 cm of water was insufficient to return Right KBG to > 70% green coverage. This could indicate that near 100% ET_o replacement may be needed for this cultivar compared to the savings with DT KBG. Subsequent years of data will need to be obtained to further evaluate TF and KBG cultivar water needs at the different mowing heights while the turf continues to mature.

Additional research is needed to properly evaluate total irrigation requirements across many different improved KBG and TF cultivars and the influence of other cultural practices, such as fertilization or soil amendments, on irrigation needs. The integration of cultivar selection with emerging environmental data acquisition technologies to develop improved data-driven irrigation management practices may also deserve study. In summary, this study reinforces the fact that significant water savings, as much as 78%, can be achieved by simply planting improved, more drought tolerant species and/or cultivars in lawns and employing a deficit irrigation approach based on demonstrated need compared to conventional supplemental irrigation approaches.

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Table 3.1. Kentucky bluegrass (*Poa pratensis* L.) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.] cultivars, drought ratings, and providers.

Species	Cultivar †	Drought Rating	Provider
Kentucky bluegrass	Apollo H_2O ‡ (TWCA)	Tolerant	ProSeeds
Kentucky bluegrass	Desert Moon § (TWCA)	Tolerant	Pure-Seed Testing, Inc.
Kentucky bluegrass	Right §	Susceptible	Pure-Seed Testing, Inc.
Tall fescue	RainDance (TWCA)	Tolerant	Pure-Seed Testing, Inc.
Tall fescue	Saltillo (TWCA)	Tolerant	Pure-Seed Testing, Inc.
Tall fescue	Dynamic II	Susceptible	Pure-Seed Testing, Inc.

† Cultivars were selected from information on drought rating provided by Pure-Seed Testing, Inc. (Canby, OR) and qualified cultivars in the Turfgrass Water Conservation Alliance (TWCA) program.

‡ Compact type Kentucky bluegrass classification.

§ Elite compact type Kentucky bluegrass classification.

Table 3.2. Summary analysis of variance (ANOVA) for Kentucky bluegrass (*Poa pratensis* L.:KBG) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF] cultivars used to determine the effect of drought tolerant (DT) cultivars and drought susceptible (DS) cultivars on supplemental irrigation needs across two mowing heights.

Species	Cultivar	Mowing Height	Days until 70% green †	Total irrigation applied †	Initial visual quality ‡	Mean visual quality ‡
		---cm ---	--- days ---	--- mm ---	--------- (0-10 scale) ----------	
KBG	Apollo H_2O	5.1	31.5 a	123.8 c	6.9 ab	6.3 a
		8.9	31.3 a	130.2 c	6.8 abc	6.1 ab
	Desert Moon	5.1	32.5 a	92.1 d	7.3 a	6.2 a
		8.9	34.0 a	95.3 d	7.4 a	6.2 ab
	Right	5.1	18.0 b	160.4 b	6.0 c	5.9 b
		8.9	18.0 b	187.3 a	6.4 bc	6.0 ab
TF	RainDance	5.1	52.5 a	60.3 a	7.8 ab	7.1 a
		8.9	47.0 a	79.4 a	7.6 ab	6.9 ab
	Saltillo	5.1	45.5 a	85.7 a	8.0 a	7.1 a
		8.9	38.5 a	104.8 a	7.4 b	6.8 ab
	Dynamic II	5.1	45.5 a	76.2 a	7.5 b	7.0 a
		8.9	41.0 a	88.9 a	7.4 b	6.8 b
	<u>ANOVA</u>					
	Species (S)		***	***	***	***
	Cultivar (C)		NS	***	***	NS
	Mowing (M)		*	*	NS	*
	S x M		*	NS	NS	*
	C x M		NS	NS	NS	NS
	S x C x M		NS	NS	NS	NS

† Green coverage was determined using digital image analysis software, where 0%=bare soil and 100% = complete turfgrass green coverage. Images were taken twice per week once drought initiated and irrigation of 12.7 mm was applied when turf was < 70% green coverage.
‡ Visual quality determined using a 0 to 10 scale; where 10=optimal greenness, density and uniformity and 6=acceptable lawn turf. Initial visual quality value was rated on day 0 and mean visual quality was averaged across the 74-day deficit irrigation event.
*Means in the same column within the same species followed by the same letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 3.3. Cumulative supplemental irrigation applied to Kentucky bluegrass (KBG) and tall fescue (TF) at two mowing heights (MH) during a deficit irrigation event.

		Days after drought initiated †								
Species	MH	18	25	32	39	46	53	60	67	74
	- cm -	Supplemental irrigation (mm) ‡								
KBG	5.1	4.2 a	13.8 a	23.8 a	47.1 a	70.4 a	83.1 a	100.0 a	106.4 a	125.4 a
	8.9	4.2 a	14.8 a	26.5 a	49.7 a	75.1 a	93.1 a	111.1 a	117.5 a	137.6 a
TF	5.1	0.0 b	0.0 b	0.0 b	3.2 b	14.8 c	26.5 c	44.5 c	52.9 c	74.1 b
	8.9	0.0 b	0.0 b	0.0 b	11.6 b	29.6 b	49.7 b	63.5 b	75.1 b	91.0 b
ANOVA										
Species (S)		***	***	***	***	***	***	***	***	***
Mowing (M)		NS	NS	NS	NS	**	***	**	**	*
S x M		NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 3.4. Cumulative supplemental irrigation applied to Kentucky bluegrass (KBG) and tall fescue cultivars (TF) at two mowing heights (MH) once plots reached a 70% green coverage threshold.

			Days after drought initiated †								
Species	Cultivar	MH	18	25	32	39	46	53	60	67	74
		-- cm --	Supplemental irrigation (mm) ‡								
KBG	Apollo H_2O	5.1	0.0 b	3.2 bc	9.5 b	31.8 b	54.0 b	76.2 c	92.1 cd	101.6 c	123.8 c
		8.9	0.0 b	6.4 b	9.5 b	31.8 b	57.2 b	79.4 c	101.6 c	108.0 c	130.2 c
	Desert Moon	5.1	0.0 b	0.0 c	6.4 b	31.8 b	57.2 b	60.3 d	76.2 d	76.2 d	92.1 d
		8.9	0.0 b	0.0 c	6.4 b	31.8 b	57.2 b	66.7 cd	76.2 d	79.4 d	95.3 d
	Right	5.1	12.7 a	38.1 a	55.6 a	77.8 a	100.1 a	112.8 b	131.8 b	141.4 b	160.4 b
		8.9	12.7 a	38.1 a	63.5 a	85.7 a	111.1 a	133.4 a	155.6 a	165.1 a	187.3 a
	<u>ANOVA</u>										
	Cultivar (C)		***	***	***	***	***	***	***	***	***
	Mowing (M)		NS	NS	NS	NS	NS	*	NS	*	NS
	C x M		NS	NS	NS	NS	NS	NS	NS	NS	NS
TF	RainDance	5.1	0.0 a	0.0 a	0.0 a	3.2 b	9.5 b	12.7 b	28.6 b	38.1 b	60.3 a
		8.9	0.0 a	0.0 a	0.0 a	12.7 a	25.4 a	44.5 a	60.3 a	69.9 ab	79.4 a
	Saltillo	5.1	0.0 a	0.0 a	0.0 a	3.2 b	15.9 ab	34.9 ab	54.0 ab	63.5 ab	85.7 a
		8.9	0.0 a	0.0 a	0.0 a	15.9 a	38.1 a	57.2 a	69.9 a	82.6 a	104.8 a
	Dynamic II	5.1	0.0 a	0.0 a	0.0 a	3.2 b	19.1 ab	31.8 ab	50.8 ab	57.2 ab	76.2 a
		8.9	0.0 a	0.0 a	0.0 a	6.4 ab	25.4 ab	47.6 a	60.3 a	73.0 ab	88.9 a
	<u>ANOVA</u>										
	Cultivar (C)		NS	NS	NS	NS	NS	NS	NS	NS	NS
	Mowing (M)		NS	NS	NS	**	**	**	*	*	NS
	C x M		NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Means in the same column within the same species followed by the same lowercase letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 3.5. Green coverage during a deficit irrigation event of Kentucky bluegrass (KBG) and tall fescue (TF) at two mowing heights (MH).

		Days after drought initiated †										
Species	MH	0	9	18	25	32	39	46	53	60	67	74
	- cm -	Green coverage (%) ‡										
KBG	5.1	89.3 a	87.8 a	80.9 c	73.4 c	73.1 c	61.8 c	63.1 b	73.1 a	60.1 b	72.2 a	63.3 a
	8.9	91.9 a	90.7 a	80.2 c	71.9 c	68.9 c	62.2 c	65.0 b	70.9 a	67.6 a	73.3 a	66.1 a
TF	5.1	92.0 a	92.9 a	91.4 a	90.2 a	89.1 a	78.6 a	72.5 a	73.7 a	68.7 a	68.9 a	66.6 a
	8.9	90.7 a	90.5 a	86.2 b	83.2 b	80.7 b	69.7 b	71.3 a	70.9 a	68.4 a	72.3 a	68.1 a
<u>ANOVA</u>												
Species (S)		NS	NS	**	***	***	***	***	NS	**	NS	NS
Mowing (M)		NS	NS	NS	NS	***	**	NS	NS	*	NS	NS
S x M		NS	NS	NS	NS	NS	**	NS	NS	*	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

‡ Green coverage was determined using digital image analysis software, Turf Analyzer to scan digital images (green pixels/total image pixels)*100, where 0%=bare soil and 100% = complete turfgrass coverage. Images were taken twice per week once drought initiated.

Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 3.6. Green coverage during a deficit irrigation event of Kentucky bluegrass (KBG) and tall fescue cultivars (TF) at two mowing heights (MH).

			Days after drought initiated †									
Species	Cultivar	MH	0	9	18	25	32	39	53	60	67	74
		- cm -	Green coverage (%) ‡									
KBG	Apollo H_2O	5.1	94.0 a	93.1 a	88.3 ab	78.1 ab	73.3 ab	60.3 a	66.1 c	59.8 a	66.7 c	59.0 c
		8.9	93.6 a	92.5 ab	86.2 b	74.6 b	75.2 ab	61.8 a	66.5 bc	64.5 a	70.2 bc	59.6 bc
	Desert Moon	5.1	95.3 a	95.0 a	91.8 a	85.2 a	78.1 a	60.1 a	84.0 a	60.4 a	81.4 a	66.7 ab
		8.9	94.6 a	93.6 a	89.3 ab	80.1 ab	70.9 ab	62.6 a	77.5 ab	70.1 a	77.2 ab	69.7 a
	Right	5.1	78.8 c	75.3 c	62.7 c	57.0 c	68.0 bc	65.0 a	69.1 bc	60.0 a	68.4 c	64.4 abc
		8.9	87.4 b	86.0 b	65.2 c	61.1 c	60.5 c	62.3 a	68.6 bc	68.2 a	72.6 bc	69.0 a
	<u>ANOVA</u>											
	Cultivar (C)		***	***	***	***	**	NS	**	NS	***	**
	Mowing (M)		NS	NS	NS	NS	NS	NS	NS	*	NS	NS
	C x M		*	*	NS	NS	NS	NS	NS	NS	NS	NS
TF	RainDance	5.1	92.0 a	93.0 a	91.5 a	90.2 a	89.3 a	81.0 a	76.2 a	68.3 a	66.1 a	68.8 a
		8.9	90.7 a	90.4 b	86.8 b	83.0 b	80.6 b	71.5 abc	71.8 a	69.6 a	73.6 a	69.8 a
	Saltillo	5.1	92.4 a	92.8 a	91.6 a	90.4 a	89.5 a	78.6 ab	71.4 a	68.9 a	70.0 a	62.7 b
		8.9	90.7 a	90.9 b	85.6 b	82.8 b	78.6 b	67.4 c	71.2 a	67.6 a	73.6 a	67.2 a
	Dynamic II	5.1	91.5 a	92.8 a	91.1 a	90.0 a	88.5 a	76.2 abc	73.5 a	69.0 a	70.7 a	68.1 a
		8.9	90.6 a	90.3 b	86.3 b	83.6 b	82.8 b	70.3 bc	69.8 a	68.0 a	69.7 a	67.3 a
	<u>ANOVA</u>											
	Cultivar (C)		NS	NS	NS	NS	NS	NS	NS	NS	NS	*
	Mowing (M)		NS	***	***	***	***	**	NS	NS	*	NS
	C x M		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

‡ Green coverage was determined using digital image analysis software, Turf Analyzer to scan digital images (green pixels/total image pixels)*100, where 0%=bare soil and 100% = complete turfgrass coverage. Images were taken twice per week once drought initiated.

Means in the same column within the same species followed by the same lowercase letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 3.7. Visual turfgrass quality of Kentucky bluegrass (KBG) and tall fescue (TF) at two mowing heights (MH) during a deficit irrigation event with supplemental irrigation applied at 70% green coverage threshold.

		Days after drought initiated †								
Species	MH	0	15	28	36	44	50	60	66	74
	- cm -	------------------------ Visual quality (0-10 scale) ‡ ------------------------								
KBG	5.1	6.7 b	6.4 c	6.0 b	5.3 c	6.1 b	6.1 b	6.1 b	6.4 b	6.1 b
	8.9	6.8 b	6.3 c	6.0 b	5.4 c	5.7 c	6.1 b	5.9 b	6.4 b	6.3 b
TF	5.1	7.8 a	7.5 a	7.3 a	7.0 a	6.9 a	6.8 a	6.7 a	6.8 a	6.8 a
	8.9	7.5 a	7.2 b	7.1 a	6.7 b	6.5 b	6.7 a	6.5 a	6.6 ab	6.7 a
ANOVA										
Species (S)		***	***	***	***	***	***	***	*	***
Mowing (M)		NS	NS	NS	NS	**	NS	NS	NS	NS
S x M		NS	*	NS	*	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

‡ Visual quality was rated using a 0-10 scale, where 0=bare soil and 10=optimum greenness, density, and uniformity, 6=minimum acceptable lawn turf. Visual quality was rated one time per week.

Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 3.8. Visual turfgrass quality of Kentucky bluegrass (KBG) and tall fescue cultivars (TF) at two mowing heights (MH) during a deficit irrigation event with supplemental irrigation applied at 70% green coverage threshold.

			Days after drought initiated †								
Species	Cultivar	MH	0	15	28	36	44	50	60	66	74
		-- cm --	Visual quality (0-10 scale) ‡								
KBG	Apollo H_2O	5.1	6.9 ab	6.4 b	6.3 a	5.8 a	6.3 a	6.0 a	6.1 a	6.4 a	6.3 a
		8.9	6.8 abc	6.6 ab	6.4 a	5.4 ab	5.8 ab	6.1 a	5.8 a	6.1 a	6.3 a
	Desert Moon	5.1	7.3 a	6.9 a	6.0 a	4.5 c	5.9 ab	6.6 a	6.1 a	6.8 a	6.1 a
		8.9	7.4 a	7.0 a	5.9 a	5.0 bc	5.5 b	6.0 a	6.0 a	6.5 a	6.5 a
	Right	5.1	6.0 c	5.8 c	5.9 a	5.5 ab	6.3 a	5.6 a	6.0 a	6.0 a	6.0 a
		8.9	6.4 bc	5.6 c	5.9 a	5.9 a	5.8 ab	6.3 a	5.9 a	6.5 a	6.3 a
	<u>ANOVA</u>										
	Cultivar (C)		**	***	NS	**	NS	NS	NS	NS	NS
	Mowing (M)		NS	NS	NS	NS	*	NS	NS	NS	NS
	C x M		NS	NS	NS	NS	NS	NS	NS	NS	NS
TF	RainDance	5.1	7.8 ab	7.6 a	7.4 a	7.0 ab	7.0 a	7.0 a	6.6 a	6.6 a	6.8 a
		8.9	7.6 ab	7.1 b	7.1 a	6.6 b	6.5 a	6.8 a	6.6 a	6.6 a	6.9 a
	Saltillo	5.1	8.0 a	7.4 ab	7.5 a	7.0 ab	6.8 a	6.6 a	6.8 a	6.9 a	6.9 a
		8.9	7.4 b	7.1 b	7.1 a	6.8 ab	6.5 a	6.6 a	6.5 a	6.9 a	6.6 a
	Dynamic II	5.1	7.5 b	7.5 a	7.1 a	7.1 a	6.9 a	6.9 a	6.6 a	6.8 a	6.9 a
		8.9	7.4 b	7.4 ab	7.1 a	6.8 ab	6.4 a	6.8 a	6.4 a	6.3 a	6.5 a
	<u>ANOVA</u>										
	Cultivar (C)		NS	NS	NS	NS	NS	NS	NS	NS	NS
	Mowing (M)		*	**	NS	*	*	NS	NS	NS	NS
	C x M		NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

‡ Visual quality was rated using a 0-10 scale, where 0=bare soil and 10=optimum greenness, density, and uniformity, 6=minimum acceptable lawn turf. Visual quality was rated one time per week.

Means in the same column within the same species followed by the same lowercase letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

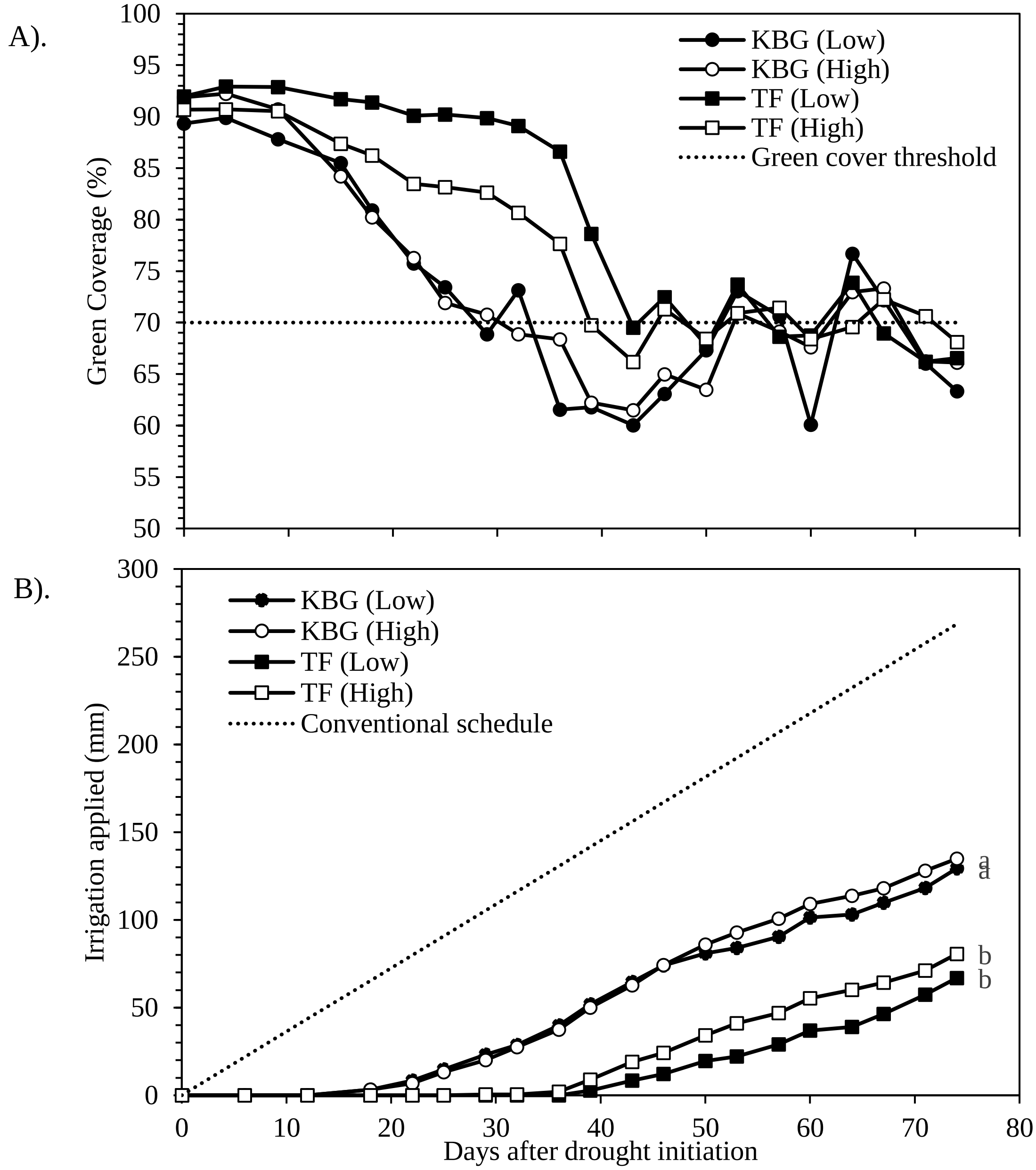

Figure 3.1. Green coverage (%) over time (A) and cumulative water applied (mm) (B) during a deficit irrigation event relation to a conventional irrigation schedule (25.4 mm wk^{-1}) in 2018 for Kentucky bluegrass (KBG) and tall fescue (TF) at two mowing heights; low (5.1 cm) and high (8.9 cm). Each data point represents the average of four replications, three cultivars, and two heights of cut (n=24). Turfgrass falling below 70% green coverage received 12.7 mm of supplemental irrigation. Lines with the same letter are not significantly different according to Fisher's protected LSD test (α=0.05).

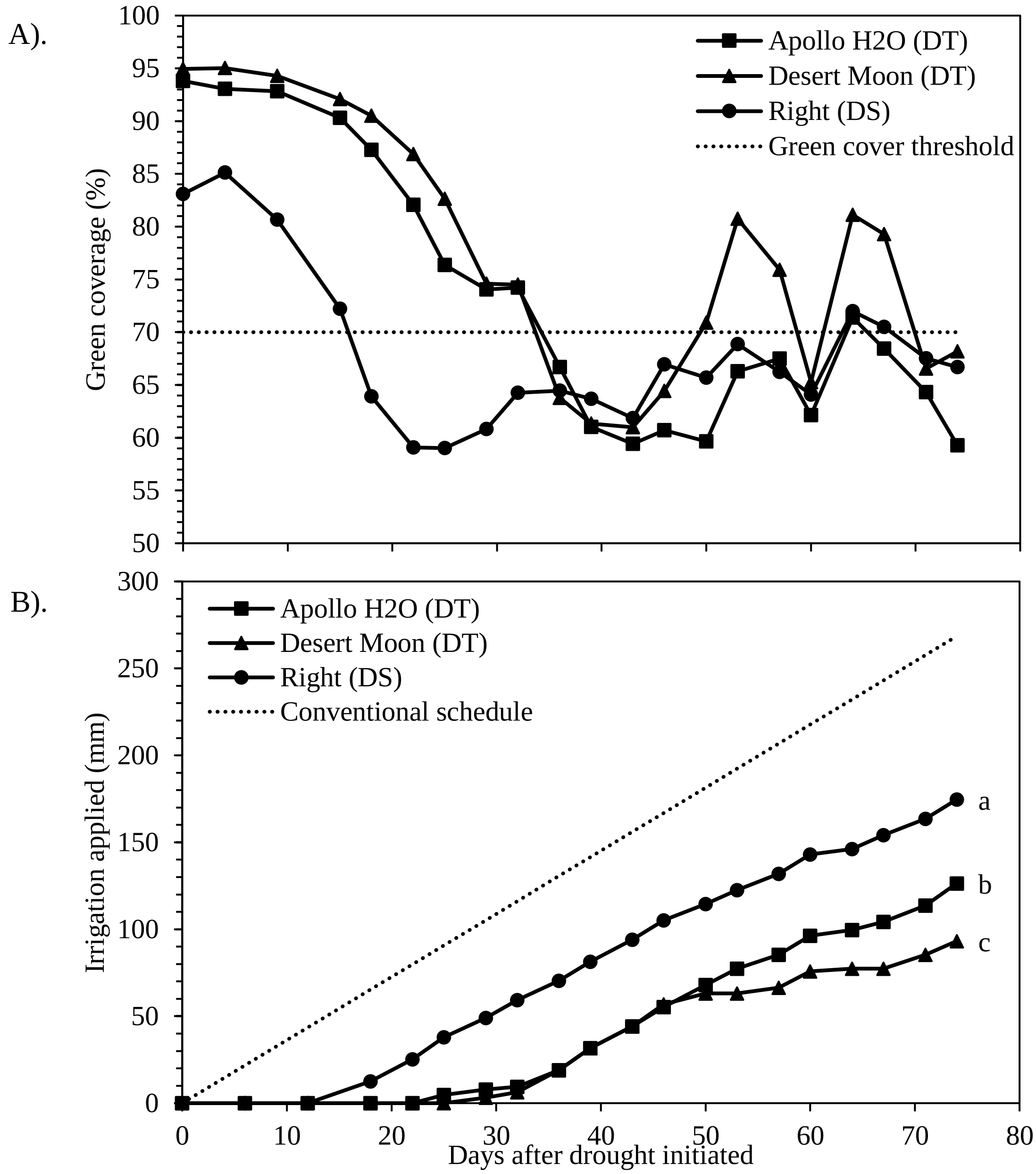

Figure 3.2. Green coverage (%) over time (A) and cumulative water applied (mm) (B) during a deficit irrigation event in relation to a conventional irrigation schedule (25.4 mm wk^{-1}) in 2018 for three drought tolerant (DT) and drought susceptible (DS) Kentucky bluegrass cultivars at two mowing heights; low (5.1 cm) and high (8.9 cm). Each data point represents the average of four replications at two mowing heights (n=8). Lines with the same letter are not significantly different according to Fisher's protected LSD test (α=0.05).

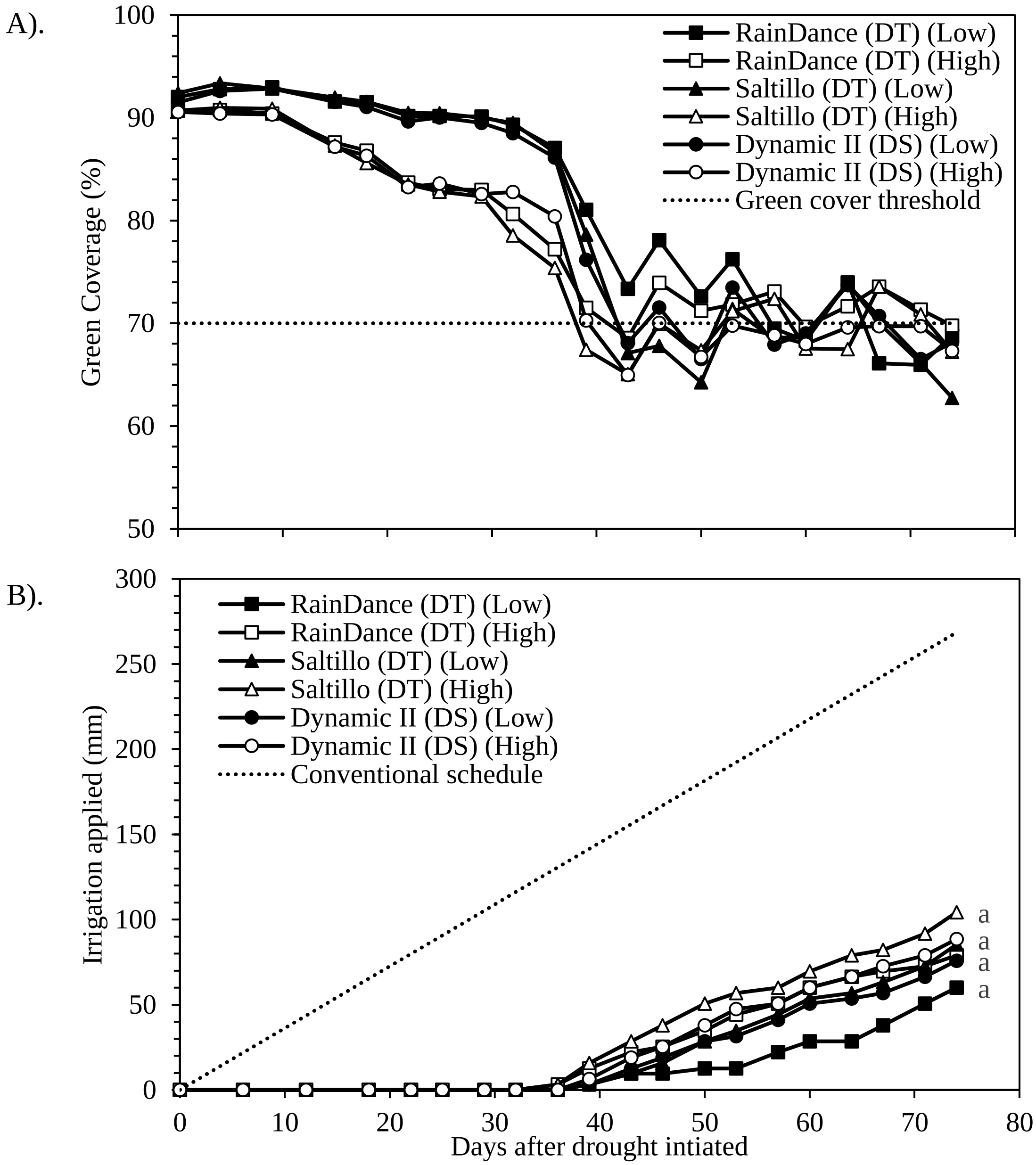

Figure 3.3. Green coverage over time (A) and cumulative water applied (mm) (B) during a deficit irrigation event in in relation to a conventional irrigation schedule (25.4 mm wk^{-1}) 2018 for three drought tolerant (DT) and drought susceptible (DS) tall fescue cultivars at two mowing heights; low (5.1 cm) and high (8.9 cm). Each data point represents the average of four replications. Lines with the same letter are not significantly different according to Fisher's protected LSD test (α=0.05).

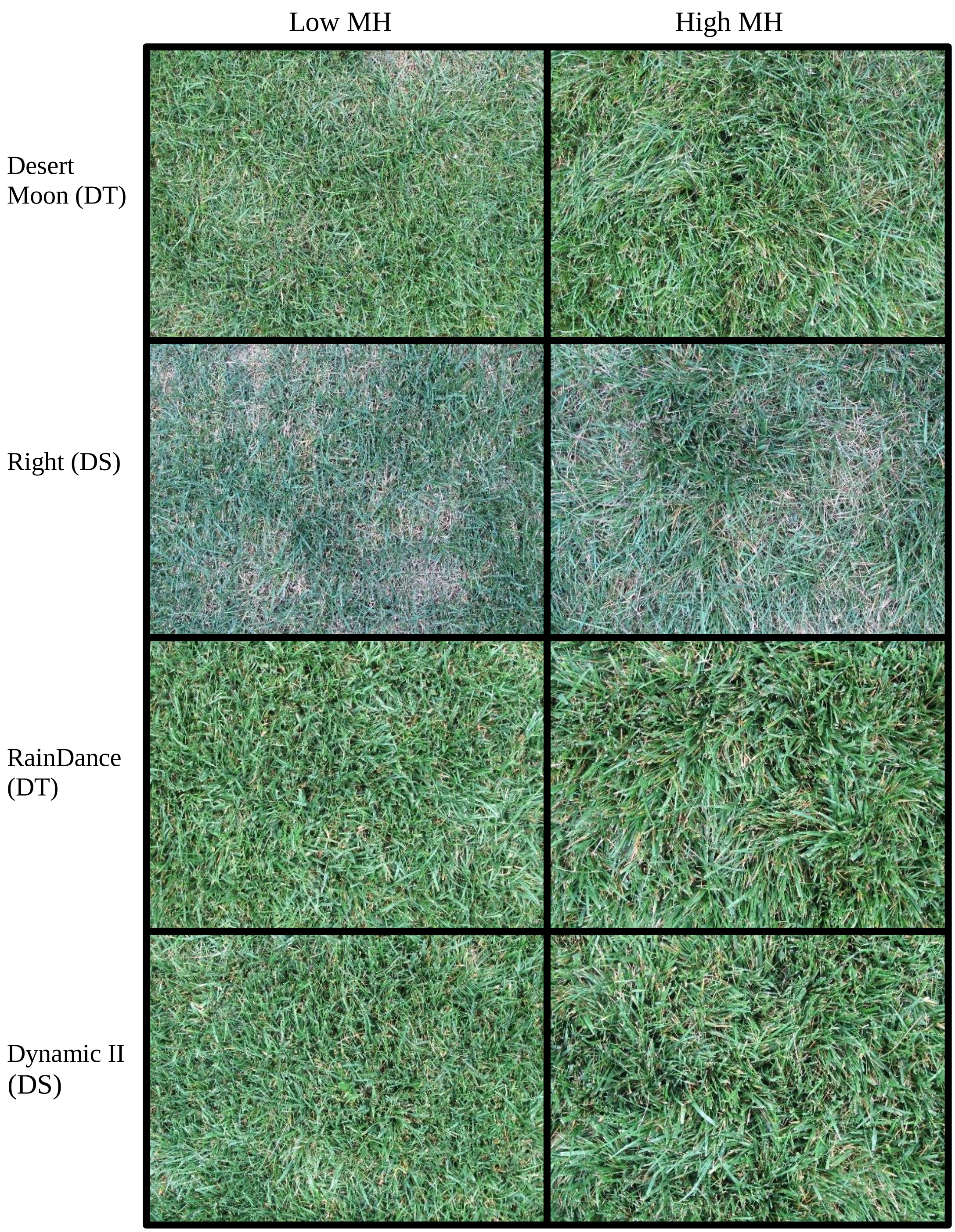

Figure 3.4. Images of Kentucky bluegrass and tall fescue cultivars maintained at a low (5.9 cm) and high (8.1 cm) mowing heights (MH) 22 days after a deficit irrigation event initiated using a rain-out shelter in West Lafayette, IN. The study ran for a total of 74 days. Digital images were taken two times per week and plots received 12.7 mm irrigation after falling below 70% green coverage (GCT_{70}).

CHAPTER 4. SUPPLEMENTAL IRRIGATION REQUIREMENTS OF VARIOUS KENTUCKY BLUEGRASS AND TALL FESCUE BLENDS AND MIXTURES SUBJECTED TO DEFICIT IRRIGATION

Abstract

Lawns in the Midwestern US typically consist of mixtures or blends of cool-season turfgrass species and cultivars. To maintain a high aesthetic appearance and maximize seasonal greenness, many lawns receive supplemental irrigation. Turfgrass breeders have developed superior cultivars with reduced water needs, but the exact proportion of these grasses to include in lawn seed blends and mixtures to improve performance and reduce irrigation needs, truly improving performance has not been well documented. A field study was conducted to determine the irrigation requirements of various blends using different ratios (0, 25, 50, 75, 100% by weight) of drought tolerant (DT) and susceptible (DS) Kentucky bluegrass (*Poa pratensis* L.: KBG) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF] cultivars at two mowing heights (5.1 or 8.9 cm). Additionally, 90:10 TF:KBG mixtures of DT and DS cultivars were evaluated to determine the supplemental irrigation needs of these mixtures. A 74-day deficit irrigation event was conducted under a fixed roof, rain-out shelter. Supplemental irrigation requirements were determined using a green coverage threshold (GCT_{70}) approach, where 12.7 mm of supplemental irrigation was applied if an individual plot fell below 70% green coverage using digital image analysis. Total irrigation needs ranged from 61.9-173.9 mm, generally ranked TF=TF:KBG<KBG. For KBG, a blend containing ≥ 75% DT cultivar required the least irrigation, required the longest time to reach GCT_{70} (31-33 days), and provided the highest overall visual quality. Mowing height had no effect on KBG irrigation needs or visual quality. TF cultivar blend composition had no effect on days to GCT_{70} , irrigation needs, or turf

quality. TF mowed at 5.1 cm had lower irrigation needs and higher overall quality than TF blends maintained at 8.9 cm. These results indicated that irrigation needs are strongly influenced by species, cultivar composition, and mowing height.

Introduction

Supplemental irrigation is commonly applied to lawns to maintain turfgrass green color and density during the growing season, especially during the absence of rainfall. A general rule of thumb is to provide 25.4 to 38.1 mm of irrigation, minus rainfall, per week to maintain a dense, healthy cool-season lawn (Christians et al., 2016). During acute drought events, water resources become limited or depleted, causing restrictions or bans to be imposed on outdoor water use. One way to conserve water during acute drought events is to plant lawns containing drought-tolerant species and cultivars that utilize less water and remain green for a longer duration during initial drought events, since brown color is often a trigger to begin applying supplemental irrigation.

A typical cool-season lawn is frequently planted as a blend of cultivars of a single species or as a mixture of two or more turfgrass species. Blends and mixtures increase genetic diversity and adaptation to varying micro-environments (Steinke and Ervin, 2013). Cultivars may also be selected based on superior tolerance to abiotic and biotic stresses. A low or mid-performing cultivar may sometimes be added to a mixture or blend to help reduce the overall seed cost but will likely reduce the overall quality of the blend or mixture (Brede, 2004; Vargas and Turgeon, 1980). Cultivar selection for a blend or mixture is critical to maintaining the intended composition over time, which can change if one cultivar or species is more aggressive, reducing the benefit of the weaker species or cultivars in the mature sward (Lickfeldt et al., 2002; Dunn et al., 2002).

The combination of turf-type tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF] and Kentucky bluegrass (*Poa pratensis* L.: KBG) is a popular seed mixture for lawns in the Midwestern US. Tall fescue possesses good heat and drought tolerance and KBG forms a dense, durable turf with better mowing characteristics than TF. Additionally, some of the benefits of adding TF is to help overcome the slower germination and poorer shade tolerance of KBG, while KBG helps increase the stand's cold tolerance and improves recovery from seasonal stress and traffic. A seed mixture containing 90% TF and 10% KBG (90:10) by weight contains approximately equal numbers of each species due to the smaller seed size of KBG (Turgeon, 2008). The percentage of each species should be carefully considered for long-term stand composition due to factors such as the aggressiveness of KBG, mowing height, fertility, etc. (Turgeon, 2008; St. John et al., 2009; Macolino et al., 2014). The influence of seeding rate, overall turf quality, brown patch (*Rhizoctonia solani*) severity/tolerance, wear tolerance, and plant population composition over time using various mowing heights have been previously evaluated using mixtures comprised of TF and KBG (Brede, 1993; Hunt and Dunn, 1993; Dunn et al., 2002; Reynolds et al., 2005; Macolino et al., 2014; Park et al., 2017). Information regarding drought performance and irrigation requirements of TF:KBG mixtures is limited.

Previous research has been conducted to quantify the supplemental irrigation needs of KBG and TF during an acute drought event. Irrigation scheduling based on a green coverage threshold could demonstrate significant water savings. Studies have shown differences of 14 to 20 days to reach a 50% or 75% green coverage, after withholding irrigation, within TF and KBG cultivars (Karcher et al., 2008; Richardson et al., 2008; Lewis et al., 2012, Goldsby et al., 2015). A study of TF and KBG cultivars, though not directly compared, demonstrated that TF cultivars reached 50% green coverage between 37.8 to 56.0 days after withholding irrigation, while KBG and hybrid bluegrasses (*Poa arachnifera* Torr. x *P. pratensis*) reached 50% green in 20.3 to 34.0 days (Richardson et al., 2012). The same study used a 40% green coverage threshold to trigger a 12.7 mm irrigation event, resulting in TF cultivars requiring 56.9 mm to 98.8 mm of total supplemental irrigation, compared to 63.5 mm to 139.7 mm for KBG during a roughly 90-day study.

While research has documented substantial differences existing among TF and KBG cultivars for their ability to retain green coverage during acute drought events, most of these studies compared single cultivars. Information regarding the irrigation requirements of TF and KBG blends and mixtures during acute drought or deficit irrigation is lacking. Further, there are numerous questions regarding the potential irrigation requirements when drought tolerant TF and/or KBG cultivars are added to seed blends/mixtures containing drought susceptible cultivars. If the overall objective is to reduce supplemental water needs for urban landscapes, a better understanding of how a drought tolerant cultivar influences a blend or mixture's overall water requirements when different percentages of the drought tolerant cultivar are added. The specific objectives of this study were to determine the overall supplemental irrigation requirements of KBG and TF seed blends when various percentages of a drought tolerant cultivar were added to a drought susceptible cultivar and using a 70% green coverage threshold (GCT_{70}) to schedule irrigation events at two mowing heights. Additionally, 90:10 mixtures of TF and KBG cultivars were combined to evaluate differences when a drought tolerant or susceptible KBG or TF were used in a seed mixture.

Materials and Methods

A field study was conducted at the William H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN. The soil type was a Starks-Fincastle silt loam (fine-silty, mixed, mesic, Aeric Ochraqualf) with a pH of 6.6, 61.75 kg P ha^{-1}, 292.5 kg K ha^{-1}, and 47 g kg^{-1} organic matter. The experimental area was fallow for one year prior to seeding; and 1.13 m^2 plots were seeded in July 2017 and covered with a germination blanket (Futerra EnviroNet: Profile Products; Buffalo Grove, IL). Two KBG or TF cultivars, one drought tolerant (DT) and one drought susceptible (DS), and three DS:DT blends at different rations (25:75, 50:50, 75:25) by weight (Table 4.1) were seeded at 98 or 294 kg ha^{-1}, for KBG and TF, respectively. The seeding rate of tall fescue-Kentucky bluegrass mixtures (TF:KBG mixtures) of DT and DS cultivars were determined by weight-based percentage of the overall seeding rate (274 kg ha^{-1}) (Table 4.1). Cultivars were selected based on prior documented drought performance provided by Pure-Seed Testing, Inc. (Canby, OR) and qualified cultivars from the Turfgrass Water Conservation Alliance (TWCA). Perennial ryegrass (*Lolium perenne* L.) was planted as a border around the experimental area.

Once established, plots were maintained at either 5.1 cm or 8.9 cm with a rotary mower (Honda #HRR216VKA, 53-cm wide deck walk-behind self-propelled mower: American Honda Motor Co., Inc., Alpharetta, GA). Plots were mowed every five days with clippings collected and plots were irrigated to promote growth and maintain optimum visual quality, until initiation of deficit irrigation in July 2018. During the study, the turf was fertilized according to regional cool-season lawn recommendations using Purdue University Extension's recommendations (Bigelow et al., 2013). From the time of seeding until July 2018, a total of 103.5 kg N, 24.4 kg of P_2O_5, and 42.0 kg K_2O ha^{-1} yr^{-1} were applied over six applications on 18 July, 30 August, 21 September, and 8 November in 2017, and 20 April and 25 May in 2018.

Mesotrione (Tenacity, Syngenta) applications were made on 7 September and 28 September 2017 at 0.28 kg ha^{-1} to suppress undesirable weeds in the seedling turf and amicarbazone (Xonerate 2SC, FMC) was applied at 0.12 kg ha^{-1} on 23 April and 7 May 2018 for postemergence control of *Poa annua* L. Preventative fungicide applications were applied before deficit irrigation on 14 September 2017 using a tank mix of chlorothalonil (Manicure Ultra, Lesco) at 0.36 kg ha^{-1} and fluxpyroxad (Xzemplar, BASF) at 0.20 kg ha^{-1} and again on 26 June 2018 with a tank mix of chlorothalonil (Manicure Ultra, Lesco) at 0.36 kg ha^{-1} and azoxystrobin (Heritage TL, Syngenta) at 0.31 kg ha^{-1}.

Visual turf quality was rated monthly prior to deficit irrigation, then every seven days during the study using a 0 to 10 scale, where 0=brown, dead turf; 6=minimally acceptable lawn turf; and 10=optimal uniformity, density, and color. On 19 July 2018, a fixed-roof rain-out shelter (9.1 m x 21.9 m) (Four Season Tools, Kansas City, MO) covered with 5 mil translucent plastic was placed over the study to exclude rainfall. During rainfall events, the plastic sides were rolled down to prevent lateral water intrusion.

The deficit irrigation event was initiated on 23 July 2018. Immediately prior to this, the trial area received 12.7 mm of water on 22 and 23 July to uniformly hydrate the study area. Thereafter, the center of each plot was imaged two times per week using a digital camera and a light box. The light box was equipped with an external battery (MotoMaster Eliminator PowerBox, Toronto, ON) to power four LED light bulbs (675 lumens, 5000 K). Images were taken using a Canon PowerShot G12 camera (Canon U.S.A. Inc., Huntington, NY). Percent green coverage of each plot was calculated by digital image analysis (Richardson et al., 2001) using a Java-based software program, Turf Analyzer (Karcher et al., 2017) (hue, saturation, and brightness ranges: 70-170, 10-100, 0-100, respectively).

Once an individual plot fell below the 70% green coverage threshold (GCT_{70}) based on digital green coverage, the corresponding plot received a total of 12.7 mm of water applied in split, 6.35 mm applications measured by a GPI Electronic Water Meter (Great Plains Industries, Inc., Wichita, KS), approximately 30 minutes apart to prevent runoff into the borders. A GCT_{70} was selected to maintain turf at a minimally acceptable turf quality rating ≥ 6. An irrigation rate of 12.7 mm was selected to represent the typical lawn irrigation cycle (Richardson et al., 2012). Irrigation was applied manually using a garden hose connected to a flow meter with a Nelson shower wand. During deficit irrigation, mowing was scheduled by the one-third rule (Crider, 1955; Madison, 1971; Beard, 1973; Christians et al., 2016) to limit traffic and injury on the plots. Weather data, including reference evapotranspiration (ET_o), was gathered using an on-site weather station (Vantage Pro2, Davis Instruments, Hayward, CA).

Plots were arranged in a strip-plot (by mowing) design with species blend and mixture randomized within each mowing block and each treatment replicated four times (n=112). All data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) procedure in SAS (SAS Institute, Cary, NC). Significant treatment means were separated using Fisher's protected least significant difference (LSD) test ($P<0.05$).

Results

When averaged across both mowing heights using drought-tolerant (DT) or drought-susceptible (DS) cultivars, the KBG blends reached the GCT_{70} before TF blends and TF:KBG mixtures, resulting in increased overall supplemental irrigation for KBG compared to TF. The time to reach GCT_{70} for all blends and mixtures ranged from 18 to 53.8 days for the 100% DS KBG and 50:50 DT:DS TF blend, respectively (Table 4.2). Additionally, total supplemental irrigation applied ranged from a low of 61.9 mm for three seed blends or mixtures (25 or 50% DT TF blend and 90:10 DT:DS TF:KBG) to a high of 173.9 mm for the 100% DS KBG (Table 4.2). The cumulative ET_o during this study was 223.4 mm, as measured by the on-site weather station, and supplemental irrigation required for all treatments in this study using the GCT_{70} ranged from 27.7 to 77.8% ET_o. The average visual turf quality across the study was in general higher for the TF blends and TF:KBG mixtures (≥ 6.8), compared to the KBG blends (≤ 6.2), but the mean quality for all treatments exceeded the minimally acceptable quality rating of 6.

Kentucky bluegrass blends

With the exception of day 53, mowing height had no significant effect on the irrigation needs for these KBG blends, and thus, the results are presented combined across mowing heights (Table 4.3). Among the KBG blends, a composition ≥ 75% DT KBG maintained green coverage for the longest period of time, reaching GCT_{70} in 31.0 and 33.3 days for 75% DT and 100% DT, respectively, compared to 100% DS KBG, which reached the GCT_{70} in 18.0 days (Table 4.2). Blend composition was highly significant for irrigation needs throughout the study. Total irrigation ranged from 93.7 to 173.9 mm for 100% DT and 100% DS KBG, respectively (Table 4.3 : Figure 4.1B). There was no significant difference between 75% DT KBG versus 100% DT KBG. Blends containing 25 and 50% DT cultivars were not different and each required 145.4 mm. The supplemental irrigation required to maintain ≥ GCT_{70} ranged from 41.9% to 77.8% of ET_o.

Percent green coverage at the start of the study ranged from 83.1 to 94.9% for turf containing 100% DS and DT, respectively, when averaged across mowing heights (Table 4.4). Initial green coverage values were slightly lower (<90% green) in plots containing ≥ 75% of DS ‘Right’, possibly due to a slower establishment rate and some competition with *Poa annua* L. in early spring, which was later chemically removed. By day 18, green coverage ranged from 63.9 to 90.5% for 100% DS and DT, respectively. Blends containing ≥ 50% of DT ‘Desert Moon’ responded positively to supplemental irrigation events, as demonstrated by the recovery in green coverage to > 70% on day 53 and day 67 (Table 4.4 : Figure 4.1B). In general, mowing height had very little effect on KBG blend performance for days to GCT_{70}, total supplemental irrigation required, visual quality, or mean green coverage over time.

Tall fescue blends

Unlike the KBG blends, TF blend cultivar composition in this study did not have a significant effect on supplemental irrigation requirements when using a GCT_{70} as a supplemental irrigation trigger in the first year following planting and establishment. Mowing height, however, had a significant effect on supplemental irrigation needs (Table 4.5), starting at day 39 and continuing through day 67, with TF mowed at 5.1 cm requiring less irrigation than 8.9 cm. These results were consistent with a study conducted by Richie et al., (2002) who found that TF cultivars maintained at 3.8 cm had higher overall visual quality than TF at 6.4 cm during year one with 80% ET_o supplemental irrigation, but these differences were not observed during year two.

There was no significant difference in the number of days to reach the GCT_{70} at either mowing height for TF. Differences in irrigation needs began at day 39 for TF blends at both mowing heights and persisted until day 67 with no difference at day 74 (Table 4.5 : Figure 4.2B). Green coverage was not affected by blend composition but mowing height had a significant effect, with the higher green coverage being associated with blends maintained at 5.1 cm (Table 4.6:Figure 4.2A).

Tall fescue:Kentucky bluegrass mixtures

The composition of DT and DS species or cultivar in the 90:10 TF:KBG mixture significantly influenced total supplemental irrigation needs, which ranged from 61.9 to 87.3 mm.

The least irrigation was needed in the mixtures containing DT 'RainDance' TF and the most with DS 'Dynamic II' TF (Table 4.7 : Figure 4.3B). In general, with the exception of day 39, mowing height had no significant effect on supplemental irrigation needs. There was no difference in the number of days to reach GCT_{70} for any of the TF:KBG mixtures, which ranged from 41.0 to 49.8 days (Table 4.2). These values were similar to the TF blends, which took 40.5 to 53.8 days, and demonstrated the fact that for this first year, TF seemed to be the dominate factor affecting mixture performance. Similar to the TF blends, the mixtures mowed at 5.1 cm had significantly higher green coverage from day 0 to day 39 (Table 4.8). In general, the inclusion of DT or DS KBG cultivars did not affect performance of any measured properties in the first year following planting and establishment. Additional trialing years will be needed to determine if these effects change over time as the stand matures.

Discussion

The reduction of supplemental irrigation in outdoor landscapes is a critical step toward urban water conservation, especially during prolonged acute drought events. This 74-day summer study demonstrated significant water savings [e.g. by as much as 73% compared to 100% ET_o (223.4 mm)] when a deficit irrigation approach with a GCT_{70} was used to trigger irrigation events and a DT species/cultivar was used (Table 4.5). In this study period, a conventional "set it and forget it" irrigation schedule of 25.4 mm wk^{-1} would have received 268.5 mm of water. By changing the irrigation strategy to using a GCT_{70} approach instead of a set schedule, a water savings of 35% could be achieved, even when using a DS KBG cultivar (173.9 mm). The combination of DT TF mowed at 5.1 cm (60.3 mm) and GCT_{70} irrigation approach could save up to 78%, compared to a conventional irrigation schedule. Planting DT species, such as TF, and selecting DT cultivars to include in seed blends and mixtures versus DS species/cultivars resulted in a nearly three-fold reduction when using a GCT_{70} irrigation approach (60.3 vs. 173.9 mm). The overall cultivar composition of KBG blends and TF:KBG mixtures can also significantly change total irrigation requirements.

Where blending is preferred for KBG due to the desire for a cultivar with improved turf characteristics, including ≤ 25% of a DS KBG cultivar could improve the overall performance without significantly increasing total irrigation needs. Repeating this experiment will help determine the irrigation needs of the DS Right KBG, since the deficit irrigation event was initiated when this KBG cultivar appeared to still be reaching full maturity. The inclusion of a DT TF was found to be more significant in a TF:KBG mixture than the DT KBG cultivar one year after establishment. The influence of mowing height on TF cultivars and blends will need to be further evaluated over time as the turf sward matures.

Differences in overall irrigation requirements among TF and KBG cultivars are attributed to differing drought tolerance and avoidance mechanisms, including deeper rooting (Huang and Gao, 2000; Pan et al., 2013), leaf rolling or stomatal closure (Frank and Berdahl, 2001), osmotic adjustments (Jiang and Huang, 2001; DaCosta and Huang, 2006), and modifications in cuticle thickness (Fu and Huang, 2004). The use of these mechanisms within the turfgrass plant can help delay overall symptoms of drought stress and require less total irrigation during the growing season, however, these mechanisms were not evaluated in this study.

Future research will need to continue to quantify supplemental irrigation requirements of lawn mixtures and blends, especially using commercial blends and mixtures compared to improved, elite cultivars. Drought mechanisms of the species and cultivars used in this study will also need to be further evaluated. Overall, this research continues to demonstrate the importance of species and cultivar selection, and to some extent, the effect of cultural management practices, like mowing height, on water conservation for lawns.

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Table 4.1. Overview of the Kentucky bluegrass (*Poa pratensis* L.: KBG) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF] blends and mixtures (w/w) used to determine the effect of including drought tolerant (DT) cultivars with drought susceptible (DS) cultivars on supplemental irrigation needs.

Species	Cultivar 1	Cultivar 2	Seeding Rate
	---- w/w ----	---- w/w ----	--- kg ha^{-1} --
KBG	100% DT‡	---	98
KBG blend	75% DT	25% DS	98
KBG blend	50% DT	50% DS	98
KBG blend	25% DT	75% DS	98
KBG	---	100% DS	98
TF	100% DT	---	294
TF blend	75% DT	25% DS	294
TF blend	50% DT	25% DS	294
TF blend	25% DT	75% DS	294
TF	---	100% DS	294
TF:KBG mixture	90% DS	10% DS	274 †
TF:KBG mixture	90% DT	10% DS	274
TF:KBG mixture	90% DS	10% DT	274
TF:KBG mixture	90% DT	10% DT	274

‡‘Desert Moon’ KBG and ‘RainDance’ TF represented DT cultivars and ‘Right’ KBG and ‘Dynamic II’ TF represented DS cultivars. Individual cultivars were selected from information on drought rating provided by Pure-Seed Testing, Inc. (Canby, OR).

† The seeding rate of tall fescue-Kentucky bluegrass mixtures determined by weight-based (w/w) percentage of overall seeding rate.

Table 4.2. Summary analysis of variance (ANOVA) for Kentucky bluegrass (*Poa pratensis* L.:KBG) and tall fescue [*Schedonorus arundinaceus* (Schreb.) Durmort.: TF] blends and mixtures used to determine the effect of drought tolerant (DT) cultivars with drought susceptible (DS) cultivars on supplemental irrigation needs across two mowing heights.

Species	Blend-mixture	Days to GCT_{70} †	Total irrigation applied †	Mean visual quality ‡	Mean green coverage †
	-- Species ratio --	--- days ---	--- mm ---	- (0-10 scale) -	--- % ---
KBG	100% DT §	33.3 a	93.7 c	6.2 a	77.2 a
KBG	75% DT	31.0 a	109.5 c	6.2 a	75.6 a
KBG	50% DT	24.4 b	146.1 b	6.2 a	72.2 b
KBG	25% DT	21.8 b	146.1 b	6.0 a	71.0 b
KBG	100% DS	18.0 c	173.9 a	6.0 a	67.9 c
	<u>ANOVA</u>				
	Cultivar (C)	***	***	NS	***
	Mowing (M)	NS	NS	NS	NS
	C x M	NS	NS	NS	NS
TF	100% DT	49.8 a	69.9 a	7.0 a	79.6 a
TF	75% DT	44.5 a	73.0 a	6.9 a	79.1 a
TF	50% DT	53.8 a	61.9 a	6.9 a	80.1 a
TF	25% DT	52.3 a	61.9 a	6.8 a	79.4 a
TF	100% DS	43.0 a	82.6 a	6.9 a	78.3 a
	<u>ANOVA</u>				
	Cultivar (C)	NS	NS	NS	NS
	Mowing (M)	NS	NS	***	***
	C x M	NS	NS	NS	NS
Mixture	90:10 DT:DT	49.8 a	65.1 b	6.9 a	79.5 a
Mixture	90:10 DT:DS	48.9 a	61.9 b	7.0 a	79.4 a
Mixture	90:10 DS:DT	45.9 a	87.3 a	6.8 a	77.9 ab
Mixture	90:10 DS:DS	41.0 a	87.3 a	6.8 a	77.7 b
	<u>ANOVA</u>				
	Cultivar (C)	NS	*	NS	NS
	Mowing (M)	NS	NS	***	***
	C x M	NS	NS	NS	NS

† Green coverage was determined using digital image analysis software, where 0%=bare soil and 100% = complete green coverage. Images were taken twice per week once drought initiated; irrigation (12.7 mm) was applied when turf was < 70% green coverage threshold (GCT_{70}).
‡ Visual quality was determined using a 0 to 10 scale; where 10=optimal greenness, density and uniformity; 6=acceptable lawn turf; 0=brown, dead turf.
§‘Desert Moon’ KBG and ‘RainDance’ TF represented DT cultivars and ‘Right’ KBG and ‘Dynamic II’ TF represented DS cultivars.
Each value represented the average of four replications at two mowing heights; low (5.1 cm) and high (8.9 cm) (n=8). Means in the same column within each species followed by the same lowercase letter were not significantly different according to Fisher’s protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 4.3. Cumulative supplemental irrigation applied to Kentucky bluegrass (KBG) blends with varying ratios of drought tolerant (DT) and drought susceptible (DS) cultivars.

	Days after drought initiated †								
KBG Blend Ratio §	18	25	32	39	46	53	60	67	74
	--- Supplemental irrigation (mm) ‡ ---								
100% DT	0.0 c	0.0 c	6.4 c	31.8 c	57.2 c	63.5 c	76.2 c	77.8 d	93.7 c
75% DT	0.0 c	0.0 c	12.7 c	38.1 c	61.9 c	71.4 c	81.0 c	93.7 c	109.5 c
50% DT	1.6 bc	17.5 b	38.1 b	61.9 b	84.1 b	98.4 b	119.1 b	128.6 b	146.1 b
25% DT	4.8 b	23.8 b	42.9 b	61.9 b	82.6 b	98.4 b	117.5 b	128.6 b	146.1 b
100% DS	12.7 a	38.1 a	59.6 a	81.8 a	105.6 a	123.1 a	143.7 a	153.2 a	173.9 a
ANOVA									
Blend (B)	***	***	***	***	***	***	***	***	***
Mowing (M)	NS	NS	NS	NS	NS	*	NS	NS	NS
B x M	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

§ KBG blends comprised of DT 'Desert Moon' and DS 'Right.'

‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Each value represents the average of four replications at two mowing heights; low (5.1 cm) and high (8.9 cm) (n=8). Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 4.4. Green coverage during 2018 drought event of Kentucky bluegrass (KBG) blends with varying ratios of drought tolerant (DT) and drought susceptible (DS) cultivars.

	Days after drought initiated †									
KBG Blend Ratio §	0	18	25	32	39	46	53	60	67	74
	---------- Green coverage (%) ‡ ----------									
100% DT	94.9 a	90.5 a	82.6 a	74.5 a	61.3 a	64.4 a	80.8 a	65.3 a	79.3 a	68.2 a
75% DT	94.7 a	89.3 a	79.4 a	69.7 a	63.4 a	67.3 a	76.0 ab	67.0 a	69.5 b	67.2 a
50% DT	92.1 ab	80.0 b	67.5 b	68.5 a	63.7 a	65.8 a	72.9 bc	65.1 a	69.2 b	67.5 a
25% DT	89.1 b	74.4 b	64.1 bc	67.2 a	64.8 a	68.0 a	72.0 bc	66.1 a	67.7 b	65.1 a
100% DS	83.1 c	63.9 c	59.0 c	64.2 a	63.7 a	66.9 a	68.9 c	64.1 a	70.5 b	66.7 a
ANOVA										
Blend (B)	***	***	***	NS	NS	NS	***	NS	**	NS
Mowing (M)	NS	NS	NS	NS	NS	NS	***	**	NS	*
B x M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.
§ KBG blends comprised of DT 'Desert Moon' and DS 'Right.'
‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Each value represents the average of four replications at two mowing heights; low (5.1 cm) and high (8.9 cm) (n=8). Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 4.5. Cumulative supplemental irrigation of tall fescue (TF) blends with varying ratios of drought tolerant (DT) and drought susceptible (DS) cultivars at two mowing heights (MH); low (5.1 cm) and high (8.9 cm).

		Days after drought initiated †							
TF Blend Ratio §	MH	18	32	39	46	53	60	67	74
	- cm -	Supplemental irrigation (mm) ‡							
100% DT	5.1	0.0 a	0.0 a	3.2 b	9.5 ab	12.7 c	28.6 b	38.1 c	60.3 a
	8.9	0.0 a	0.0 a	12.7 a	25.4 a	44.5 a	60.3 a	69.9 ab	79.4 a
75% DT	5.1	0.0 a	0.0 a	0.0 b	9.5 ab	19.1 bc	31.8 b	41.3 bc	60.3 a
	8.9	0.0 a	0.0 a	6.4 ab	22.2 ab	34.9 abc	50.8 ab	66.7 abc	85.7 a
50% DT	5.1	0.0 a	0.0 a	0.0 b	6.4 b	15.9 bc	28.6 b	38.1 c	63.5 a
	8.9	0.0 a	0.0 a	0.0 b	9.5 ab	25.4 abc	44.5 ab	47.6 abc	60.3 a
25% DT	5.1	0.0 a	0.0 a	6.4 ab	12.7 ab	19.1 bc	28.6 b	41.3 bc	57.2 a
	8.9	0.0 a	3.2 a	12.7 a	25.4 a	38.1 ab	47.6 ab	47.6 abc	66.7 a
100% DS	5.1	0.0 a	0.0 a	3.2 b	19.1 ab	31.8 abc	50.8 ab	57.2 abc	76.2 a
	8.9	0.0 a	0.0 a	6.3 ab	25.4 a	47.6 a	60.3 a	73.0 a	88.9 a
ANOVA									
Blend (B)		NS	NS	*	NS	NS	NS	NS	NS
Mowing (M)		NS	NS	*	**	**	**	**	NS
B x M		NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.
§ TF blends comprised of DT 'RainDance' and DS 'Dynamic II.'
‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 4.6. Green coverage during 2018 drought event of tall fescue (TF) blends using varying ratios of drought tolerant (DT) and drought susceptible (DS) cultivars at two mowing heights (MH); low (5.1 cm) and high (8.9 cm).

		Days after drought initiated †									
TF Blend Ratio §	MH	0	18	25	32	39	46	53	60	67	74
	- cm -	Green coverage (%) ‡									
100% DT	5.1	92.0 a	91.5 a	90.2 a	89.3 a	81.0 abc	78.1 a	76.2 ab	68.3 a	66.1 d	68.8 a
	8.9	90.7 abc	86.8 b	83.0 b	80.6 c	71.5 d	73.9 a	71.8 bc	69.6 a	73.6 a	69.8 a
75% DT	5.1	92.1 a	91.4 a	90.3 a	89.3 a	83.3 ab	75.3 a	76.0 ab	67.3 a	69.9 bc	67.0 a
	8.9	89.9 bc	85.4 b	83.6 b	82.9 bc	71.8 d	72.3 a	72.4 bc	69.7 a	71.3 abc	69.0 a
50% DT	5.1	91.4 ab	91.0 a	90.5 a	90.0 a	85.1 a	75.0 a	74.6 abc	66.6 a	69.8 bc	67.4 a
	8.9	89.3 c	85.4 b	84.6 b	84.7 b	76.5 bcd	73.9 a	70.1 c	68.1 a	72.7 ab	70.1 a
25% DT	5.1	91.9 a	90.8 a	89.7 a	88.5 a	77.5 abcd	75.4 a	77.7 a	70.6 a	67.9 cd	68.7 a
	8.9	89.9 bc	84.8 b	82.2 b	80.7 c	73.0 cd	73.7 a	72.7 abc	70.8 a	73.9 a	67.2 a
100% DS	5.1	91.5 ab	91.1 a	90.0 a	88.5 a	76.2 bcd	71.5 a	73.5 abc	69.0 a	70.7 abc	68.1 a
	8.9	90.6 abc	86.3 b	83.6 b	82.8 bc	70.3 d	70.0 a	69.8 c	68.0 a	69.7 bcd	67.3 a
ANOVA											
Blend (B)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mowing (M)		***	***	***	***	***	NS	***	NS	***	NS
B x M		NS	NS	NS	NS	NS	NS	NS	NS	*	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.
§ TF blends comprised of DT ‘RainDance’ and DS ‘Dynamic II.’
‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Means in the same column followed by the same lowercase letter are not significantly different according to Fisher’s protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 4.7. Cumulative supplemental irrigation of 90:10 tall fescue-Kentucky bluegrass (TF:KBG) mixtures using different drought tolerant (DT) and drought susceptible (DS) cultivars.

	Days after drought initiated †							
TF:KBG Mixture §	18	32	39	46	53	60	67	74
	------------------------------- Supplemental irrigation (mm) ‡ -------------------------------							
90:10 DT:DT	0.0 a	0.0 a	3.2 b	11.1 a	22.2 c	36.5 b	46.0 b	65.1 b
90:10 DT:DS	0.0 a	0.0 a	1.6 b	14.3 a	23.8 bc	36.5 b	42.9 b	61.9 b
90:10 DS:DT	0.0 a	0.0 a	9.5 a	22.2 a	39.7 ab	52.4 ab	65.1 a	87.3 a
90:10 DS:DS	0.0 a	0.0 a	6.4 ab	23.8 a	42.9 a	58.7 a	69.9 a	87.3 a
ANOVA								
Cultivar (C)	NS	NS	*	NS	*	*	**	*
Mowing (M)	NS	NS	*	NS	NS	NS	NS	NS
C x M	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

§ Tall fescue-Kentucky bluegrass mixtures were combined based on drought rating; DT (‘RainDance’ TF and ‘Desert Moon’ KBG) and DS (‘Dynamic II’ TF and ‘Right’ KBG).

‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Each value represents the average of four replications at two mowing heights; low (5.1 cm) and high (8.9 cm) (n=8). Means in the same column followed by the same lowercase letter are not significantly different according to Fisher’s protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table 4.8. Green coverage during 2018 drought event of various tall fescue-Kentucky bluegrass (TF:KBG) mixtures with different drought tolerant (DT) and drought susceptible (DS) cultivars.

	Days after drought initiated †									
TF:KBG Mixture §	0	18	25	32	39	46	53	60	67	74
	---------- Green coverage (%) ‡ ----------									
90:10 DT:DT	91.5 ab	88.9 a	87.8 a	87.0 a	76.9 a	74.7 a	73.9 a	68.2 a	70.0 a	66.3 a
90:10 DT:DS	91.6 a	88.9 a	87.6 a	86.5 ab	77.2 a	73.7 a	74.0 a	66.8 a	70.3 a	65.9 a
90:10 DS:DT	90.5 c	87.8 ab	85.1 b	83.7 c	72.2 a	71.6 a	71.2 a	67.5 a	70.4 a	66.0 a
90:10 DS:DS	90.5 bc	87.0 b	85.4 b	84.0 bc	72.2 a	71.5 a	71.0 a	68.9 a	71.8 a	66.9 a
ANOVA										
Cultivar (C)	*	*	**	*	NS	NS	NS	NS	NS	NS
Mowing (M)	***	***	***	***	*	NS	NS	NS	NS	*
C x M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018. The entire study area received a total of 25.4 mm of water split between two days prior to drought initiation.

§ Tall fescue-Kentucky bluegrass mixtures were combined based on drought rating; DT (‘RainDance’ TF and ‘Desert Moon’ KBG) and DS (‘Dynamic II’ TF and ‘Right’ KBG).

‡ Supplemental irrigation of 12.7 mm was applied once an individual plot reached 70% green coverage (GCT_{70}) using Turf Analyzer imaging software. Irrigation was applied using a garden hose attached to a flow meter for measurement of water (gallons). Images analyzed twice per week. Each value represents the average of four replications at two mowing heights; low (5.1 cm) and high (8.9 cm) (n=8). Means in the same column followed by the same lowercase letter are not significantly different according to Fisher’s protected LSD (P<0.05). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

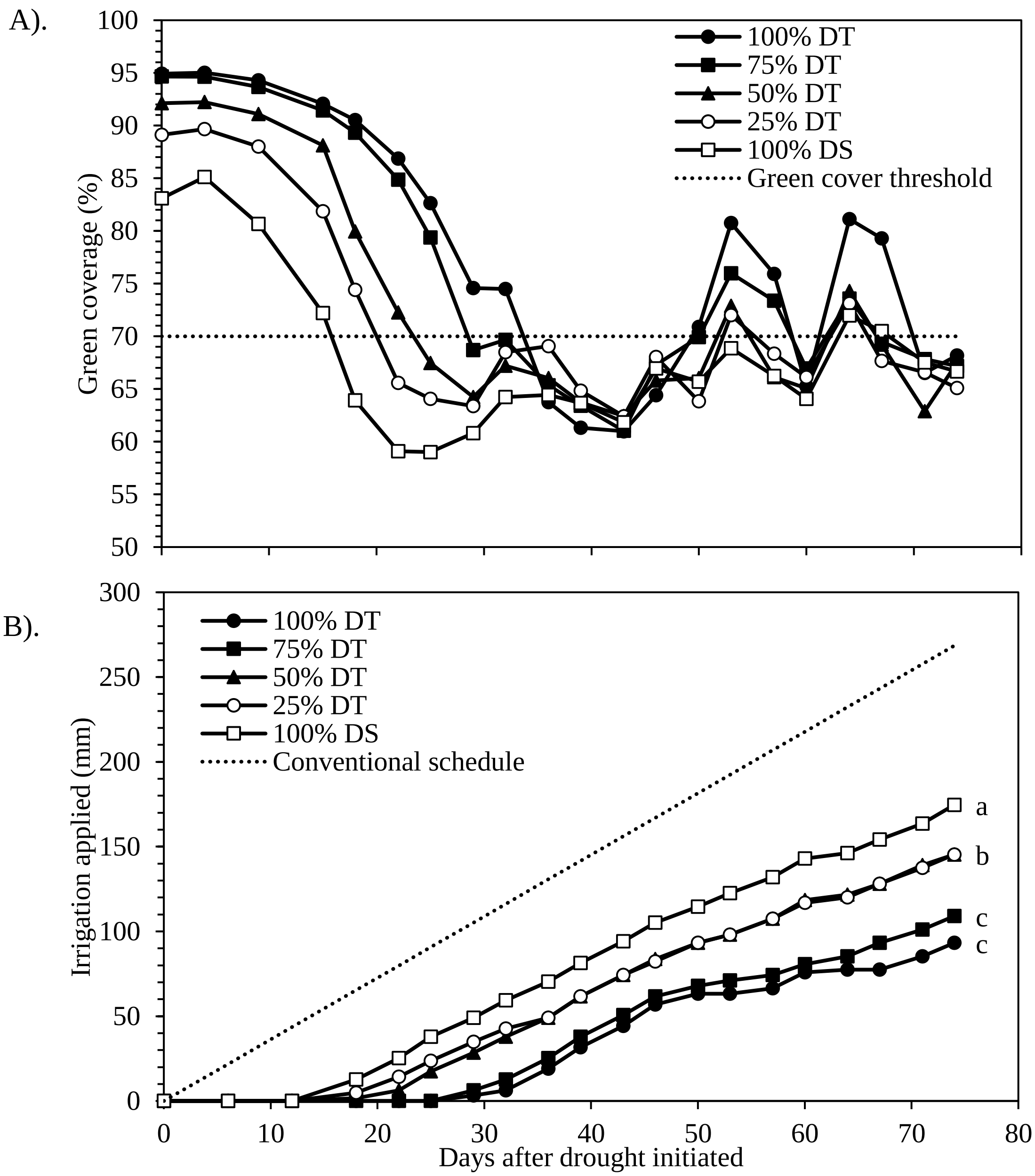

Figure 4.1. Green coverage over time (A) and cumulative water applied (mm) (B) during 2018 deficit irrigation event in relation to a conventional irrigation schedule (25.4 mm wk^{-1}) for Kentucky bluegrass (KBG) blends with different percentages of drought tolerant (DT), ‘Desert Moon’ and drought susceptible (DS), ‘Right’ KBG. Each data point represents the average of four replications at two mowing heights (n=8). Lines with the same letter are not significantly different according to Fisher’s protected LSD test (α=0.05).

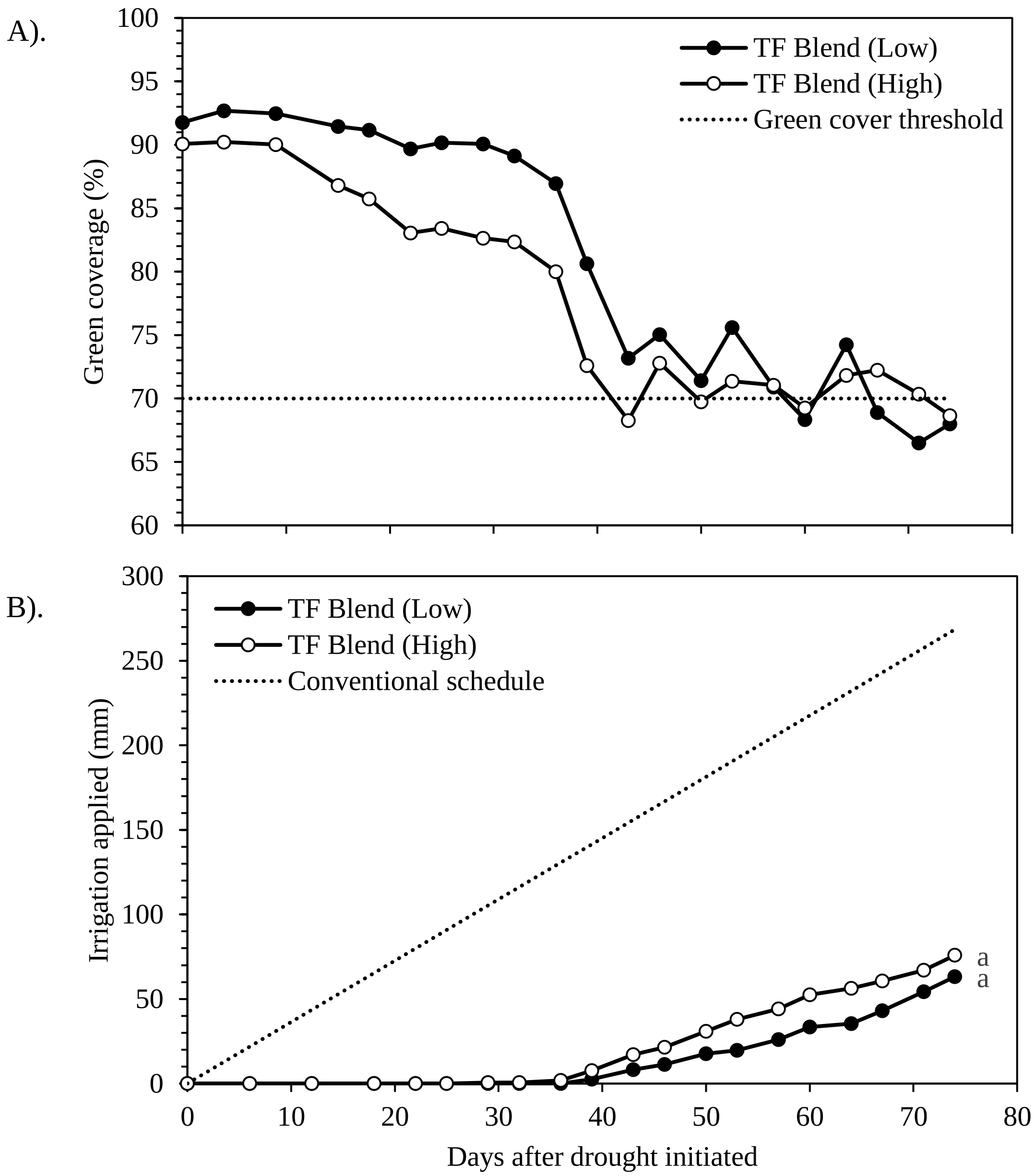

Figure 4.2. Green coverage over time (A) and cumulative water applied (mm) (B) during 2018 deficit irrigation event in relation to a conventional irrigation schedule (25.4 mm wk^{-1}) for tall fescue (TF) blends with different percentages of drought tolerant (DT), 'RainDance' and drought susceptible (DS), 'Dynamic II' TF at two mowing heights; low (5.1 cm) and high (8.9 cm). Each data point represents the average of four replications with five treatments (n=20). Lines with the same letter are not significantly different according to Fisher's protected LSD test (α=0.05).

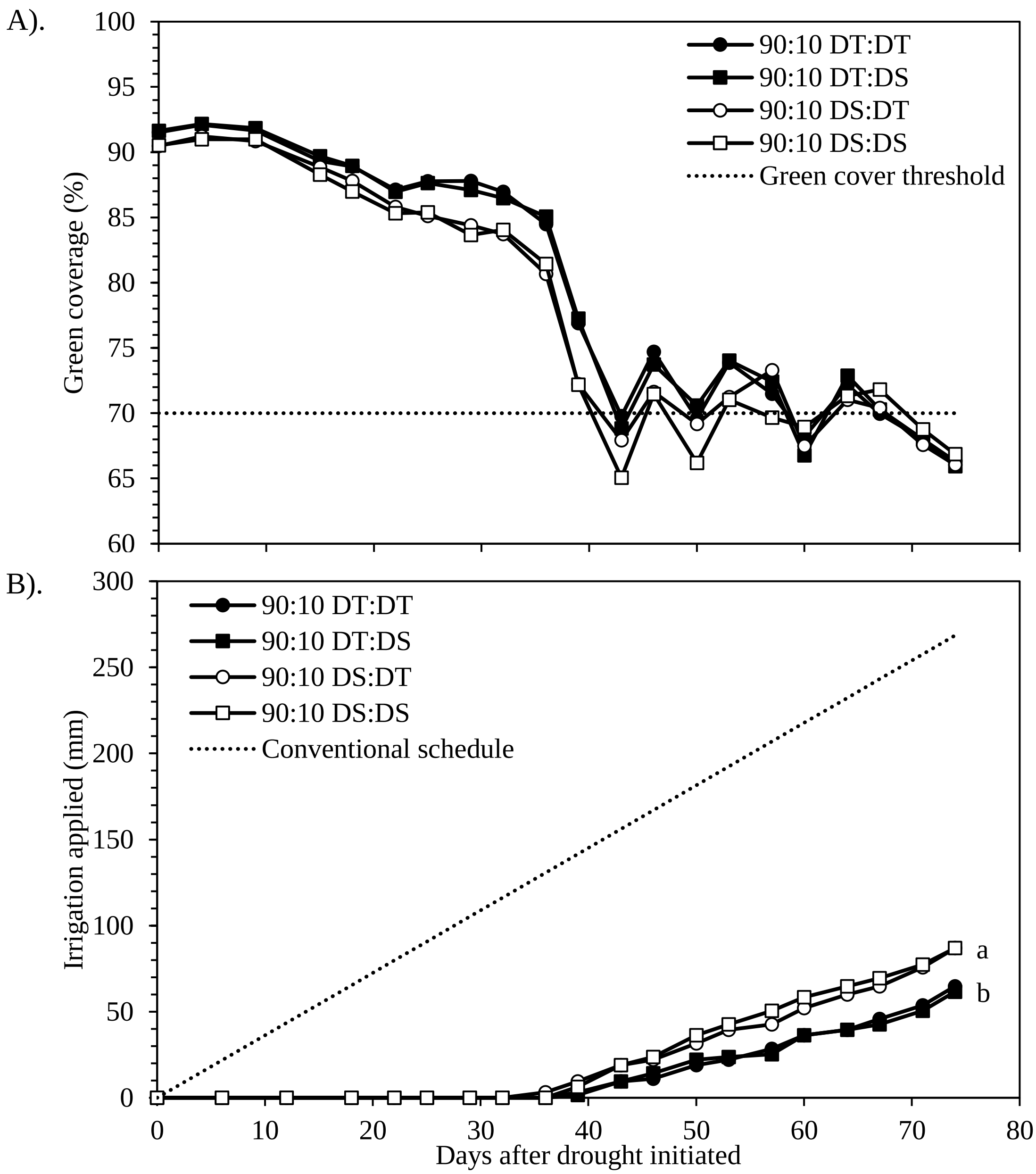

Figure 4.3. Green coverage over time (A) and cumulative water applied (mm) (B) during 2018 deficit irrigation event in relation to a conventional irrigation schedule (25.4 mm wk^{-1}) for mixtures of tall fescue and Kentucky bluegrass using cultivars with different drought rating; drought tolerant (DT) (‘RainDance’ TF and ‘Desert Moon’ KBG) and drought susceptible (DS) (‘Dynamic II’ TF and ‘Right’ KBG). Each data point represents the average of four replications at two mowing heights (n=8). Lines with the same letter are not significantly different according to Fisher’s protected LSD test (α=0.05).

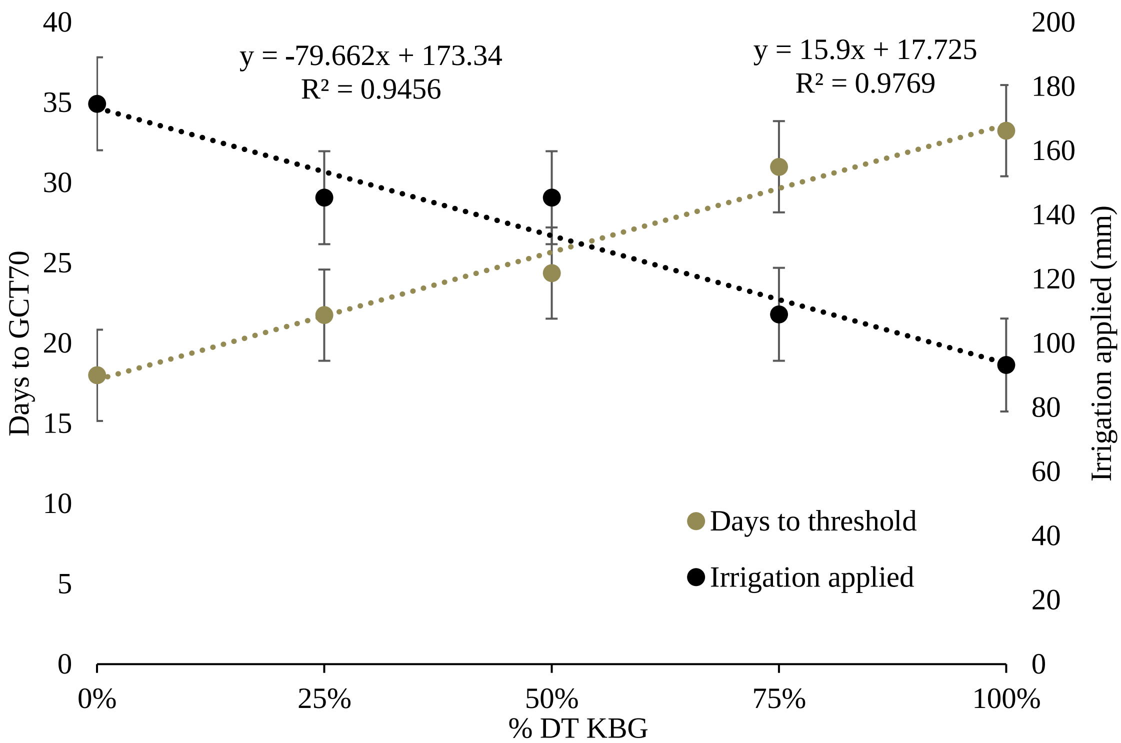

Figure 4.4. Relationship between number of days to reach 70% green coverage threshold (GCT_{70}) and total supplemental irrigation with the percent composition of drought tolerant (DT) Kentucky bluegrass (KBG) cultivars in a blend. Each data point represents the average of four replications at two mowing heights (n=8).

Figure 4.5. Images of Kentucky bluegrass blends and cultivars maintained at a low (5.9 cm) and high (8.1 cm) mowing height (MH) 25 days after deficit irrigation event initiated using a rain-out shelter in West Lafayette, IN. The study ran for a total of 74 days. Digital images were taken two times per week and plots received 12.7 mm of irrigation after falling below 70% green coverage (GCT_{70}).

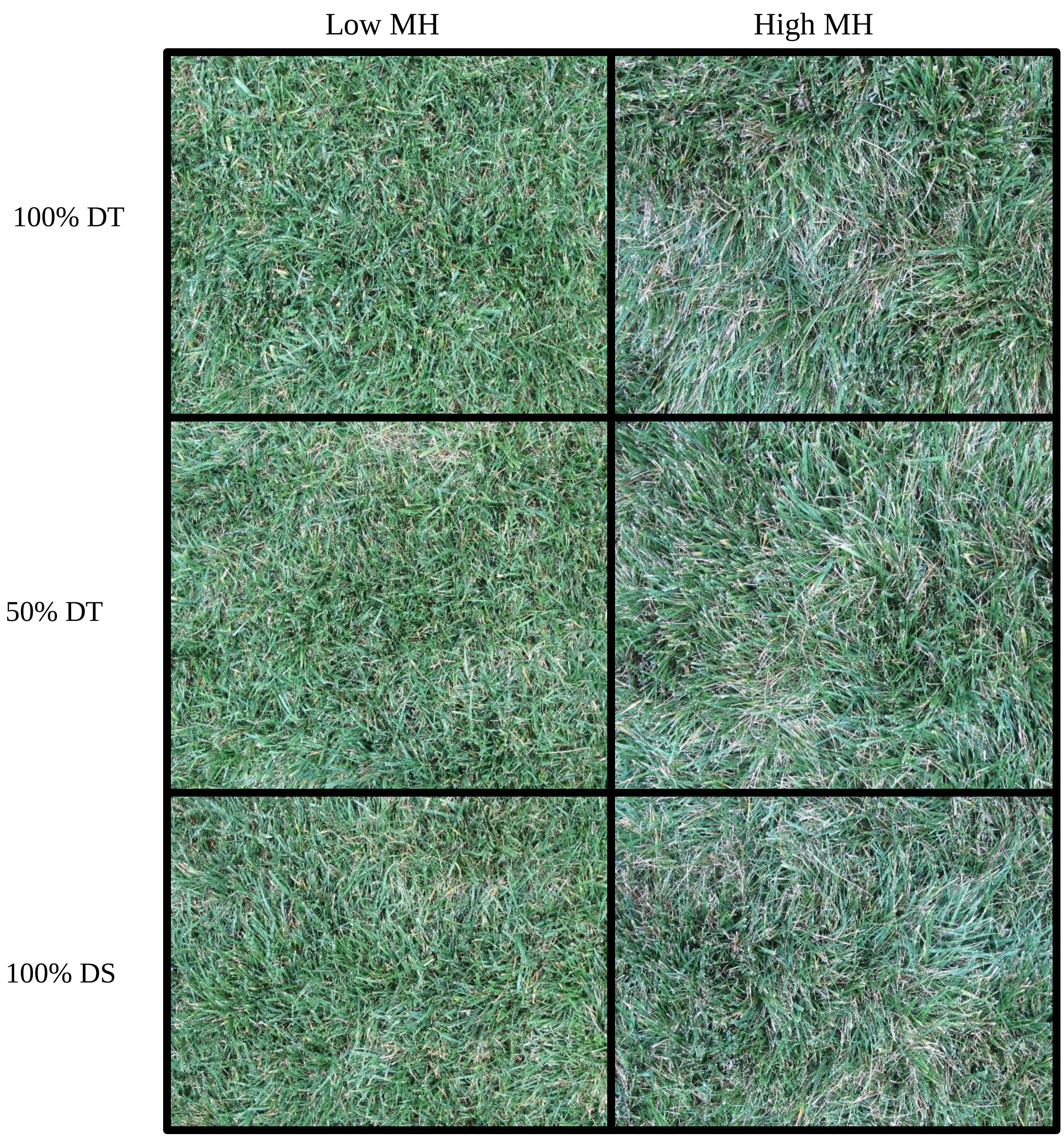

Figure 4.6. Images of tall fescue blend and cultivars maintained at a low (5.9 cm) and high (8.1 cm) mowing height (MH) 39 days after deficit irrigation event initiated using a rain-out shelter in West Lafayette, IN. The study ran for a total of 74 days. Digital images were taken two times per week and plots received 12.7 mm irrigation after falling below 70% green coverage (GCT_{70}).

CHAPTER 5. SUMMARY AND CONCLUSION

Supplemental irrigation is used throughout the growing season in many lawns to maintain consistent green color and density during periods of low precipitation. There is a strong tendency for homeowners to irrigate based on a programmatic schedule (i.e. M-W-F) or an evapotranspiration (ET_o) replacement approach (80 to 100% ET_o), which often provides more water to the turf than is needed. Water resources throughout the United States will continue to become limited, especially as the human population continues to increase. This creates a need to explore water conservation strategies for the outdoor landscape, while still maintaining an aesthetically pleasing lawn.

A series of greenhouse and field studies were conducted to determine how much irrigation could be reduced by using turfgrass species and cultivars with demonstrated improved drought tolerance while using a 70% green coverage threshold (GCT_{70}) deficit irrigation approach and comparing these practices to a conventional lawn grass and supplemental irrigation practices.

The initial greenhouse screenings of Kentucky bluegrass, tall fescue, and consumer/commercial mixtures resulted in the highest water use and poorest visual quality to be associated with inexpensive consumer/commercial mixtures. The highest visual quality and least water used was associated with improved Kentucky bluegrass cultivars. Valuable information was gained through these screening studies to help separate differences among cultivars within each species, and then compare those cultivars to commercially available seed mixtures and blends to determine possible candidates for field evaluation. The responses among tall fescue and Kentucky bluegrass cultivars in these short-term greenhouse drought events may not reflect performance in the field for tall fescue due to the limited rootzone in the lysimeters, and the use of a sandy media with a low water-holding capacity (e.g. a worst-case scenario). The results, however, could reflect the drought performance of these grasses under situations were rootzones are limited, such as compacted soils. More research needs to be conducted using those conditions in the field.

When evaluating Kentucky bluegrass and tall fescue in the field, 78% of supplemental irrigation could be saved when using a drought tolerant tall fescue cultivar and irrigating based on GCT_{70} as compared to a programmatic irrigation approach (60.3 vs. 268.5 mm). Supplemental irrigation can be withheld from drought tolerant tall fescues for up to 52.5 days and still remain ≥ 70% green coverage. A drought tolerant Kentucky bluegrass cultivar could save 66% supplemental irrigation and receive no irrigation for up to 34 days, while remaining ≥ 70% green. The number of days to reach 70% green coverage in this thesis was similar to the number of days for tall fescue and Kentucky bluegrass cultivars to reach 75% green coverage in previous studies (Karcher et al., 2008; Richardson et al., 2008; Richardson et al., 2012; Goldsby et al., 2015). Irrigation totals were slightly higher using the methods in this thesis for tall fescue and Kentucky bluegrass cultivars, blends, and mixtures, compared to totals found by Richardson et al. (2012). This is not surprising though, since irrigation was triggered at 70% green coverage instead of 40% green coverage.

Even though lawns of cool-season turfgrass species are often comprised of several species and cultivars, there is a lack of information on the overall performance or irrigation requirements of blends and mixtures when different quantities of a drought susceptible or tolerant species or cultivars are used. The results of this field study indicated significant water savings can be obtained when including ≥ 75% of a drought tolerant Kentucky bluegrass cultivar by weight in a blend. Reductions in irrigation were also found when ≥ 25% of a drought tolerant

Kentucky bluegrass cultivar by weight was used, compared to cultivars or blends without improved drought tolerance. The tall fescue cultivar drought rating influenced the performance of the tall fescue:Kentucky bluegrass mixtures more than the Kentucky bluegrass drought rating. Subsequent years of data, however, will be needed for field studies to evaluate changes in drought performance as the turf matures.

Maintaining tall fescue cultivars and blends at a lower mowing height (5.1 cm) resulted in higher green coverage and less supplemental irrigation as compared to a higher mowing height (8.9 cm). Among Kentucky bluegrass cultivars and blends, there was no effect of mowing height on green coverage or supplemental irrigation. The increase in green coverage of tall fescue at a lower mowing height during year one is similar to results found by Richie et al. (2002). Again, subsequent years of data will need to be gathered to determine if mowing height influences drought performance over time.

Even though high-quality seed that has demonstrated drought tolerance may sell for a slightly higher price when compared to many commercially available seed mixtures and blends, it is likely that the investment will more than pay for itself over the lifespan of the lawn in terms of water conservation and superior performance/persistence. Continued research is needed to evaluate the irrigation requirements of improved cultivars as compared to commercially available blends and mixtures typically planted in lawns. Further studies that evaluate other cultural management practices, such as soil cultivation and fertilization, will need to be conducted to improve the clarity of best management practices for water conservation and management in existing lawns. Further, with the continued advancements in data driven management, integrating data from devices such as unmanned aerial vehicles (UAVs), on-site weather stations, and soil moisture sensors into decision making for irrigation will continue to be an area to be furthered studied.

Overall, when compared to conventional lawn seed mixtures/blends and irrigation scheduling practices, significant water savings can be achieved by simply specifying and planting drought tolerant turf-type tall fescue cultivars compared to Kentucky bluegrass or many poor-quality commercial seed mixtures, saving as much as 1,269,941 L ha^{-1} during 60 days of a deficit irrigation event. Further, irrigating based on a deficit irrigation program and/or using the GCT_{70} threshold approach in combination with a drought tolerant tall fescue could result in 1,890,912 L ha^{-1} of water saved compared to a traditional programmatic or 80 to 100% ET replacement approach during 60 days of a drought event. In summary, these studies continue to demonstrate that planting species and cultivars with superior drought tolerance, combined with a deficit irrigation approach, could significantly save irrigation applied to lawns compared to other cool-season species and conventional irrigation approaches.

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APPENDIX

Table A.1. Summary of the experiment 1 greenhouse study of Kentucky bluegrass (KBG), tall fescue (TF), and commercial mixtures for total water loss, visual quality, and rootmass over a 14-day acute drought event.

	Water lost †			Visual quality ‡			Rootmass §
Species	Day 0-4	Day 5-10	Day 11-14	Day 0	Day 7	Day 14	
	---------------- mm d^{-1} ---------------			------- 10=optimal ------			----g----
KBG	3.7 c	4.8 c	2.4 a	6.9 c	6.7 b	5.7 a	1.1 b
TF	4.4 a	5.5 a	1.7 c	8.0 a	7.9 a	4.0 c	1.9 a
Mix	4.1 b	5.3 b	2.1 b	7.3 b	6.8 b	4.5 b	1.8 a
ANOVA							
Species	***	***	***	***	***	***	***

†Lysimeters brought to field capacity at the initiation of the experiment and weighed every three to four days to calculate water loss (mm d^{-1}) using the gravimetric mass balance method.

‡Visual quality determined using a 0 to 10 scale; where 10=optimal greenness, density and uniformity; 6=acceptable lawn turf; 0=bare soil.

§Turf was removed from the lysimeters, sand was shaken from the roots, roots were washed, leaf tissue/crown-thatch layer separated, and all tissue dried and weighed to calculate rootmass.

*Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table A.2. Summary of the experiment 2 greenhouse study of Kentucky bluegrass (KBG) cultivars, tall fescue (TF) cultivars, and various blends and mixtures of water loss and green coverage over a 20-day acute drought event.

	Water lost †			Green coverage ‡				
Species	Day 0-6	Day 7-13	Day 14-20	Day 6	Day 13	Day 20	Day 27	Day 34
	------------------ mm d^{-1} -----------------			---------------------------- % ----------------------------				
KBG	4.3 a	3.6 a	1.6 a	84.3 b	70.3 b	27.0 a	51.1 a	71.6 a
TF	4.1 a	3.5 a	1.6 a	89.1 a	78.8 a	13.6 b	58.6 a	79.7 b
Mix	4.3 a	3.5 a	1.5 a	83.1 b	69.0 b	15.5 b	54.7 a	75.1 a
ANOVA								
Species	NS	NS	NS	***	*	***	NS	**

†Lysimeters brought to field capacity at the initiation of the experiment and weighed every three to four days to calculate water loss (mm d^{-1}) using the gravimetric method.
‡Green coverage was determined using digital image analysis software, ImageJ to scan digital images (green pixels/total image pixels)*100, where 0%=bare soil and 100% = complete turfgrass coverage. Images were taken two to three times per week once drought initiated and during recovery. Irrigation was applied after day 20 and recovery was evaluated on day 27 and 34.
*Means in the same column followed by the same lowercase letter are not significantly different according to Fisher's protected LSD ($P<0.05$). *, **, ***, NS indicates significance at $P \leq 0.05$, 0.01, and 0.001, and non-significant, respectively.

Table A.3. Weekly weather data during 2018 drought study at the William H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN.

Week †	Avg. High Temp. ‡	Avg. Low Temp. ‡	ET_o ‡	Precipitation ‡
	--------- °C ---------	--------°C --------	--- mm ---	----- mm ----
1	28.3	16.0	22.2	4.1
2	27.9	18.1	24.3	25.1
3	30.4	19.5	25.8	19.1
4	28.3	19.5	20.4	33.0
5	27.3	17.7	20.0	27.9
6	30.2	19.9	27.9	4.8
7	25.7	20.1	10.0	46.2
8	28.1	15.2	24.5	0.0
9	28.8	16.5	21.9	3.0
10	22.7	12.1	14.9	16.8
11	26.8	14.4	11.5	17.3
74-day study	27.7 mean	17.3 mean	223.4 total	197.4 total

† Deficit irrigation event initiated on 23 July 2018 under a fixed-roof rain-out shelter and continued until 5 October 2018.
‡ Weather data were gathered by an on-site weather station (Vantage Pro2, Davis Instruments, Hayward, CA).

Table A.4. Settings for cameras used in greenhouse and field studies to calculate percent green coverage using digital image analysis techniques.

Camera ‡	Shutter speed	Aperture	Focal length	Image size
	----- sec -----		---- mm ----	--- pixels ---
PowerShot G12 (field)	1/40	F2.8	6.1	2736 x 3648
PowerShot ELPH (greenhouse)	1/60	F4.0	12.12	2112 x 2816

‡Canon digital cameras were used in both studies (Canon U.S.A. Inc., Huntington, NY).

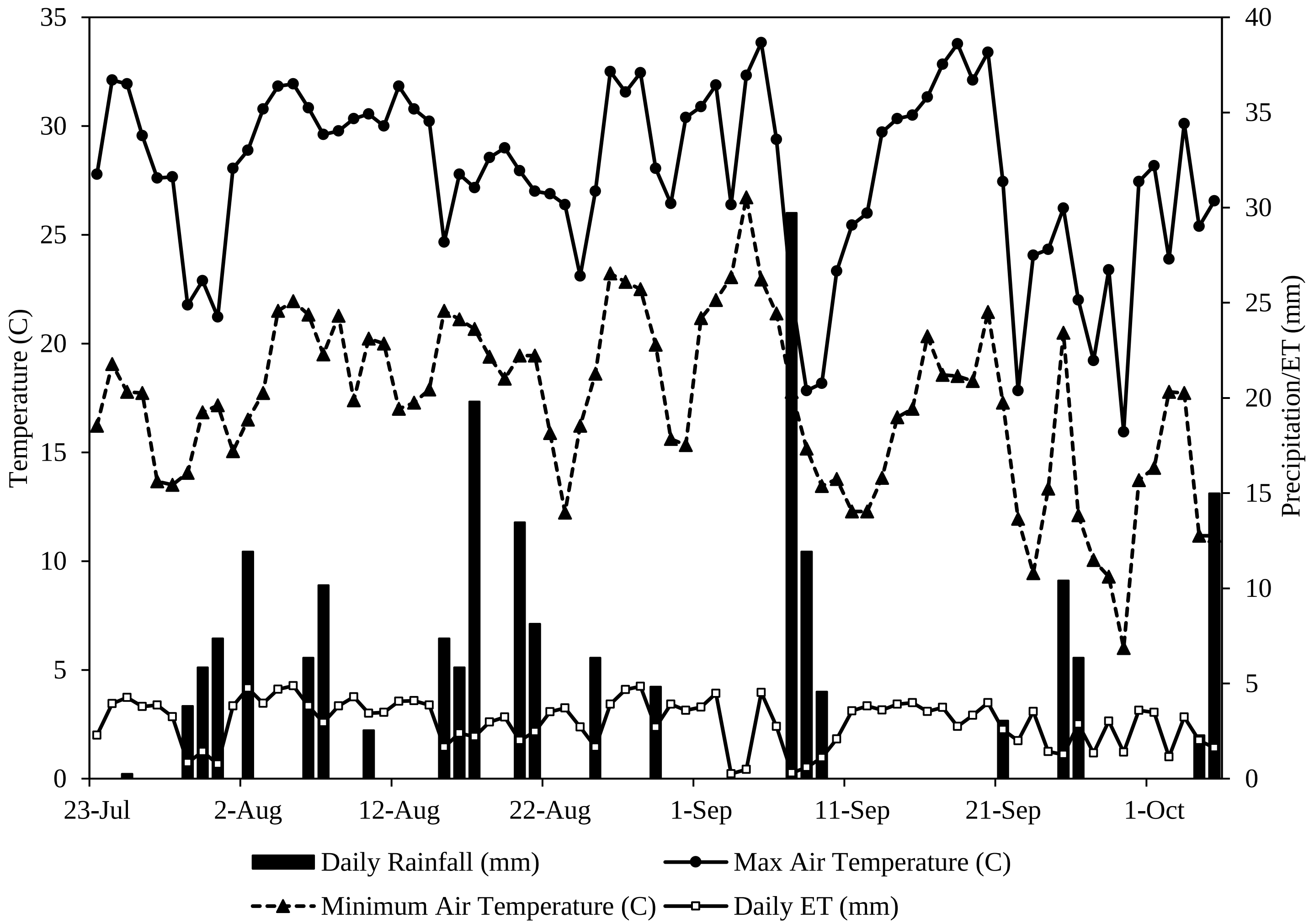


Figure A.1. Daily weather data during days of drought initiated in 2018, including daily rainfall, ET rate (mm), maximum and minimum air temperature (°C). Data were collected using a Davis weather station (Vantage Pro2, Davis Instruments, Hayward, CA).

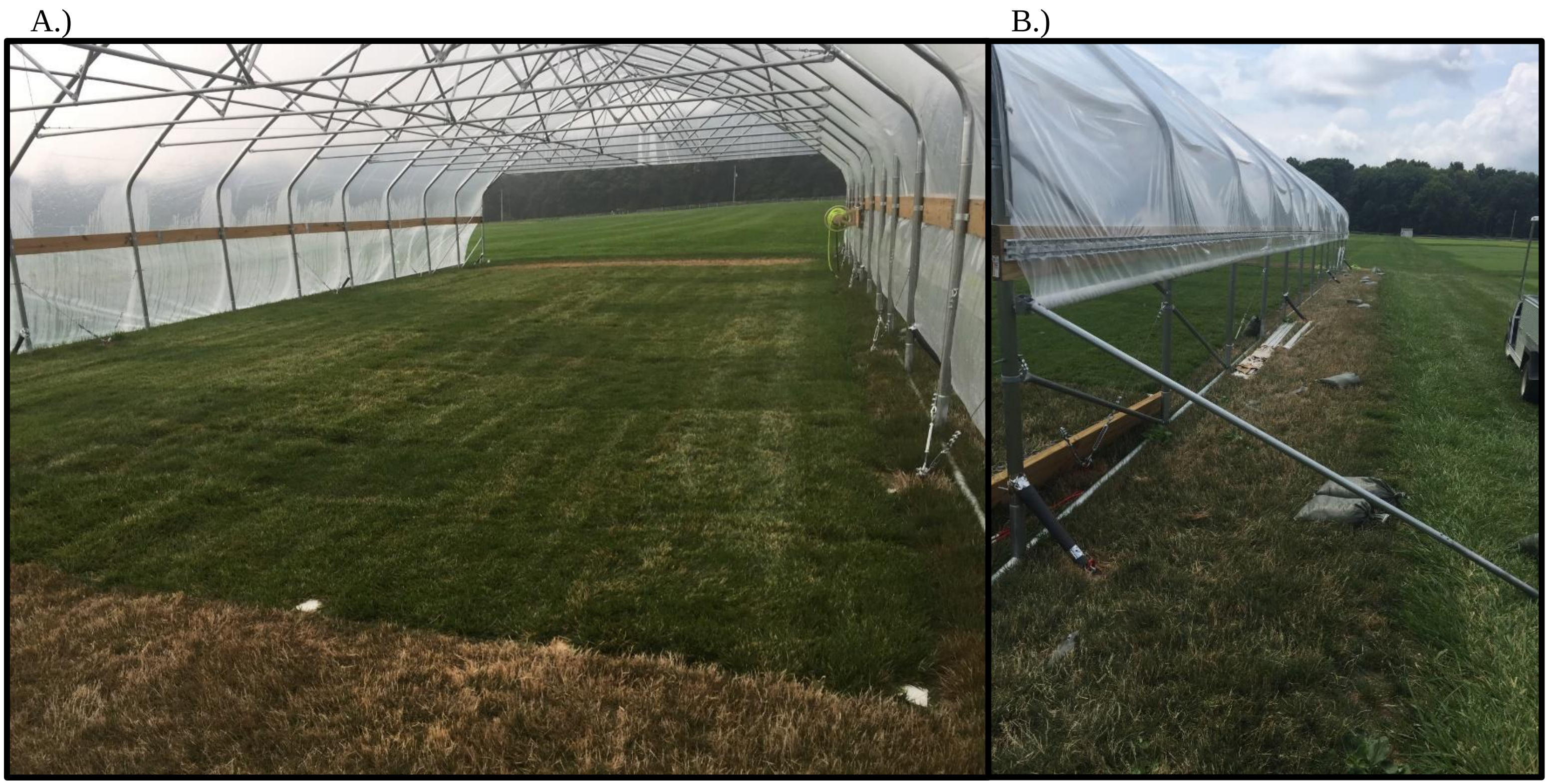
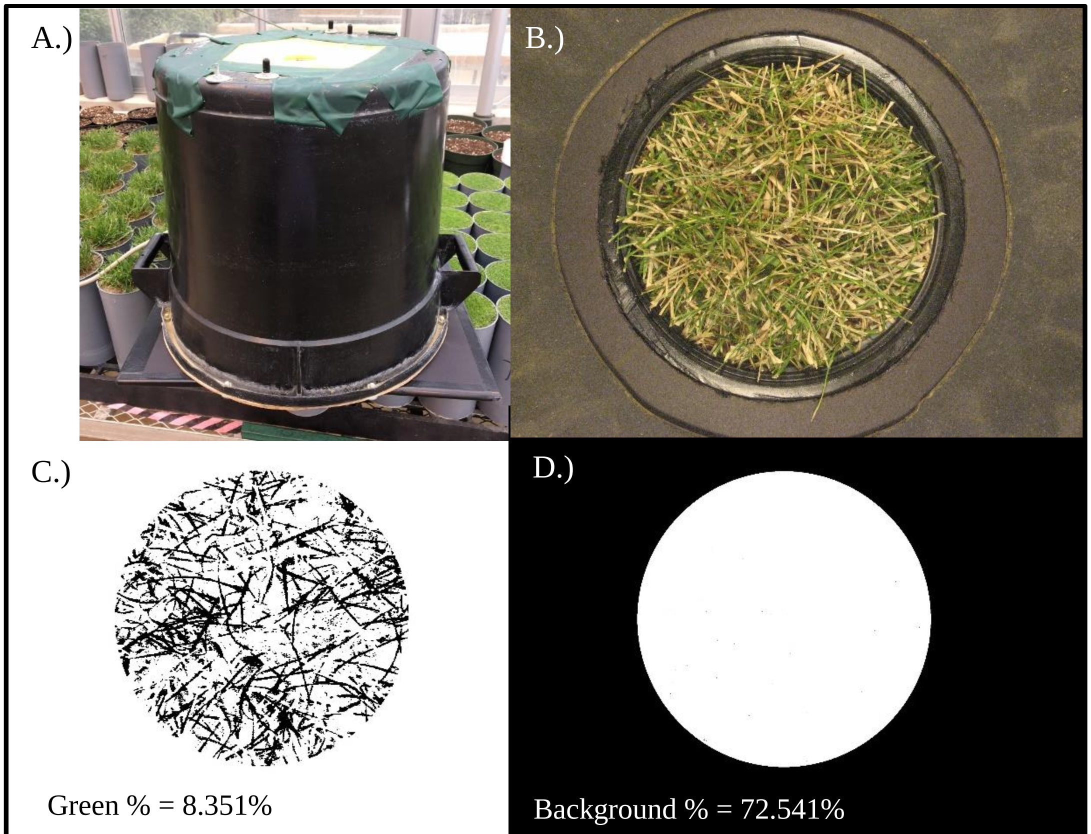


Figure A.2. Overview of field rain-out shelter to induce drought event. Rain-out shelter was covered with 5 mil translucent plastic (A); and during rainfall events, plastic sides were rolled down to prevent lateral water intrusion and rolled up immediately following rain event (B).

A.) B.) C.)

Figure A.3. Field study digital image measurement and analysis procedures. Digital image analysis was performed two times per week to quantify green coverage during deficit irrigation event. A light box equipped with an external battery (MotoMaster Eliminator PowerBox, Toronto, ON) to power four LED light bulbs (675 lumens, 5000 K) (A) was placed over the center of each plot to take a digital image (B). Images were taken using a Canon PowerShot G12 camera (Canon U.S.A. Inc., Huntington, NY). A Java-based software program, Turf Analyzer, was used to calculate green coverage (hue, saturation, and brightness ranges: 70-170, 10-100, 0-100, respectively) for the irrigation trigger using a 70% green coverage threshold (GCT_{70}) (C).



Green coverage = Green % / (100 – Background %) * 100

Green coverage = 8.351 / (100 – 72.541) * 100 = 30.413%

Figure A.4. Greenhouse digital image measurement and analysis procedures. A light box (A) was place over each lysimeter for consistent lighting to take a digital image (B). Images were downloaded in the computer software program, ImageJ (National Institutes of Health [USA]). Images were analyzed two times, once for green coverage (C) and again for the background percent (D) to generate turfgrass green coverage.