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Hybrid Bermudagrass and Kentucky Bluegrass Response Under Deficit Irrigation in a Semi-Arid, Cool Season Climate

Hanna R. Burgin
Brigham Young University

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Bryan G. Hopkins, Chair
Glenl A. Wear
Neil C. Hansen
Bradley D. Geary

Department of Plant and Wildlife Sciences

Brigham Young University

ABSTRACT

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Hanna R. Burgin
Department of Plant and Wildlife Sciences, BYU
Master of Science

As average global temperatures rise, cool-season C_3 turfgrasses, such as the most commonly grown Kentucky bluegrass (*Poa pratensis* L.; KBG), struggle to tolerate extreme summer heat and increase their water consumption. Hybrid Bermudagrass (*Cynodon dactylon* [L.] Pers. × *Cynodon transvaalensis* Burtt Davy; HBG) is a warm-season C_4 grass that may be increasingly suited for northern ecosystems traditionally classified as transition or cool-season climate zones. Glasshouse and field studies were conducted to compare HBG and KBG water use. The objective of the glasshouse study was to evaluate plant health and growth for two HBG cultivars (‘DT-1’ and ‘NorthBridge’) compared to a blend of KBG cultivars in all combinations of deficit, moderate, and high irrigation at optimum or short mowing height. The study was conducted in a glasshouse at Provo, UT, USA from 2020-2021. Grass was grown in pots arranged in a randomized complete block, full factorial design, with four replications of each treatment. The moderate KBG was also significantly different from both high and deficit for verdure and for the last half of NDVI. The objective of the field study was to evaluate two HBG cultivars (‘Tahoma 31’ and ‘Latitude 36’) compared to a blend of KBG cultivars for water loss and canopy health, temperature, and growth when subjected to deficit, moderate, and high irrigation. The study was arranged in a randomized complete block, full factorial design with three replications per treatment, and was conducted at Provo, UT, USA throughout the summer of 2021. In both the glasshouse and field trials, the deficit irrigated KBG consistently scored lower for NDVI and visual turf quality than all other treatments, including moderate and high KBG. This same trend was seen in the field study for percent cover. Although not observed in the glasshouse trial, it was observed in the field trial that the different irrigation levels of HBG resulted in no significant differences for any measurements but the HBG regularly scored better than KBG. The canopy temperatures of deficit irrigated KBG were also higher than all other treatments on most dates. The shoot mass, thatch mass, and total biomass of KBG were significantly less than either HBG cultivar. In the glasshouse trial it was observed that all deficit grasses were significantly lower than the other irrigation treatments and HBG had significantly deeper roots than KBG, although these results were not seen in the field trial. The data suggest that irrigation needs will be less for HBG than KBG and that HBG could provide a water-saving turfgrass alternative to KBG in semi-arid, cool-season regions with increasing water scarcity.

Keywords: Hybrid Bermudagrass, Kentucky bluegrass, irrigation, deficit irrigation, *Poa pratensis*, *Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt Davy, NorthBridge, DT-1, Latitude 36, Tahoma 31, drought, water use efficiency, NDVI, canopy temperature, turf quality, VWC, root depth

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CHAPTER 1

Cynodon dactylon (L.) Pers. × *Cynodon transvaalensis* Burtt Davy and *Poa pratensis* L. Response to Deficit Irrigation at Optimum and Short Mowing Height: Glasshouse Study

Hanna R. Burgin[1], Glenl A. Wear[2], Neil C. Hansen[1], Bryan G. Hopkins[1]
[1]Department of Plant and Wildlife Sciences, Brigham Young University, Provo, UT
[2]Grounds Department, Brigham Young University, Provo, UT
Master of Science

ABSTRACT

As average global temperatures rise and water is scarcer, hybrid Bermudagrass [*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt Davy; HBG] may be increasingly suited for replacing Kentucky bluegrass (*Poa pratensis* L.; KBG) grown in traditionally cool season climates. The objective of this study was to evaluate plant health and growth for two HBG cultivars ('DT-1' and 'NorthBridge Turf Bermudagrass') compared to a blend of KBG cultivars in all combinations of deficit, moderate, and high irrigation at optimum or short mowing height. The study was conducted in a glasshouse in Provo, UT, USA with a first round in 2020 and a second in 2021. Grass was grown in pots arranged in a randomized complete block, full factorial design, with four replications of each treatment. Drought stressed KBG was more severely impacted than HBG. Severe deficit irrigation (35% of optimum) decreased verdure and Normalized Difference Vegetative Index (NDVI) over time for all grasses, but the impact on HBG was less and delayed by ~7 d compared to KBG. Irrigation at 70% of optimum had no impact on HBG, but negatively impacted KBG. Impacts on canopy temperature and shoot growth were not consistently impacted, however, HBG rooted deeper (~8-10 cm) and had greater root mass but a lower shoot-to-root ratio (~2-10 times lower) than KBG. No clear pattern was observed between grass types in terms of volumetric water content (VWC) although it is

apparent that while water usage was comparable between grass types, the HBG was able to maintain a better turf quality than KBG-b under deficit irrigation. Heat stress may have been a contributing factor along with moisture stress as reduced irrigation resulted in higher temperatures regardless of species/cultivar or mowing height.

These data suggest that irrigation needs, especially in regions with increasing water scarcity, will likely be less for HBG than KBG as a function of both root and shoot physiology. This study estimates that HBG could thrive with at least 30% less irrigation than KBG in a cool-arid region like Utah and could be a good turfgrass option to conserve water.

INTRODUCTION

The Intermountain West (IMW) of the USA is generally an arid/semi-arid, cool-season region is the area in which the study described herein is based. Weather data shows that this area is experiencing a mega-drought and increasing average temperatures over the last several decades. For example, Salt Lake City, UT, USA, which is just north of the study site and shares a similar climate, has seen an upward trend over the last century (Fig. 1-1). Climate modeling projections suggest that the IMW will experience more frequent droughts and heat waves, reduced snowpack in the mountains, and earlier snowmelt (Carter and Culp, 2010; Harpold et al., 2012; Mote et al., 2005; Pachauri and Meyer, 2014; Saunders and Maxwell, 2005; Wang and Gillies, 2012). Although predictions are complex and uncertain, Saunders and Maxwell (2005) estimate that as early as 2039 the temperature may raise by 1°C, while precipitation levels drop 3%, snowpack levels drop 24%, runoff drop by 14%, and water storage drop by 36%. Such changes will make water supplies more strained for natural, agricultural, and municipal use (Carter and Culp, 2010; Harpold et al., 2012; Saunders and Maxwell, 2005).

In addition, the IMW region has seen tremendous population growth. Between the 1970s and the early 2000s, the population of the Rocky Mountain West region alone grew by nine million people, which lead to significant urban development and the loss of natural ecosystems (Carruthers and Vias, 2005; St. Hilaire et al., 2008). Five megaregional urban centers have developed from this growth in the IMW and it is expected that each of these regions will house over 10 million citizens by 2050, and the Colorado River, which supplies water to many of these major urban centers, is already dry before it reaches the Gulf of California (Carter and Culp, 2010). As populations grow and the IMW region becomes warmer and drier, the need to conserve water is increasingly crucial.

With increasing urbanization in the United States, grass is quickly growing as the principle managed land cover. Grass provides many societal benefits, such as beautifying landscapes, minimizing user injury, and supporting environmental processes (Beard and Green, 1994; Monteiro, 2017; U.S. National Park Service, 2018). Vegetated urban landscapes also support environmental processes through sequestration of carbon, generation of oxygen, degrading xenobiotics, minimizing soil erosion, improving soil health, cleaning dust and pollutants from the atmosphere, recharging groundwater, reducing wildfire threats, providing habitat, reducing chemical leaching and runoff to surface and groundwater (Beard and Green, 1994; Monteiro, 2017; Wentz et al., 2016). Turfgrass can directly benefit humans in urban areas by providing low-cost playing surfaces and spaces for entertainment and recreation, improving physical and mental health, and reducing allergens, glare, temperatures, noise pollution, and nuisance animal pests (Monteiro, 2017).

Despite its benefits, grasses have been brought under scrutiny due to high water demand, particularly in regions where water is increasingly scarce (St. Hilaire et al., 2008; Romero and

Dukes, 2014; Svedin et al. 2021; Wherley et al., 2014; Wentz et al., 2016). Grass requires a considerable amount of irrigation water, a resource that is increasingly scarce in these regions. Landscape irrigation often comprises 30-70% of a household's annual water use and most homeowners use significantly more water than necessary to irrigate their lawns (St. Hilaire et al., 2008; Romero and Dukes, 2014; Wherley et al., 2014; Wentz et al., 2016). The amount of water required by a grass depends on various factors, which influence its evapotranspiration (ET) rate. Cool-season grasses, those that thrive between 15 and 24°C have ET rates of 3-8 mm d^{-1} with a maximum of 7-10+ mm d^{-1} (Beard and Beard, 2005; Huang, 2008; Hatfield, 2017). Warm-season grasses, which prefer temperatures between 24 and 32°C, tend to be more water-efficient with general ET rates of 2-5 mm d^{-1} with a maximum of 6-10 mm d^{-1} (Beard and Beard, 2005; Huang, 2008; Hatfield, 2017).

Grass species vary in their water requirements, drought and heat susceptibility, and recovery rates (Bonos and Murphy, 1999; Huang, 2008; Huang and Fry, 2000). The most common turfgrass is *Poa pratensis* L. (Kentucky bluegrass; KBG), especially in cool-season zones (Bushman et al., 2012; Huang, 2008; Richardson et al., 2008). It is a cool-season C_3 grass which requires relatively high amounts of water to thrive (Brede, 2000; Bushman et al., 2012; Jazi et al., 2019). KBG is classified as moderate to low in being susceptible to drought (Aronson et al., 1987; Abraham et al., 2004). Although it is not very resistant to entering dormancy during drought, it is excellent at drought recovery (Abraham et al., 2004; Fry and Huang, 2004; Huang et al., 2014).

The so-called "cool-season" C_3 grasses, including KBG, generally are most healthy with temperature highs of ~22-25 °C. At higher temperatures, they tend to shut their stomates to avoid excessive water loss, which slows down their photosynthetic rate. Current climate projections estimate there will be longer warm periods and more high temperature extremes throughout the temperate zone, which could particularly intensify heat injury for C_3 grasses (Huang et al., 2014). The "warm-season" grasses tolerate higher temperatures by using the C_4 photosynthetic pathway that maximizes CO_2 intake and greatly reduces photorespiration, allowing them to thrive at temperature highs of ~32-35 °C. These temperatures are increasingly more common in many traditional cool-season climates, as mentioned previously.

Common Bermudagrass (*Cynodon dactylon*) and its triploid interspecific hybrid (*Cynodon dactylon* (L. Pers.) × *Cynodon transvaalensis* Burtt Davy; HBG) are the most common warm-season C_4 turfgrasses and are known for having relatively low water requirements (Huang, 2008; Pinnix and Miller, 2019). The evapotranspiration (ET) rates of HBG tend to be 6-7 mm d^{-1}. Whereas KBG can often require more than 10 mm d^{-1} (Beard and Beard, 2005; Huang, 2008), even though KBG is generally grown in areas with cooler climates than HBG. The ET rates can vary greatly within a single species, as cultivars may have different physical characteristics that impede or improve their ability to obtain or use water (Huang and Fry, 2000). The rates also change depending on the surrounding environment (solar intensity, temperature, humidity, wind, soil type, and stand density) and management practices (nitrogen fertilization rates, mowing height and frequency, and traffic pressure) (Carroll et al., 2017; Huang and Fry, 2000; Huang, 2008; Wherley et al., 2014).

The HBG cultivar 'Midlawn' was able to maintain a good quality over two summers after receiving only enough irrigation to replenish 60% of ET (Fu et al., 2004). Similarly, a few fine-textured, sports-type cultivars were acceptable after receiving equal to only 10-15% of ET (Wherley et al., 2014). Some cultivars are so drought-tolerant that they can recover from a 55 or 90 d drought in less than two weeks (Severmutlu et al., 2011; Steinke et al., 2011).

Researchers found that the KBG cultivar Brilliant® (PST-B2-42) required irrigation levels that replenished its full ET loss in order to maintain an acceptable grass quality, while other grass species [hybrid Bermudagrass (*C. dactylon* (L.) Pers. × *C. transvaalensis* Davy), zoysiagrass (*Zoysia japonica* Steud.), and tall fescue (*Festuca arundinacea* Schreb.)] could get by with significantly lower water levels (Fu et al., 2004). Jazi et al. (2019) conducted a similar experiment, with perennial ryegrass (*Lolium perenne*) instead of zoysiagrass, and found that Kentucky bluegrass was the most susceptible to water stress of the four species evaluated.

While experts still lack a complete understanding as to how Bermudagrass conserves water, proposed methods include the use of a deep, dense, efficient root system (Carrow, 1996; Fu et al., 2004; Garrot Jnr and Mancino, 1994; Husmoen et al., 2012; Zhou et al., 2013), bulliform cells (Bizhani and Salehi, 2014), accumulation of specific metabolites (namely sugars, sugar alcohols, organic acids, and amino acids) (Du et al., 2011), and closing wax-protected stomata quickly in dry periods (Kim, 1987; Huang and Fry, 2000; Zhou et al., 2013).

Despite their benefits, HBG cultivars have not been used in cool-season climate zones extensively because they are reported to not do well under prolonged freezing conditions (Anderson and Taliaferro, 2002; Xiang et al., 2019). Some new cultivars are available that can withstand both cool and arid environments, especially as climate change results in increasing average temperatures in cool-season regions (Hatfield, 2017). Demonstration plots at Brigham Young University have resulted in almost no winter kill for the HBG cultivars Hollywood™, Jackpot™, and Southern Star™ which have been grown there for the last 15 years, in contrast to other warm-season grasses that mostly do not survive the cold winters of Provo, UT, USA (Bryan G. Hopkins, personal communication). Hybrid Bermudagrass cultivars with some cold tolerance will potentially allow continued use of lawn grasses but with less water consumption in cool-season regions.

Another factor impacting irrigation needs is the height at which grass is mowed. Increased mowing heights often lead to increased transpiration rates but may also allow the grass to develop a deeper root system (Madison and Hagan, 1962; Biran et al., 1981; Christians et al., 2017; Feldhake et al., 1983; Waltz and Pauley, 2014; Wherley et al., 2014). Whether an increased mowing height is beneficial or detrimental to the grass during a period of drought depends on species and cultivar (Wherley et al., 2014).

As HBG and KBG have not been compared directly under identical, cool-season conditions, the objective of this study is to evaluate two glasshouse-grown HBG cultivars compared to a blend of KBG cultivars mowed at moderate or short heights in all combinations of deficit, moderate, and high irrigation rates evaluated for plant health (NDVI and visual turf quality), canopy temperature, water use, and shoot and root growth.

MATERIALS AND METHODS

Establishment

Two rounds of this study were conducted in a controlled glasshouse environment at Provo, Utah, USA (40° 14′ 43″ N, 111° 38′ 29″ W, 1406 m above mean sea level) from 10 February to 8 April 2020 and 28 July to 13 September 2021. The glasshouse temperature was targeted between daytime high and nighttime low temperature set points of 28 and 18 °C, respectively. Daytime temperatures were set to last 14 h and night for 10 h.

Treatments consisted of all combinations of three irrigation rates, two cutting heights, and three grasses with four replications arranged in a randomized complete block, full factorial design. Irrigation treatments consisted of deficit, moderate, or high amounts of applied water with 35, 70, or 100% of an approximated reference ET, respectively. Cutting treatments consisted of short or optimum heights at 1.9 or 3.2 cm, respectively. The grasses were *C. dactylon* × *C. transvaalensis* 'DT-1' (TifTuf®) and 'NorthBridge Turf Bermudagrass' (NorthBridge™), the latter cultivar name hereinafter abbreviated to NorthBridge, and *P. pratensis* with a blend of cultivars (35% 'Midnight', 35% 'Blueberry', 15% 'Legend', and 15% 'Blue Note'; abbreviated as KBG-b).

Grass was planted into locally sourced quarry sand (Table 1-1). Control-release fertilizer was added at a rate of 1,000 kg ha^{-1} (14-14-14; Osmocote® Classic, ICL Everris, Geldermalsen, The Netherlands), which is 140 kg of N, P_2O_5, and K_2O per ha, and mixed into the top 5 cm of each soil prior to planting. The KBG-b was obtained as 2 cm cut sod with the soil mostly rinsed off and cut to fit the pots (25 cm height, 10 x 10 cm width at the top rim tapering to 7.5 x 7.5 cm at the bottom) immediately prior to planting on 31 October 2019 for the first round and 8 July 2021 for the second. Both types of HBG were obtained as sprigs, which were planted about 3-5 cm deep in pots on 29 October and 6 November for NorthBridge and DT-1, respectively, for the first round, and on 21 April 2021 for DT-1 and on 24 April 2021 for NorthBridge, respectively, for the second round. During establishment, irrigation occurred every 1-2 d as necessary and grasses were trimmed with scissors to ~5 cm every 2-3 d. Additional nutrients were added during establishment on 4 February 2020 and 19 June 2021 as a quick-release fertilizer source at 38 kg ha^{-1} (24-8-16; MiracleGro® All-Purpose Plant Food, Scotts MiracleGro Company, OH, USA), which is 9 kg of N, 3 kg P_2O_5, and 6 kg K_2O per ha, applied as a liquid soak.

The grass was treated with a labelled rate of Dynasty 100FS (Azoxystrobin, Syngenta, Ontario, Canada) fungicide on 24 March, 31 March 2020, 16 July, and 4 August 2021.

Prior to the formal beginning of the first round, the KBG-b was mildly afflicted with rust (*Puccinia* and *Uromyces* spp.) shortly after sod installation. The rust appeared to be controlled approximately 7 days after a labelled rate of propiconazole fungicide (Propiconazole 14.3, Quali-Pro, TX, USA) was applied (0.25 mL in 650 mL water) on 11 December 2019. About 30 days after the treatments were initiated, the KBG-b began showing signs of an anthracnose (*Colletotrichum graminicola*) fungal infection, getting progressively worse with time. Not surprisingly, the impact was worse with the grass that was cut at a short height. The infection went undiagnosed for a time due to having similar visual symptoms as moisture stressed grass. Eventually, all of the grass in the experiment was sprayed with a labelled rate of Dynasty 100FS (Azoxystrobin, Syngenta, Ontario, Canada) fungicide (0.64 mL in 650 mL water) on 24 March and again on 31 March 2020. Disease impacted the KBG-b more than either HBG cultivar. This is unsurprising as *C. graminicola* rarely affects warm-season grasses, such as HBG, but infects cool season grasses, such as KBG, relatively more commonly (Khan and Hsiang, 2003; Kansas State, 2015).

There was a mild infestation of fungus gnats (*Sciaridae*) throughout the studies but they did not seem to affect the grass. No other pathogens or pests were observed during or before the experiment.

Irrigation and Measurements

For the first round, the pots of sand were weighed dry prior to establishment and then again at approximately field capacity at the beginning of the treatment period to determine the volumetric water content (VWC). The pots were saturated and then after 24 h of drainage and drying, water was slowly added back into three pots (one of each type of grass) until drainage occurred. The average VWC at field capacity was 28%, which approximated the initial daily water loss used as a benchmark for irrigation treatments. Irrigation occurred at approximately equal intervals three times per week (every 56 +/- 5 h). The amount of irrigation applied was 15.0, 10.5, and 5.3 mm day^{-1} for the “high”, “moderate”, and “deficit” irrigation treatments, respectively.

The second round used a slightly different method for irrigation with the exception of after 24 h of drainage and dry down, all of the “high” pots were weighed and the difference in weight was used to calculate the average daily water loss. This rate of 2.3 mm day^{-1} was used as a baseline for the 100% ET level corresponding to the “high” irrigation while the “moderate” and “deficit” irrigation treatments received 70% and 35% of that value, respectively. During each irrigation event, the amount applied was customized by multiplying the “high” rate by the amount of time predicted until the next event. The amount of irrigation applied was 2.3, 1.6, and 0.8 mm day^{-1} for the “high”, “moderate”, and “deficit” irrigation treatments, respectively.

Canopy temperature, visual turf quality, normalized difference vegetation index (NDVI), and VWC were evaluated periodically through the trial. NDVI measurements (Trimble Handheld Greenseeker, Trimble Agriculture, Sunnyvale, CA, USA) and canopy temperatures (FLIR E6 thermal imaging camera, FLIR, Wilsonville, OR, USA) were taken every ~7 d for every pot. Visual turf quality ratings were evaluated three times during the first study and every ~7 days during the second study on a scale from 1-9, with 9 being perfect turf quality and 1 being dead. The VWC was measured every ~3-7 days during the second study only (Theta Probe ML3, Delta-T Devices, Cambridge, England).

Rooting depth, shoot height, and root and shoot biomass were measured at the end of the trial. Root and shoot biomass were determined after drying at 105 °C in a forced air oven. Shoot to root ratio was calculated by dividing the shoot mass by the root mass.

Statistical significance for each measurement was determined by Analysis of Variance (P-value >0.05) with mean separation by the Tukey-Kramer method (JMP software, Cary, NC, USA).

RESULTS

All measured parameters (NDVI, canopy temperature, visual turf ratings, root depth, root mass, shoot mass, thatch mass, and shoot-to-root ratio) were statistically significant for the overall models. For the purposes of this study, the three-way interaction of grass type, irrigation rate, and mowing height are of greatest interest. When this is not significant, the two-way grass type x irrigation rate interaction becomes the primary focus as the emphasis is a comparison across species by irrigation rate. The grass type x mowing height and the irrigation x mowing height findings are also presented for general interest.

NDVI

For NDVI, the three-way interactions (grass type x irrigation rate x mowing height) were significant for just one date (Tables 1-2 and 1-3) in the second study. The grass type x irrigation interactions were not significant for the first study, but highly significant for all but one date for the second study. While all deficit irrigated grasses decreased in plant health (as NDVI) over time in the second study, the impacts on KBG-b health occurred sooner than both HBG cultivars (Fig. 1-2). The KBG-b irrigated at the moderate level was also negatively impacted relative to the high irrigation rate, although not as large of a magnitude as the deficit irrigated. However, the moderate HBGs never showed signs of moisture stress. Although not significant and with less magnitude, similar trends were observed in the first study (Table 1-2; Fig. 1-a in Supplemental Materials).

It is also noteworthy for NDVI that the two-way interactions of irrigation with mowing height were not significant in either study, but the grass type x mowing height were highly significant for all but one date for the second study (Tables 1-2 and 1-3). There was a differential response to mowing height for the grasses during the second study as the short mowed DT-1 was significantly lower than optimum mowed DT-1 for all but the last two dates (Tables 1-2 and 1-3; Fig. 1-b in Supplemental Materials).

Visual Ratings (Verdure)

For verdure, the three-way interactions were not significant, but the grass type x irrigation rate interactions were highly significant across all dates for the second study and one date for the first study, as well as another date significant at the P=0.092 level. These verdure results from the second study were similar to NDVI (Figs. 1-2 and 1-3) in that all the deficit irrigated grasses were visibly moisture stressed, but the deficit irrigated KBG-b declined earlier than the HBG cultivars. By 26 d, all of the deficit irrigated grasses had significantly reduced verdure than their moderate and high counterparts. Similarly, KBG-b was visibly moisture stressed at the moderate irrigation rate. The magnitude of the moisture stress for moderate irrigated KBG-b was not as great as the deficit irrigated, although it trended sharply downward at the final date. Notably, the HBG cultivars showed no significant difference from their high irrigated counterparts at the moderate irrigation rate. For the first study, there was not as much of a response and the magnitude was not as great, but it had similar trends (Table 1-4; Fig. 1-c in Supplemental Materials).

It is also noteworthy that there were significant interactions between irrigation rate x mowing height for the averages, the final day of the first study, and for all but the first two dates of the second study, although the effect was similar across grass types (Table 1-4; Fig. 1-d in Supplemental Materials). The short and optimum mowed grass at deficit irrigation were significantly lower than their moderate and high counterparts for nearly the entire second study. The grass type x mowing height interaction was generally not significant, with significance only appearing on 35 d and 47 d of the second study (Table 1-4).

Canopy Temperature

Despite differences in NDVI and verdure, the three- and two-way interactions were not generally significant with no clear differential response for the grasses as a function of irrigation (Tables 1-5 and 1-6). However, grass type was significant across several days for the first study, where NorthBridge was cooler than the others for the first two dates and warmer than DT-1 on the fourth. Irrigation rate was also generally significant across most dates and for the averages of both studies, with the canopy of the deficit irrigated grasses being significantly warmer than the moderate or high for the first study. Similarly, in the second study, the deficit irrigated grass was significantly warmer than both moderate and high irrigation and the moderate irrigation was also significantly warmer than high. The average increases in canopy temperature for the moderate and deficit irrigation compared to the high rate were 0.26°C and 1.8°C, respectively, for the first study, and 0.87°C and 2.3°C, respectively, for the second study.

Shoot and Root Growth

None of the root and shoot measurements were significant for any three-way or two-way interactions in the second study, and only a few instances for the first (Tables 1-7 and 1-8). It is noteworthy that there was some disease pressure that impacted the KBG-b, especially at the end of the study, which may have impacted the shoot results. Although there was a significant grass x irrigation interaction and significant three-way interactions for shoot and total biomass in the first study (Table 1-7), as these were not duplicated in the second study these are discounted as possible anomalies as a function of disease impacting the shoot growth.

For shoot height, the three-way interaction was highly significant for the first study (Table 1-7; Fig. 1-4). Unfortunately, the data for the second study were lost and, thus, this interaction is explored herein.

At the short mowing height, there was no difference in shoot regrowth height based on irrigation levels for either HBG cultivar (Table 1-7; Fig. 1-4). In contrast, the moderate and deficit irrigated KBG-b that was mowed short were significantly lower than all of the HBG mowed at the same height. There was no statistical difference between irrigation rates for short mowed KBG-b, although the high irrigation rate trended towards greater regrowth.

At the optimum mowing height, the deficit irrigated grasses had significantly less regrowth than the moderate and high irrigation rates, except for NorthBridge at the high rate, when compared to within each grass type (Table 1-7; Fig. 1-4). Additionally, the HBG cultivars generally had significantly higher shoot regrowth under high and moderate irrigation than KBG-b at the same irrigation rates.

In addition to the interactions, it is noteworthy that there were significant differences across grass types for all shoot and root measurements in both studies, although not impacted variably by irrigation rates and/or mowing heights (Tables 1-7 and 1-8; Fig. 1-5). Although grass type was significant for shoot biomass, the results differed between studies with KBG-b having significantly less shoot biomass than the HBG cultivars, which had similar biomass to each other, in the first study and a dramatically opposite response in the second. This further supports the idea that there was a negative impact on shoot growth due to disease in the first study.

Despite the differing irrigation levels, disease pressure, etc. between the studies, the HBG cultivars rooted deeper than KBG-b in both studies (Tables 1-7 and 1-8; Fig. 1-5). Also, although the pots used in this study were relatively deep, more than half of the HBG pots in the first round contained roots that extended the entire length of the soil and accumulated at the bottom—indicating being root-bound. In the second study, only one HBG pot was root bound. None of the KBG-b roots reached the bottom of pots in either study.

Root biomass followed a similar trend (Tables 1-7 and 1-8; Fig. 1-5). Root biomass for NorthBridge was significantly greater than KBG-b in both studies. Root biomass for DT-1 was significantly greater than KBG-b in the first study and trended in that same way in the second. NorthBridge had significantly more root biomass than DT-1 in the first study and trended to the same in the second.

It is also noteworthy that the KBG-b had a dramatically higher shoot-to-root ratio than the HBG even though there was diminished shoot growth due to disease in the first study (Tables 1-7 and 1-8; Fig. 1-5). Furthermore, in the first study the DT-1 had a higher shoot-to-root ratio than NorthBridge and trended in that same way in the second.

Another interesting observation from the first study was that after the trial was ended and the pots stopped receiving any amount of water, shoots from both HBG types in the deficit irrigation pots dried out and lost their quality much quicker when they had been subject to the optimum mowing height. The shorter shoots maintained a healthy, green, and full appearance for several days longer than their taller counterparts. This was not observed in the second study as the deficit pots were already dry by the end of the trial.

Volumetric Water Content (VWC)

Due to the interest in water use, VWC was added as a measurement for the second study. Irrigation rate was significant on all dates measured, and grass type was significant on all dates but one (Table 1-9). The two-way interaction between grass type and irrigation rate was significant or near significant for most dates, as well as the average for the study (Table 1-9; Fig. 1-6). The measurements began on 16 d, and by that point the VWC values of the deficit irrigated grasses were significantly lower than their moderate and high irrigation counterparts and stayed lower throughout the remainder of the study (Fig. 1-6). However, no clear pattern was observed between species in terms of irrigation usage. It is apparent that although water usage was comparable between grass types, the HBG was able to maintain a better turf quality than KBG-b under deficit irrigation.

DISCUSSION

Deficit irrigation negatively impacted KBG-b verdure and health (NDVI) more quickly than HBG at both optimum and short mowing heights when irrigated at 35% of optimum. When irrigated at 70% of optimum, the KBG-b was negatively impacted while HBG did not show signs of moisture stress. Although shoot growth was variably impacted, likely due to differences in disease pressure, root depth and mass and shoot-to-root ratio were greater for HBG than KBG-b regardless of irrigation rate or mowing height. We note that these were short-term studies. It is possible that longer periods of deficit irrigation may eventually result in an interaction between grass type and irrigation level for the shoot and root growth as non-significant trends were beginning to develop. Although heat stress may have been a contributing factor, along with moisture stress, to our findings with reduced irrigation resulting in higher temperatures, the canopy temperature was not impacted differentially for the grass types and mowing heights as a function of irrigation rate.

Other studies have seen clear correlations between drought and turf quality or greenness, supporting the idea that warm-season grasses perform better than cool-season grasses under drought conditions (Fu et al., 2004; Steinke et al., 2011; Marín et al., 2020). Marín et al. (2020) found that two C_4-C_3 mixes of *C. dactylon-Brachypodium distachyon* and *Buchloe dactyloides-B. distachyon* had significantly higher greenness levels (NDVI) than the C_3 only mix (*Lolium perenne*, *Festuca arundinacea,* and *P. pratensis)* when under an irrigation level equal to 50% of container capacity. Fu et al. (2004), in a field study using a mobile rainout shelter in Manhattan, Kansas, USA, compared a cultivar each of zoysiagrass, tall fescue, HBG, and KBG for turf quality at varying irrigation levels and found that HBG was the most drought tolerant—followed by tall fescue, zoysiagrass, and lastly KBG. Steinke et al. (2011), in a field study in San Antonio, TX, USA, found that four common Bermudagrass cultivars lasted over 60 d in a summer with no irrigation to reach 50% ground cover. These results support our findings that deficit-irrigated cool-season KBG-b was less suitable under drought conditions than warm-season HBG.

In addition to verdure and NDVI impacts, we measured differences in shoot growth. However, the results were varied as the HBG cultivars produced greater shoot biomass than KBG-b in the first study, but the opposite was measured in the second. The KBG-b shoot growth in the first study was likely impacted by disease that did not appear to impact the HBG. Although we did measure consistent differences for grass type as influenced by irrigation rate, Marín et al. (2020) found that a C_4-C_3 grass mix of *C. dactylon* and *B. distachyon* produced a higher shoot biomass than their C_3-only mix when subjected to 75% or 50% irrigation levels. This supports the idea that C_4 grasses like HBG (*C. dactylon* × *C. transvaalensis*) produce greater shoot biomass than C_3 grasses like KBG (*P. pratensis*) when under some amount of drought stress. Our findings for shoot growth are not conclusive and further evaluation is needed.

More importantly from a water efficiency standpoint, root growth was consistently impacted in our studies. The HBG significantly and consistently developed deeper roots than KBG. Similarly, HBG generally had greater root biomass than KBG as well as a smaller shoot-to-root ratio. These findings are similar to those of others (Carrow, 1996; Fu et al., 2004; Huang, 2008; Wherley et al., 2014; Zhang et al., 2017).

However, there was no consistent impact on rooting depth or biomass as a function of irrigation rate in our studies. Similarly, Sinclair et al. (2011) concluded that deficit irrigation did not consistently result in greater root biomass for 'Tifway 419' hybrid Bermudagrass. These findings are in contrast to the observations of others that have shown that grasses often produce greater root biomass and/or deeper roots when subjected to repeated drying periods (Baldwin et al., 2006; Carrow, 1994; Hays et al., 1991; Huang et al., 1997; Huang, 1999; Husmoen et al., 2012; Zhou et al., 2013). However, Sadeghi et al. (2015) found the opposite with five KBG cultivars all developing significantly less root biomass when under drought conditions. Greater root biomass/depth are important drought resistance attributes for plants. Other studies evaluated a total of eighteen common and hybrid Bermudagrass cultivars and concluded that greater root biomass was associated with greater turf quality during water stress, and especially at greater soil and rooting depths (Baldwin et al., 2006; Hays et al., 1991; Husmoen et al., 2012). Since no irrigation rate interactions existed for root depth or root mass in our studies, it is possible that the grasses required a longer drought period and/or repeated drought periods for rooting to be affected.

It should be noted that in the present study the pots limited HBG root growth somewhat, with a soil depth of 25 cm. Other studies have shown that shallow soil depths are not conducive to healthy, drought tolerant plants (Steinke et al., 2011; Zhou et al., 2014; Monje-Jiménez et al., 2019). Steinke et al. (2011) showed that 10 cm of soil was too little for eight Bermudagrass cultivars to withstand drought, but when grown in a natural soil of unrestricted depth, the same cultivars survived the drought period. Zhou et al. (2014) suggests that soil profiles less than 30 cm are too shallow for many common Bermudagrass cultivars to take full advantage of their soil water extraction abilities and that evaporation at the soil surface may even confound results. In this present study, the pots and sand within them also limited the ability of the soil to store water as the pot size and soil type were not conducive to holding as much water as is commonly found in natural soils. Thus, while the KBG-b root growth in this study was likely not limited, the HBG cultivars in this study may not have been not fully tested in their ability of lengthening roots to obtain stored water (Husmoen et al., 2012; Monje-Jiménez et al., 2019). However, despite the limitations, the HBG performed better than KBG. Results may be slightly different in a natural environment.

Most C_3 grasses are less tolerant of extreme high temperatures than C_4 grasses (Wang and Huang, 2004; Du et al., 2011) and KBG is known to struggle more under heat stress than drought stress (Jiang and Huang, 2000; Abraham et al., 2008). Canopy temperature is also related to stomatal resistance in grass shoots, and in other studies it has been shown that lower canopy temperatures are commonly seen in more drought-tolerant grass varieties (Bonos and Murphy, 1999). It should be noted, however, that these other studies compared cultivars within a single grass species. In our study, it was somewhat surprising that the canopy temperatures resulted in so few relationships for grass type as a function of irrigation rate. Again, these studies were conducted over relatively short time frames, which mimic conditions that often occur in nature, and longer periods may result in greater impacts on canopy temperatures. Other contributing factors for this lack of an interaction between grass type and irrigation rate response potentially include the inevitable reduction in solar radiation as a function of glasshouse conditions and/or the relatively low temperature set points (although these set point temperatures are frequently exceeded under full sun days when the cooling system is overwhelmed by solar radiation).

Finally, mowing height did not seem to impact the irrigation requirements of the grasses used in this study. This is odd since many experts recommend raising the mowing height during times of drought because maintaining grass at a shorter mowing height often requires more water (Waltz and Pauley, 2014). However, similarly to our study, Wherley et al. (2014) conducted an irrigation study including a number of sports-type, medium-textured, and fine-textured HBG cultivars and determined that supplemental irrigation did not interact with mowing height.

CONCLUSION

We hypothesized that the HBG cultivars used in this study would perform better under deficit irrigation than KBG-b, and therefore suggest that they may offer a better solution for sports surfaces and landscaping in arid and semi-arid regions as the climate continues to warm. We found that drought stressed KBG was more severely impacted than HBG. Plant health and verdure of KBG were impacted earlier than HBG when irrigated at 35% of optimum. When irrigated at 70% of optimum, the KBG was negatively impacted while HBG did not show signs of moisture stress. Although shoot growth was variably impacted, likely due to differences in disease pressure, root depth and mass and shoot-to-root ratio were greater for HBG than KBG regardless of irrigation rate or mowing height. Heat stress may have been a contributing factor along with moisture stress as reduced irrigation resulted higher temperatures regardless of species/cultivar or mowing height. These results suggest increased root depth and shoot biomass for HBG compared to KBG-b, and more dramatic decreases in NDVI and turf quality over time for deficit irrigated KBG-b compared to all other treatments, which support our hypothesis. Further work is needed to verify this data under long-term field conditions and to quantify irrigation needs, as well to evaluate various HBG cultivars for growth in areas with relatively cooler climatic conditions.

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FIGURES

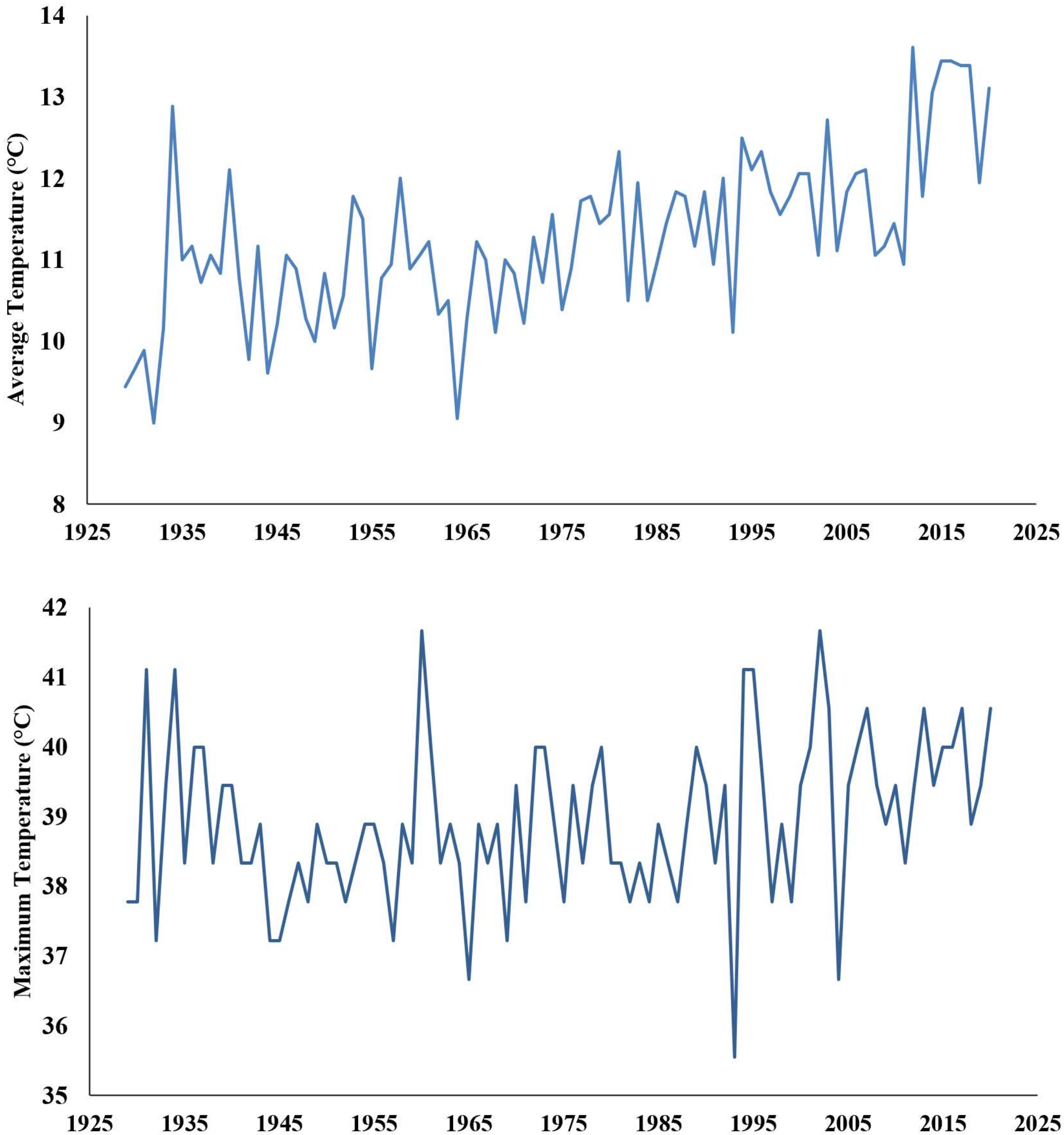

Figure 1.1 Average annual and maximum temperatures for Salt Lake City, UT, USA 1925-2020 (NOAA, 2020).

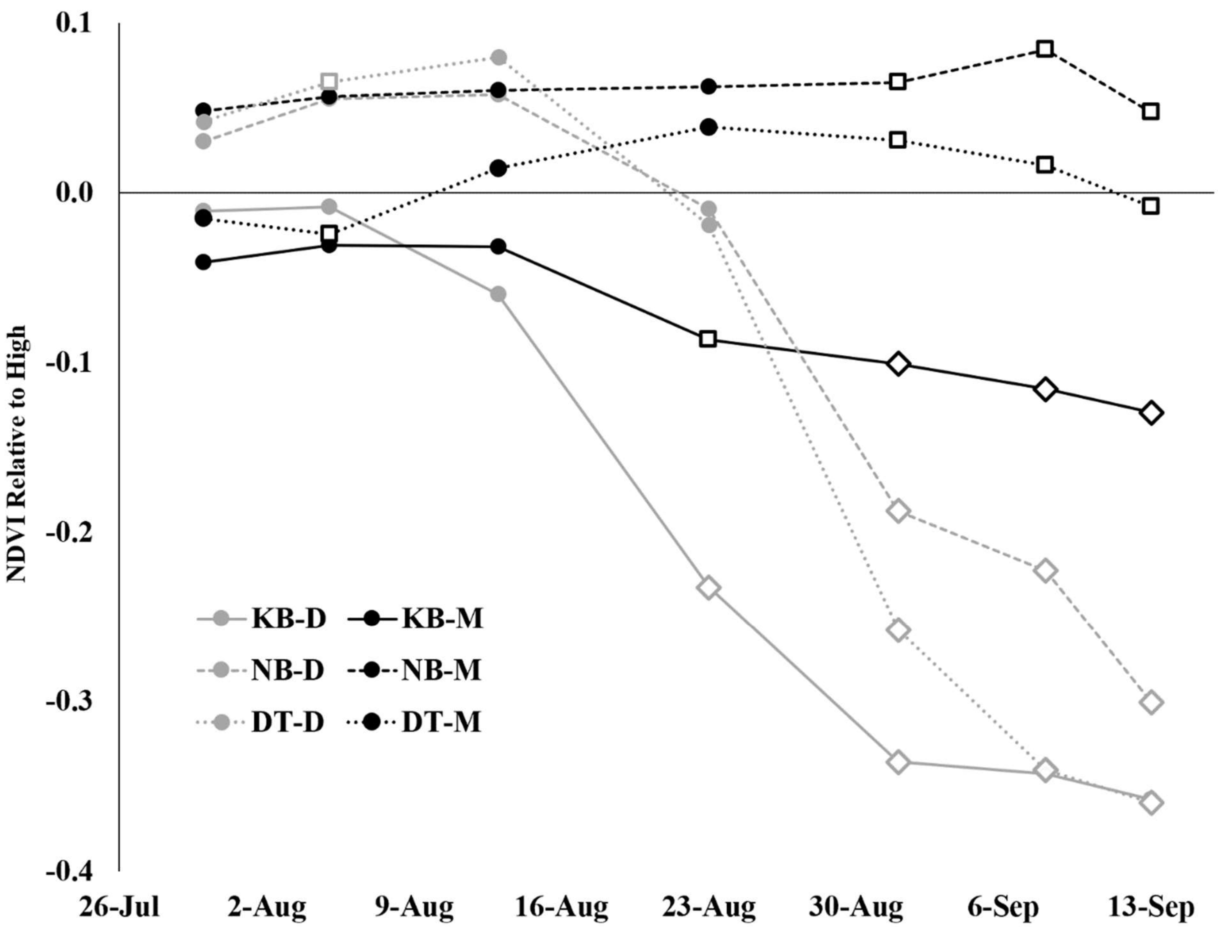

Figure 1-2. Change in relative Normalized Difference Vegetation Index (NDVI) values for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at deficit (-D) and moderate (-M) irrigation rates relative to the high rate (control) for each grass for a glasshouse study in 2021. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments.

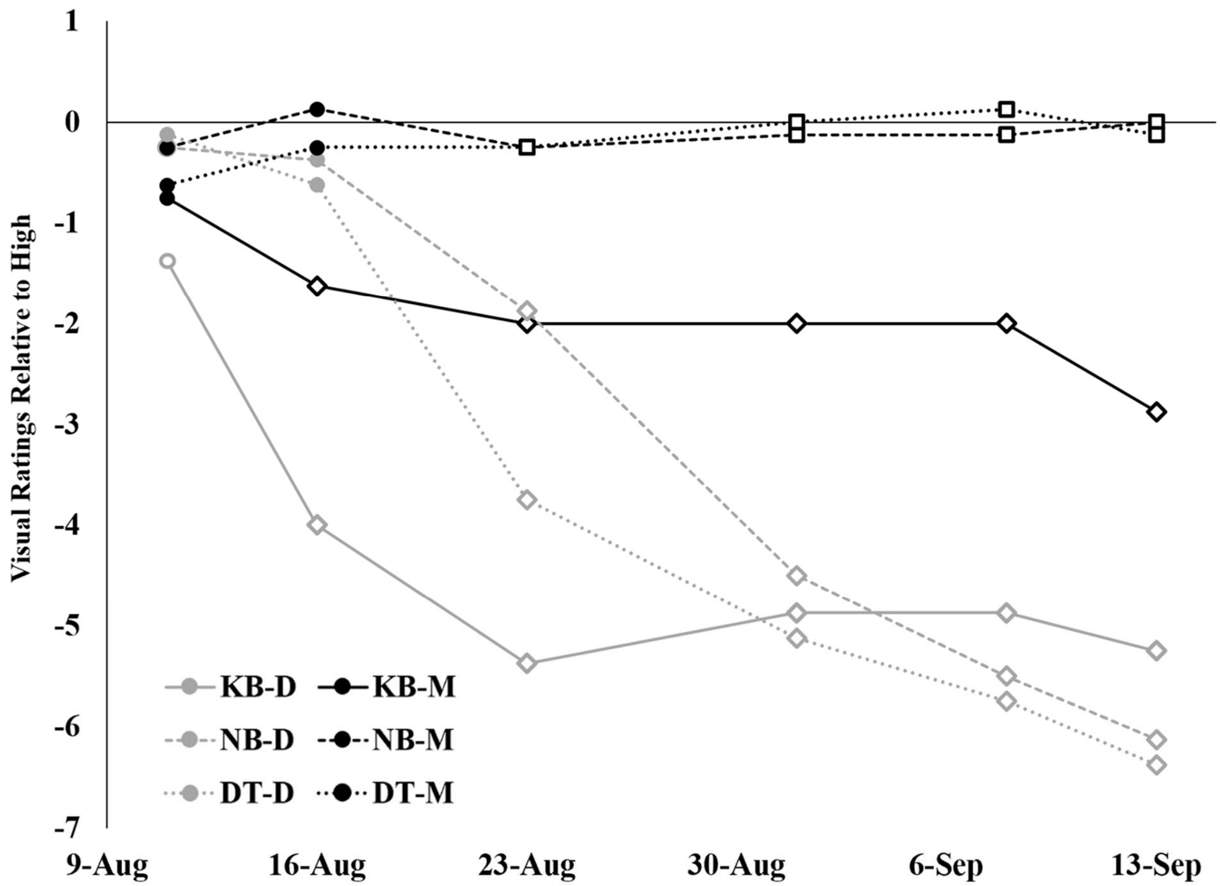

Figure 1-3. Change in visual turf quality ratings for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at deficit (-D) and moderate (-M) irrigation rates relative to the high rate (control) for each grass for a glasshouse study in 2021. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments.

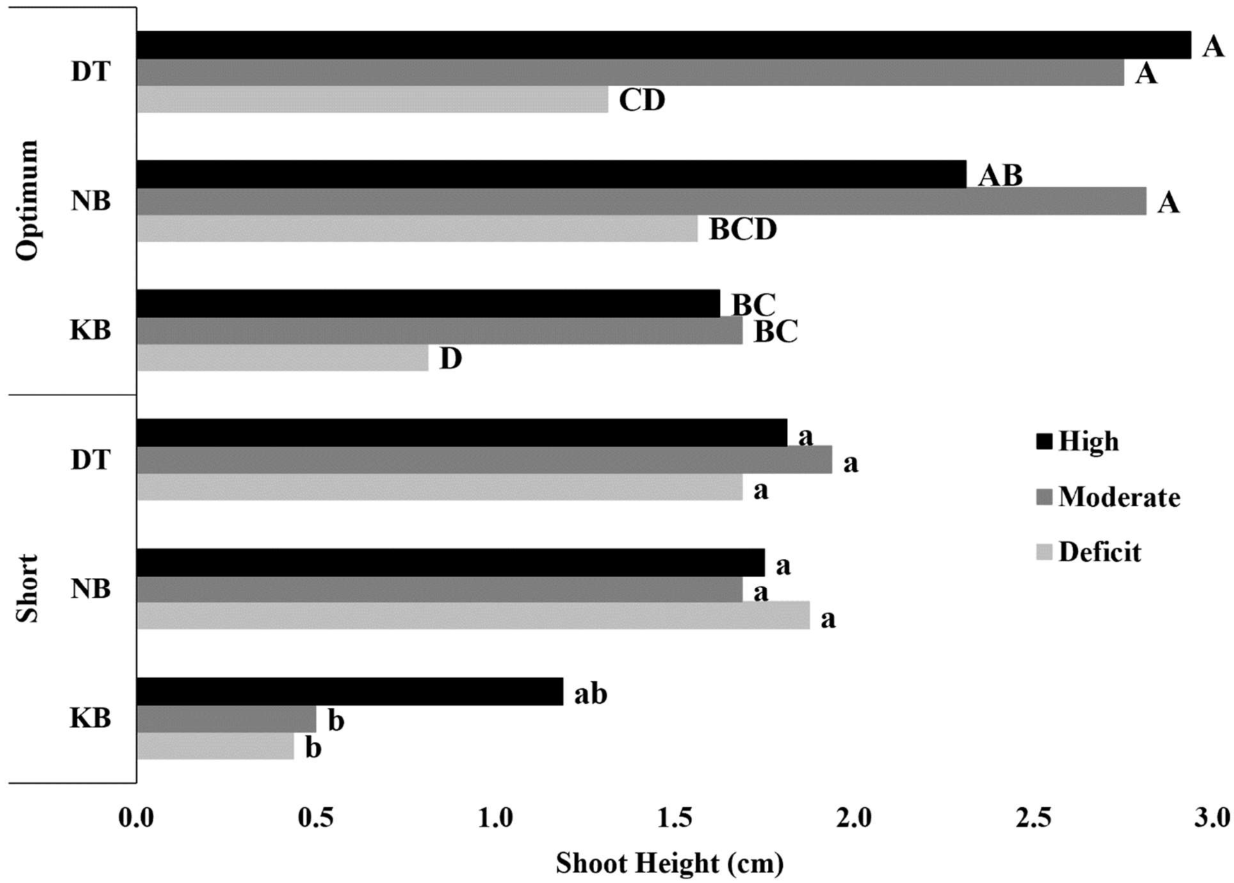

Figure 1-4. Shoot regrowth height (cm) for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at deficit, moderate, and high irrigation rates, and optimum and short mowing heights for a glasshouse study in 2020. Data bars within each mowing height sharing the same letter(s) indicates a lack of statistical difference (P = 0.05).

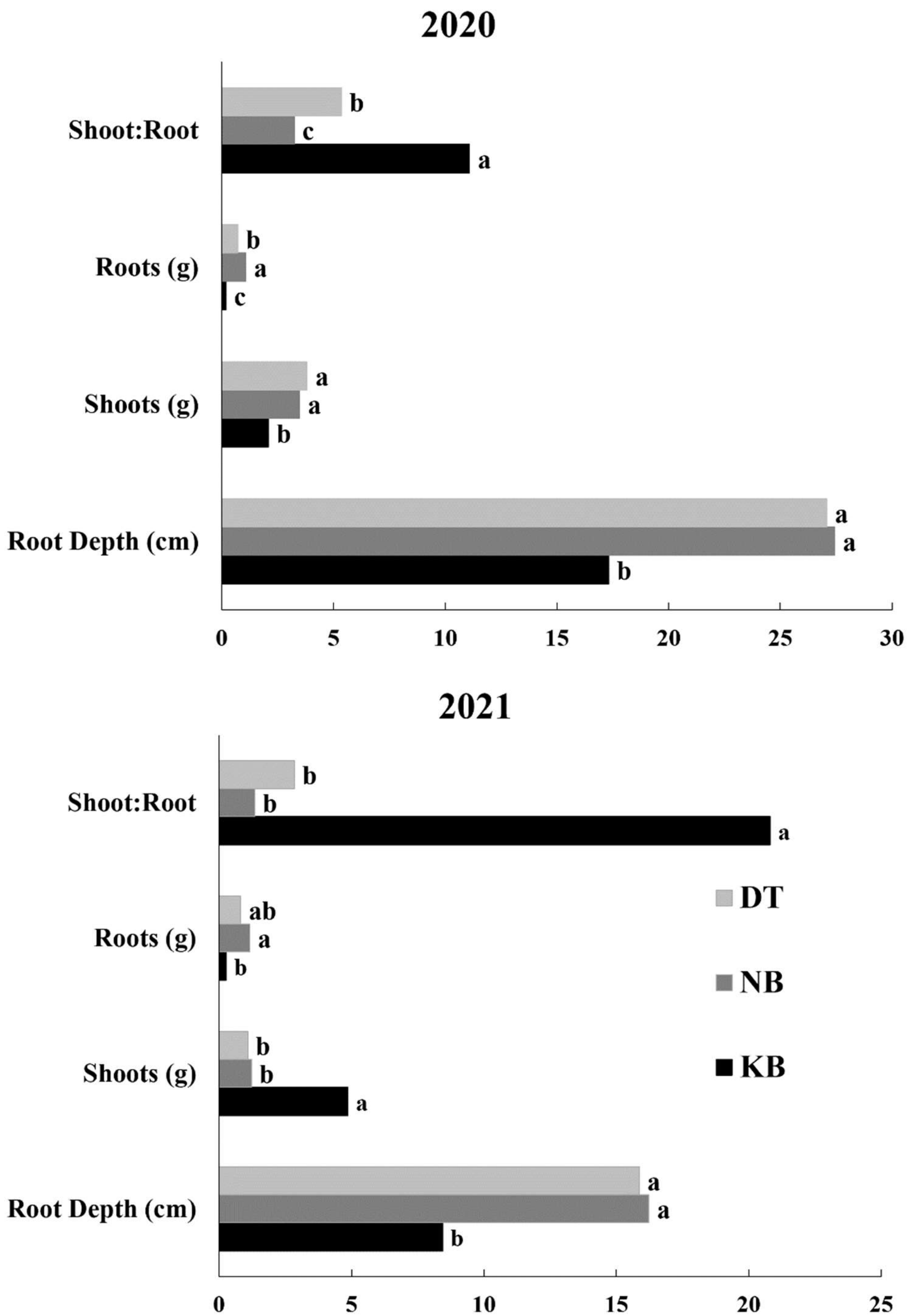

Figure 1-5. Biomass values for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) for two glasshouse studies. Data bars within each study and measurement sharing the same letter(s) indicates a lack of statistical difference (P = 0.05).

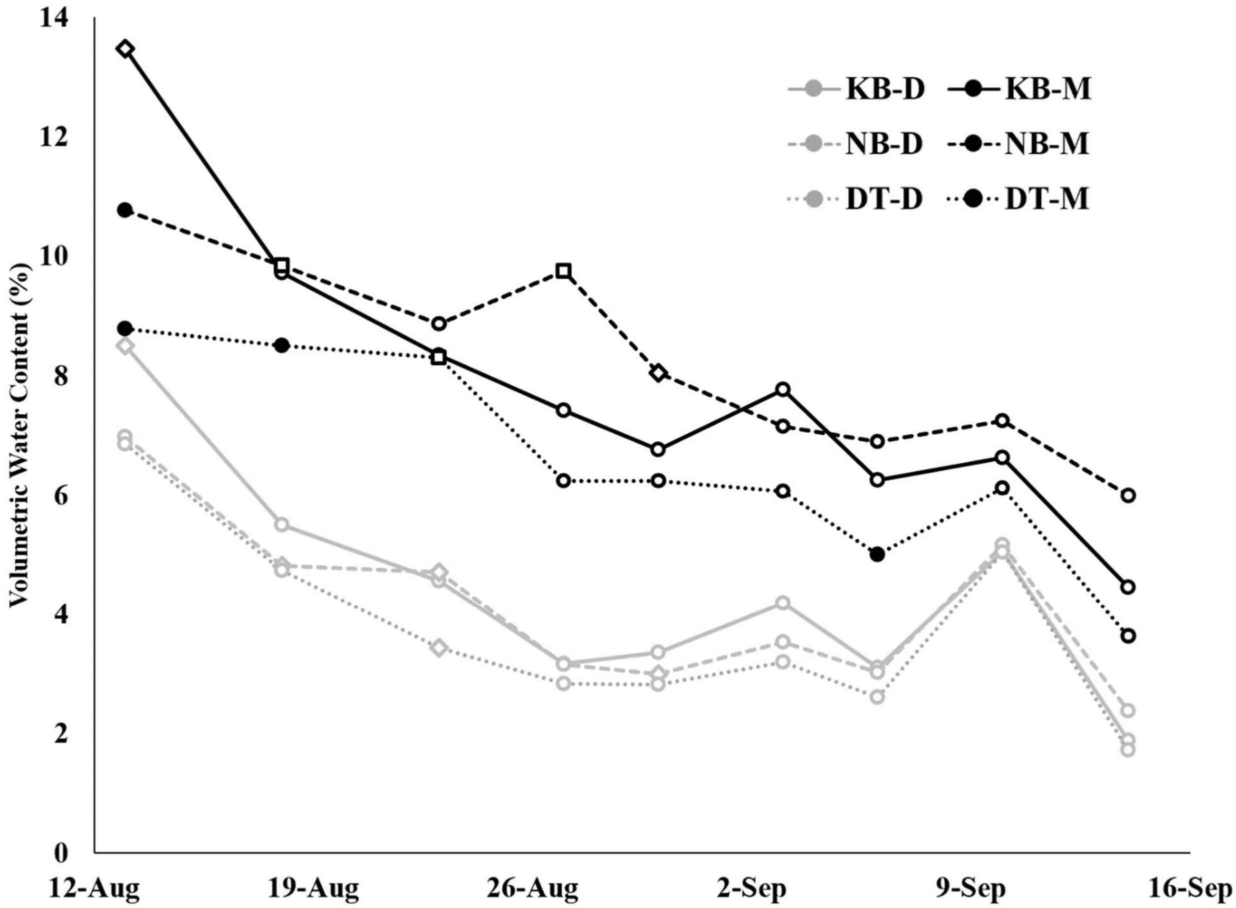

Figure 1-6. Changes in volumetric water content (VWC) values for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at deficit (-D) and moderate (-M) irrigation rates for a glasshouse study in 2021. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments.

TABLES

Table 1-1. Properties of sand prior to fertilization

Property	**Value**	**Method**
VWC at field capacity, %	28	Volumetric[1]
Texture	sand	Hydrometer[2]
Sand, %	90.2	
Silt, %	3.1	
Clay, %	6.7	
Bulk density, g cm^{-3}	1.5	Gravimetric[2]
pH	7.6	Saturated Paste[2]
EC, dS m^{-1}	2.9	″ ″
OM, %	0.1	Walkely-Black Method[2]
NO_3-N, ppm	71	KCl 2M[2]
P, ppm	22	Olsen Bicarbonate[2]
K, ppm	150	″ ″
Zn, ppm	2.0	DTPA Extraction[2]
Mn, ppm	1.2	″ ″
Fe, ppm	2.7	″ ″
Cu, ppm	0.14	″ ″

[1] GS3 Sensor; METER Group, Pullman, WA, USA
[2] Gavlak et al., 1994.

Table 1-2. Normalized Difference Vegetation Index (NDVI) values for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2020. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

		Day of Study and Date							
		4	16	23	30	37	44	51	
Irrigation Rate	**Mowing Height**	2/14	2/26	3/4	3/11	3/18	3/25	4/1	Avg.
		Kentucky Bluegrass – Blend of cultivars							
Deficit	Optimum	0.539	0.529	0.530	0.523	0.479	0.435	0.394	0.490
	Short	0.445	0.396	0.378	0.398	0.361	0.385	0.326	0.384
Moderate	Optimum	0.497	0.504	0.515	0.539	0.502	0.481	0.495	0.505
	Short	0.424	0.342	0.337	0.355	0.328	0.298	0.295	0.340
High	Optimum	0.543	0.530	0.545	0.559	0.516	0.506	0.480	0.525
	Short	0.415	0.390	0.392	0.400	0.409	0.402	0.393	0.400
		Hybrid Bermudagrass – NorthBridge							
Deficit	Optimum	0.588	0.659	0.694	0.708	0.680	0.685	0.681	0.670
	Short	0.501	0.536	0.566	0.588	0.571	0.596	0.656	0.573
Moderate	Optimum	0.600	0.667	0.669	0.698	0.664	0.680	0.719	0.671
	Short	0.522	0.568	0.587	0.613	0.594	0.630	0.673	0.598
High	Optimum	0.609	0.649	0.673	0.701	0.689	0.695	0.720	0.677
	Short	0.556	0.563	0.587	0.628	0.615	0.649	0.679	0.611
		Hybrid Bermudagrass – DT-1							
Deficit	Optimum	0.602	0.652	0.672	0.696	0.633	0.656	0.639	0.650
	Short	0.553	0.590	0.605	0.641	0.610	0.649	0.702	0.621
Moderate	Optimum	0.614	0.663	0.673	0.712	0.672	0.692	0.730	0.679
	Short	0.475	0.534	0.582	0.642	0.633	0.684	0.720	0.610
High	Optimum	0.599	0.673	0.698	0.714	0.685	0.708	0.736	0.688
	Short	0.487	0.539	0.563	0.619	0.630	0.666	0.687	0.599
		***P*-values**							
Grass type (G)		*0.101*	*0.571*	*0.304*	*0.381*	*0.588*	*0.270*	*0.146*	*0.324*
Irrigation rate (I)		*0.513*	*0.583*	*0.492*	*0.724*	*0.103*	*0.068*	***0.012***	*0.333*
Mowing height (M)		*0.551*	*0.899*	*0.635*	*0.906*	*0.634*	*0.988*	*0.560*	*0.824*
G x I		*0.314*	*0.452*	*0.774*	*0.842*	*0.848*	*0.492*	*0.655*	*0.740*
G x M		*0.233*	*0.312*	*0.174*	*0.412*	*0.447*	*0.436*	*0.059*	*0.287*
I x M		*0.717*	*0.691*	*0.944*	*0.909*	*0.896*	*0.610*	*0.083*	*0.634*
G x I x M		*0.367*	*0.581*	*0.543*	*0.657*	*0.704*	*0.199*	*0.321*	*0.550*

Table 1-3. Normalized Difference Vegetation Index (NDVI) values for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2021. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

		Day of Study and Date							
		2	8	16	26	35	42	47	
Irrigation Rate	**Mowing Height**	7/30	8/5	8/13	8/23	9/1	9/8	9/13	Avg.
		Kentucky Bluegrass – Blend of cultivars							
Deficit	Optimum	0.668	0.685	0.645	0.497	0.351	0.320	0.300	0.495
	Short	0.629	0.639	0.561	0.361	0.277	0.252	0.249	0.424
Moderate	Optimum	0.646	0.673	0.677	0.639	0.617	0.590	0.575	0.631
	Short	0.590	0.605	0.586	0.510	0.480	0.435	0.430	0.519
High	Optimum	0.677	0.691	0.697	0.697	0.690	0.670	0.678	0.686
	Short	0.641	0.649	0.628	0.625	0.609	0.587	0.585	0.618
		Hybrid Bermudagrass – NorthBridge							
Deficit	Optimum	0.564	0.661	0.670	0.577	0.392	0.289	0.251	0.486
	Short	0.550	0.567	0.559	0.458	0.305	0.293	0.221	0.422
Moderate	Optimum	0.582	0.615	0.642	0.621	0.617	0.626	0.613	0.616
	Short	0.567	0.615	0.591	0.558	0.585	0.570	0.554	0.577
High	Optimum	0.521	0.579	0.598	0.569	0.601	0.576	0.592	0.576
	Short	0.532	0.538	0.515	0.485	0.471	0.452	0.481	0.496
		Hybrid Bermudagrass – DT-1							
Deficit	Optimum	0.610	0.678	0.670	0.562	0.348	0.271	0.252	0.484
	Short	0.593	0.639	0.617	0.495	0.289	0.206	0.204	0.435
Moderate	Optimum	0.543	0.598	0.627	0.641	0.667	0.646	0.617	0.620
	Short	0.546	0.540	0.529	0.531	0.547	0.543	0.542	0.540
High	Optimum	0.635	0.663	0.654	0.675	0.679	0.668	0.654	0.661
	Short	0.484	0.523	0.473	0.420	0.473	0.490	0.521	0.484
		***P*-values**							
Grass type (G)		*0.056*	***0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
Irrigation rate (I)		*0.388*	***0.009***	*0.196*	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
Mowing height (M)		*0.120*	*0.154*	*0.066*	*0.100*	***0.004***	***0.008***	***0.022***	***0.023***
G x I		*0.219*	***0.008***	***0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***0.001***
G x M		***0.006***	***0.020***	***0.007***	***<0.001***	***0.007***	***0.018***	*0.180*	***0.006***
I x M		*0.538*	*0.478*	*0.397*	*0.471*	*0.105*	*0.060*	*0.131*	*0.225*
G x I x M		*0.230*	*0.088*	*0.153*	***0.029***	*0.117*	*0.285*	*0.534*	*0.172*

Table 1-4. Visual turf quality ratings (on a scale of 1-9, with 9 being the best) for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for glasshouse studies in 2020 and 2021. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

		Day of Study and Date										
		-4	11	51		14	19	26	35	42	47	
		-----2020-----				-----2021-----						
Irrigation Rate	**Mowing Height**	2/6	2/21	4/1	Avg.	8/11	8/16	8/23	9/1	9/8	9/13	Avg.
		Kentucky Bluegrass – Blend of cultivars										
Deficit	Optimum	4.4	4.1	1.0	3.2	7.0	4.8	3.3	2.8	2.0	1.3	2.8
	Short	4.0	2.4	1.3	2.5	6.0	4.8	3.3	2.8	2.0	1.5	3.5
Moderate	Optimum	4.5	4.3	1.9	1.9	7.5	7.0	6.8	6.5	6.0	4.5	6.4
	Short	3.9	2.5	1.0	1.0	6.8	5.8	5.3	4.3	3.8	3.0	4.8
Excessive	Optimum	4.8	4.8	2.5	2.5	8.3	8.3	8.8	8.0	7.8	7.8	8.1
	Short	3.3	2.6	1.5	1.5	7.5	7.8	7.3	6.8	6.0	5.5	6.8
		Hybrid Bermudagrass – NorthBridge										
Deficit	Optimum	4.3	5.9	3.8	3.8	8.5	8.0	5.8	3.3	2.3	1.3	4.8
	Short	3.5	4.4	4.8	4.8	7.3	7.3	6.3	3.5	2.5	1.8	4.8
Moderate	Optimum	4.6	7.0	6.9	6.9	8.0	8.5	8.0	8.3	8.3	8.0	8.2
	Short	4.3	5.3	5.8	5.8	7.8	7.8	7.3	7.3	7.3	7.3	7.4
Excessive	Optimum	5.0	6.5	7.6	7.6	8.5	8.5	8.5	8.8	8.8	8.8	8.6
	Short	4.4	5.6	6.5	6.5	7.8	7.5	7.3	7.0	7.0	6.5	7.2
		Hybrid Bermudagrass – DT-1										
Deficit	Optimum	2.9	5.6	3.6	3.6	8.3	7.3	4.0	2.5	2.3	1.5	4.3
	Short	3.1	4.5	5.4	4.0	7.8	7.3	5.0	3.5	2.3	1.3	4.5
Moderate	Optimum	4.3	6.5	8.0	6.3	8.0	8.3	8.5	8.8	8.8	8.0	8.4
	Short	2.6	4.1	6.8	4.5	7.0	7.0	7.5	7.5	7.5	7.3	7.3
Excessive	Optimum	3.5	6.3	7.9	5.9	8.5	8.3	9.0	9.0	8.5	8.3	8.6
	Short	2.8	4.3	6.6	4.5	7.8	7.5	7.5	7.3	7.5	7.3	7.5
		***P*-values**										
Grass type (G)		*0.169*	*0.591*	***0.022***	*0.107*	***0.002***	***<0.001***	***<0.001***	***0.005***	*0.125*	***0.006***	***<0.001***
Irrigation rate (I)		*0.448*	*0.101*	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
Mowing height (M)		***0.002***	***<0.001***	*0.052*	*0.060*	*0.824*	*0.567*	***0.010***	***0.001***	***0.007***	***<0.001***	***0.003***
G x I		*0.625*	*0.605*	***<0.001***	*0.092*	***0.006***	***<0.001***	***<0.001***	***0.001***	***<0.001***	***<0.001***	***<0.001***
G x M		*0.900*	*0.569*	*0.842*	*0.604*	*0.951*	*0.230*	*0.247*	***0.030***	*0.333*	***0.043***	*0.216*
I x M		*0.415*	*0.629*	***<0.001***	***0.017***	*0.706*	*0.720*	***0.025***	***<0.001***	***0.001***	***<0.001***	***0.003***
G x I x M		*0.425*	*0.676*	*0.568*	*0.474*	*0.403*	*0.495*	*0.551*	*0.352*	*0.707*	*0.409*	*0.697*

Table 1-5. Forward-looking infrared (FLIR) canopy temperatures (°C) for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2020. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

		Day of Study and Date						
		16	23	30	37	44	51	
Irrigation Rate	**Mowing Height**	2/26	3/4	3/11	3/18	3/25	4/1	Avg.
		Kentucky Bluegrass – Blend of cultivars						
Deficit	Optimum	31.1	35.3	29.3	33.6	33.3	34.8	32.9
	Short	30.9	35.7	29.1	32.7	33.1	35.1	32.7
Moderate	Optimum	31.1	32.0	27.2	29.8	29.7	30.6	30.1
	Short	31.4	33.8	29.1	31.5	31.6	31.2	31.4
High	Optimum	29.2	30.6	27.9	30.8	30.4	29.9	29.8
	Short	30.7	32.8	29.0	31.4	30.7	30.3	30.8
		Hybrid Bermudagrass – NorthBridge						
Deficit	Optimum	30.5	32.3	28.6	31.9	32.3	34.5	31.7
	Short	30.7	34.1	30.9	34.0	33.4	32.5	32.6
Moderate	Optimum	27.8	30.2	29.7	32.5	33.0	31.9	30.8
	Short	32.0	34.0	28.9	31.3	31.7	32.0	31.7
High	Optimum	31.2	31.4	28.3	29.4	30.4	31.7	30.4
	Short	32.5	34.0	28.6	30.6	30.2	31.6	31.2
		Hybrid Bermudagrass – DT-1						
Deficit	Optimum	32.1	35.7	29.2	32.0	32.4	35.3	32.8
	Short	30.9	33.8	29.9	32.0	32.3	34.5	32.2
Moderate	Optimum	31.1	32.1	27.7	29.2	29.8	30.9	30.1
	Short	32.7	33.1	28.3	30.3	30.1	31.1	30.9
High	Optimum	30.1	31.6	28.6	30.8	30.7	31.2	30.5
	Short	32.7	32.4	28.1	30.3	30.1	31.7	30.8
		***P*-values**						
Grass type (G)		***0.001***	***<0.001***	*0.352*	***0.042***	*0.108*	*0.051*	*0.216*
Irrigation rate (I)		*0.885*	***<0.001***	*0.053*	***0.003***	***<0.001***	***<0.001***	***<0.001***
Mowing height (M)		*0.216*	*0.094*	*0.472*	*0.938*	*0.620*	*0.362*	*0.460*
G x I		*0.062*	***0.014***	*0.431*	*0.203*	*0.165*	*0.072*	*0.229*
G x M		*0.060*	*0.384*	*0.411*	*0.402*	*0.780*	*0.715*	*0.872*
I x M		***0.030***	***0.015***	*0.588*	*0.897*	*0.895*	*0.295*	*0.181*
G x I x M		*0.170*	*0.800*	*0.173*	*0.269*	*0.436*	*0.929*	*0.693*

Table 1-6. Forward-looking infrared (FLIR) canopy temperatures (°C) for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2021. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

		Day of Study and Date							
		2	9	21	28	35	42	47	
Irrigation Rate	**Mowing Height**	7/30	8/6	8/18	8/25	9/1	9/8	9/13	Avg.
		Kentucky Bluegrass – Blend of cultivars							
Deficit	Optimum	31.2	36.9	25.2	36.9	32.0	29.4	33.6	32.1
	Short	30.4	36.6	26.6	36.6	30.7	27.9	31.0	31.4
Moderate	Optimum	30.5	33.5	25.0	34.9	29.7	27.0	31.8	30.3
	Short	30.7	33.0	25.4	35.0	30.1	26.7	31.3	30.3
High	Optimum	30.7	33.5	23.9	32.4	28.0	26.3	30.1	29.3
	Short	31.0	32.6	25.0	32.6	27.5	25.6	29.6	29.1
		Hybrid Bermudagrass – NorthBridge							
Deficit	Optimum	32.4	36.1	24.0	36.5	31.2	29.8	33.5	31.9
	Short	31.4	34.5	26.3	34.8	31.7	28.7	31.8	31.3
Moderate	Optimum	32.7	34.2	25.7	32.7	29.0	26.7	30.2	30.2
	Short	31.3	34.9	25.5	33.3	29.1	27.4	30.7	30.3
High	Optimum	32.1	34.8	24.0	32.1	28.8	27.2	30.8	30.0
	Short	32.3	32.9	25.3	32.0	28.1	26.4	28.9	29.4
		Hybrid Bermudagrass – DT-1							
Deficit	Optimum	33.0	35.4	24.5	37.0	31.4	29.4	33.2	32.0
	Short	32.4	35.3	24.7	35.8	30.5	28.6	32.7	31.4
Moderate	Optimum	31.6	33.4	25.7	31.6	29.9	27.2	29.0	29.8
	Short	31.7	35.3	24.3	33.1	29.8	28.1	31.8	30.6
High	Optimum	31.2	32.7	25.8	30.9	28.0	25.5	28.5	28.9
	Short	32.2	33.6	24.0	32.1	28.3	27.2	29.3	29.5
		***P*-values**							
Grass type (G)		*0.494*	*0.391*	*0.148*	*0.174*	*0.141*	*0.423*	*0.305*	*0.091*
Irrigation rate (I)		*0.721*	***<0.001***	*0.280*	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
Mowing height (M)		*0.066*	*0.244*	*0.600*	*0.256*	*0.867*	*0.336*	*0.743*	*0.638*
G x I		*0.752*	*0.095*	*0.445*	*0.091*	*0.370*	*0.749*	*0.440*	*0.623*
G x M		*0.790*	*0.614*	*0.388*	*0.730*	*0.245*	*0.110*	*0.298*	*0.420*
I x M		*0.382*	*0.245*	*0.108*	***0.044***	*0.587*	*0.071*	***0.042***	*0.060*
G x I x M		*0.954*	*0.752*	*0.825*	*0.731*	*0.585*	*0.661*	*0.820*	*0.848*

Table 1-7. Shoot height, root and shoot biomass, root depth, and shoot-to-root ratio for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2020. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

Irrigation Rate	Mowing Height	Shoot Height	---------- Biomass ---------- Shoot	Root	Total	Root Depth	Shoot: Root
		cm	g	g	g	cm	
		Kentucky Bluegrass – Blend of varieties					
Deficit	Optimum	0.8	2.1	0.2	2.3	15.4	10.5
	Short	0.4	1.7	0.2	1.9	19.4	10.9
Moderate	Optimum	1.7	2.5	0.2	2.7	16.7	11.8
	Short	0.5	2.0	0.2	2.2	16.2	13.2
High	Optimum	1.6	2.3	0.3	2.6	16.7	8.5
	Short	1.2	1.8	0.1	2.0	17.1	13.7
		Hybrid Bermudagrass – NorthBridge					
Deficit	Optimum	1.6	3.1	0.7	3.8	28.1	4.2
	Short	1.9	2.6	0.7	3.3	31.6	3.5
Moderate	Optimum	2.8	3.8	1.2	5.0	26.1	3.1
	Short	1.7	3.8	1.1	4.9	29.4	3.3
High	Optimum	2.3	4.3	1.4	5.7	24.6	3.1
	Short	1.8	3.4	1.2	4.6	24.8	2.8
		Hybrid Bermudagrass – DT-1					
Deficit	Optimum	1.3	3.0	0.8	3.8	25.6	3.8
	Short	1.7	3.4	0.8	4.3	25.9	4.2
Moderate	Optimum	2.8	4.7	0.8	5.5	27.8	5.8
	Short	1.9	2.8	0.6	3.4	27.4	4.8
High	Optimum	2.9	3.7	0.6	4.3	27.7	5.7
	Short	1.8	5.3	0.6	6.0	28.0	8.3
		***P*-values**					
Grass type (G)		***<0.001***	***0.016***	***0.007***	***<0.001***	***<0.001***	***<0.001***
Irrigation rate (I)		***<0.001***	***0.002***	*0.262*	***<0.001***	*0.605*	*0.148*
Mowing height (M)		***<0.001***	*0.138*	*0.322*	*0.072*	*0.218*	*0.242*
G x I		*0.059*	*0.238*	***0.022***	*0.099*	*0.175*	*0.105*
G x M		*0.542*	*0.398*	*0.999*	*0.414*	*0.638*	*0.493*
I x M		***<0.001***	*0.125*	*0.789*	*0.110*	*0.621*	*0.430*
G x I x M		***0.033***	***0.003***	*0.954*	***0.002***	*0.889*	*0.532*

Table 1-8. Shoot height, biomass (root, shoot, and thatch), root depth, and shoot-to-root ratio for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2021. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

Irrigation Rate	Mowing Height	---------------- Biomass ---------------- Shoot	Root	Thatch	Total	Root Depth	Shoot: Root
		g	g	g	g	cm	
		Kentucky Bluegrass – Blend of cultivars					
Deficit	Optimum	5.0	0.4	201.8	207.3	8.9	12.0
	Short	4.8	0.2	180.2	185.2	5.0	23.0
Moderate	Optimum	4.2	0.3	144.0	148.5	10.8	15.5
	Short	5.1	0.2	164.2	169.4	7.6	31.8
High	Optimum	5.8	0.3	100.2	106.3	9.4	16.6
	Short	4.3	0.2	132.6	137.1	8.9	25.9
		Hybrid Bermudagrass – NorthBridge					
Deficit	Optimum	1.6	1.2	6.1	8.9	15.4	1.3
	Short	1.0	0.4	6.7	8.1	13.1	2.1
Moderate	Optimum	1.8	1.1	5.0	7.8	20.8	1.6
	Short	1.1	0.9	8.1	10.0	14.6	1.2
High	Optimum	1.0	0.7	5.4	7.1	18.8	1.4
	Short	1.0	2.6	6.1	9.7	14.6	0.4
		Hybrid Bermudagrass – DT-1					
Deficit	Optimum	1.1	0.7	1.3	3.0	15.6	1.6
	Short	1.0	0.4	2.1	3.5	16.6	2.9
Moderate	Optimum	1.0	1.0	1.4	3.4	15.3	1.0
	Short	1.1	0.8	2.6	4.5	17.2	1.4
High	Optimum	1.4	1.3	2.8	5.5	16.3	1.1
	Short	0.8	0.8	2.0	3.6	14.3	1.1
		***P*-values**					
Grass type (G)		***<0.001***	***0.015***	***<0.001***	***<0.001***	***<0.001***	***0.005***
Irrigation rate (I)		*0.996*	*0.371*	*0.128*	*0.142*	*0.233*	*0.558*
Mowing height (M)		*0.387*	*0.794*	*0.680*	*0.711*	***0.025***	*0.165*
G x I		*0.963*	*0.757*	*0.088*	*0.091*	*0.698*	*0.618*
G x M		*0.949*	*0.519*	*0.902*	*0.906*	*0.143*	*0.152*
I x M		*0.679*	*0.351*	*0.726*	*0.728*	*0.947*	*0.599*
G x I x M		*0.724*	*0.250*	*0.870*	*0.885*	*0.594*	*0.712*

Table 1-9. Volumetric water content (VWC) values for Kentucky bluegrass, NorthBridge hybrid Bermudagrass, and DT-1 hybrid Bermudagrass at deficit, moderate, or high irrigation rates mowed at optimum or short heights for a glasshouse study in 2021. *P*-values are shown by *italics* with significance with an 0.05 alpha indicated by **bold-face** type.

		Day of Study and Date									
		16	21	26	30	33	37	40	44	48	
Irrigation Rate	**Mowing Height**	8/13	8/18	8/23	8/27	8/30	9/3	9/6	9/10	9/14	Avg.
		Kentucky Bluegrass – Blend of cultivars									
Deficit	Optimum	9.0	5.5	4.5	3.5	3.1	4.1	2.7	4.9	1.7	4.3
	Short	8.0	5.5	4.7	2.9	3.6	4.3	3.5	5.2	2.1	4.4
Moderate	Optimum	12.6	8.7	7.5	6.9	6.2	7.0	5.6	6.5	3.4	7.1
	Short	14.4	10.8	9.2	8.0	7.3	8.6	7.0	6.7	5.6	8.6
High	Optimum	21.4	19.3	18.3	16.3	16.3	17.5	16.9	15.7	15.7	17.5
	Short	21.4	18.5	18.3	18.6	17.0	17.5	17.2	18.0	16.5	18.1
		Hybrid Bermudagrass – NorthBridge									
Deficit	Optimum	7.5	4.5	3.7	3.3	3.1	3.5	2.5	5.1	2.5	3.9
	Short	6.5	5.2	5.8	3.1	2.9	3.6	3.6	5.2	2.3	4.2
Moderate	Optimum	11.2	10.2	9.0	11.4	7.3	6.3	5.9	6.6	5.4	8.1
	Short	10.4	9.6	8.8	8.1	8.8	8.0	7.9	7.9	6.7	8.4
High	Optimum	15.2	15.2	15.6	15.4	16.5	17.6	15.5	12.3	14.2	15.3
	Short	12.0	12.4	13.5	14.1	13.6	13.6	15.3	14.8	12.3	13.5
		Hybrid Bermudagrass – DT-1									
Deficit	Optimum	6.6	5.1	3.7	2.9	3.0	2.8	2.6	5.3	1.7	3.7
	Short	7.1	4.4	3.2	2.8	2.7	3.6	2.7	4.8	1.8	3.7
Moderate	Optimum	9.4	8.8	9.6	6.5	6.2	6.3	5.0	5.8	3.8	6.8
	Short	8.2	8.2	7.0	6.0	6.3	5.8	5.0	6.4	3.4	6.3
High	Optimum	11.4	12.2	12.5	13.7	10.9	11.7	11.7	11.2	10.2	11.7
	Short	12.4	12.5	10.9	12.6	12.8	12.6	11.5	10.2	10.0	11.7
		***P*-values**									
Grass type (G)		***<0.001***	***0.002***	***0.014***	*0.101*	***0.015***	***0.004***	***0.005***	***0.033***	***0.006***	***<0.001***
Irrigation rate (I)		***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
Mowing height (M)		*0.397*	*0.568*	*0.519*	*0.608*	*0.650*	*0.844*	*0.298*	*0.309*	*0.767*	*0.924*
G x I		***<0.001***	***0.011***	***0.007***	*0.185*	*0.061*	*0.130*	*0.065*	***0.025***	***0.020***	***0.008***
G x M		*0.354*	*0.724*	*0.258*	*0.423*	*0.662*	*0.605*	*0.765*	*0.623*	*0.676*	*0.666*
I x M		*0.822*	*0.668*	*0.450*	*0.889*	*0.740*	*0.393*	*0.710*	*0.759*	*0.615*	*0.839*
G x I x M		*0.472*	*0.601*	*0.662*	*0.844*	*0.460*	*0.375*	*0.995*	*0.879*	*0.877*	*0.868*

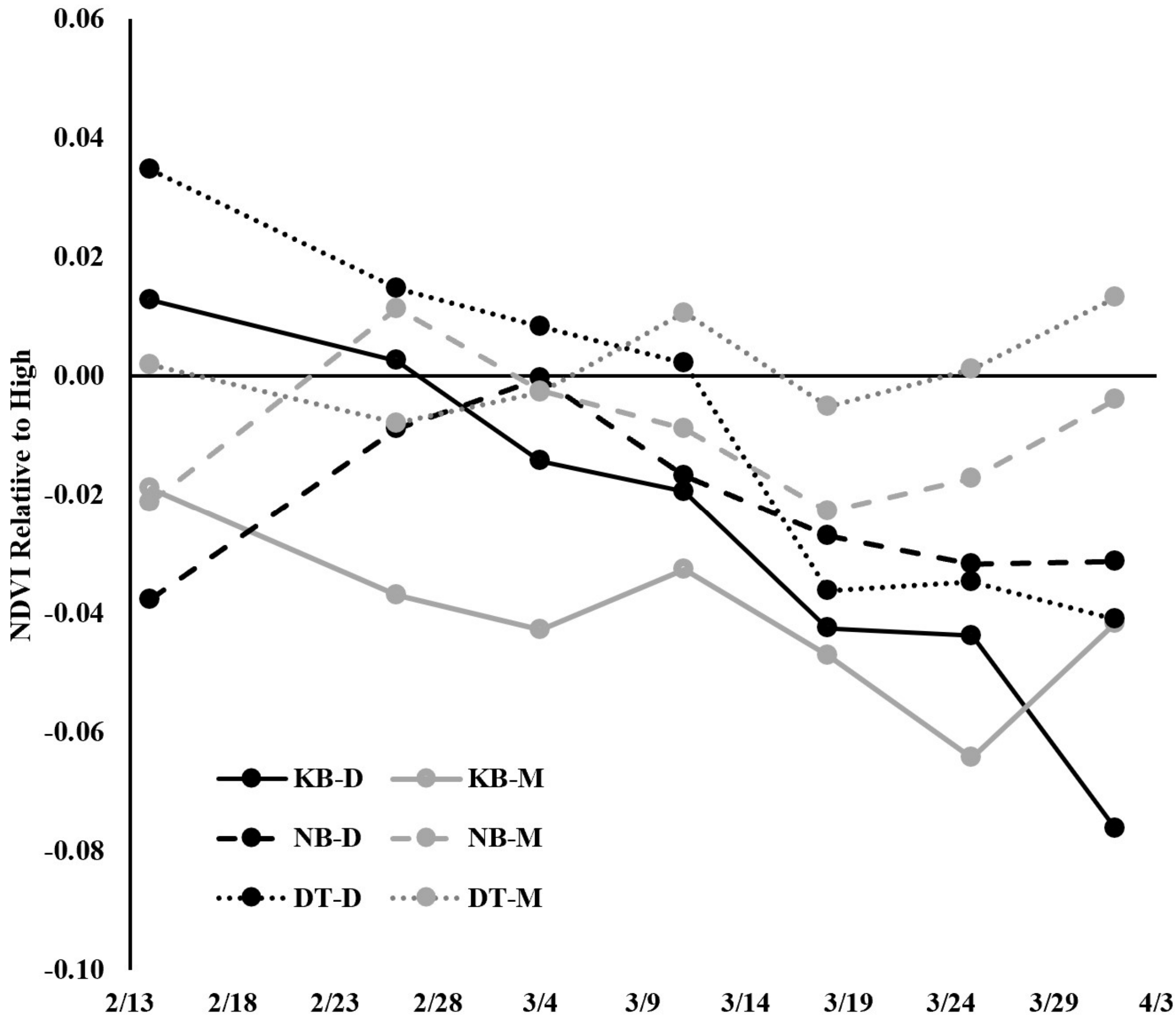

Figure 1-a. Change in relative Normalized Difference Vegetation Index (NDVI) values for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at deficit (-D) and moderate (-M) irrigation rates relative to the high rate (control) for each grass for a glasshouse study in 2020.

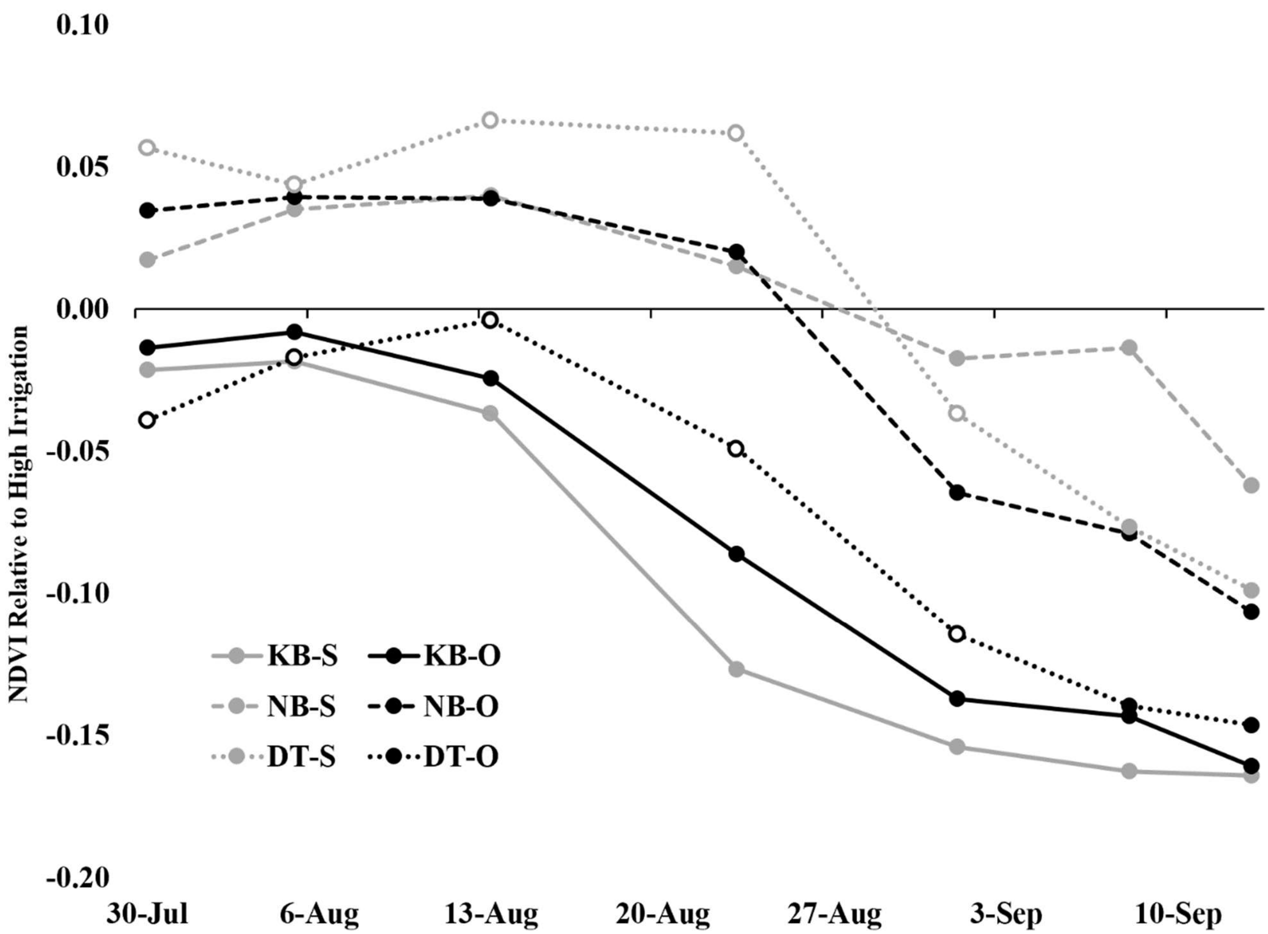

Figure 1-b. Change in Normalized Difference Vegetation Index (NDVI) values for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at short (-S) and optimum (-O) mowing heights relative to the high irrigation rates (control) for each grass for a glasshouse study in 2021. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments.

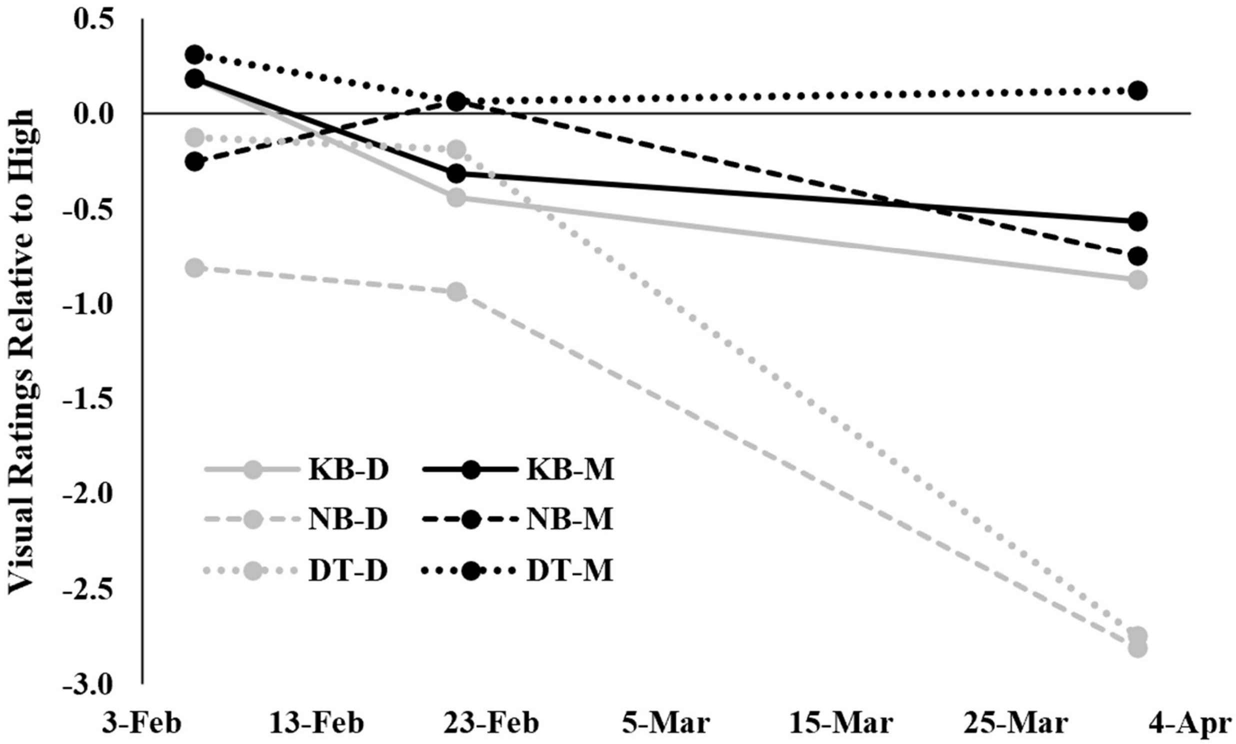

Figure 1-c. Change in relative visual turf quality ratings for Kentucky bluegrass (KB), NorthBridge hybrid Bermudagrass (NB), and DT-1 hybrid Bermudagrass (DT) at deficit (-D) and moderate (-M) irrigation rates relative to the high rate (control) for each grass for a glasshouse study in 2020.

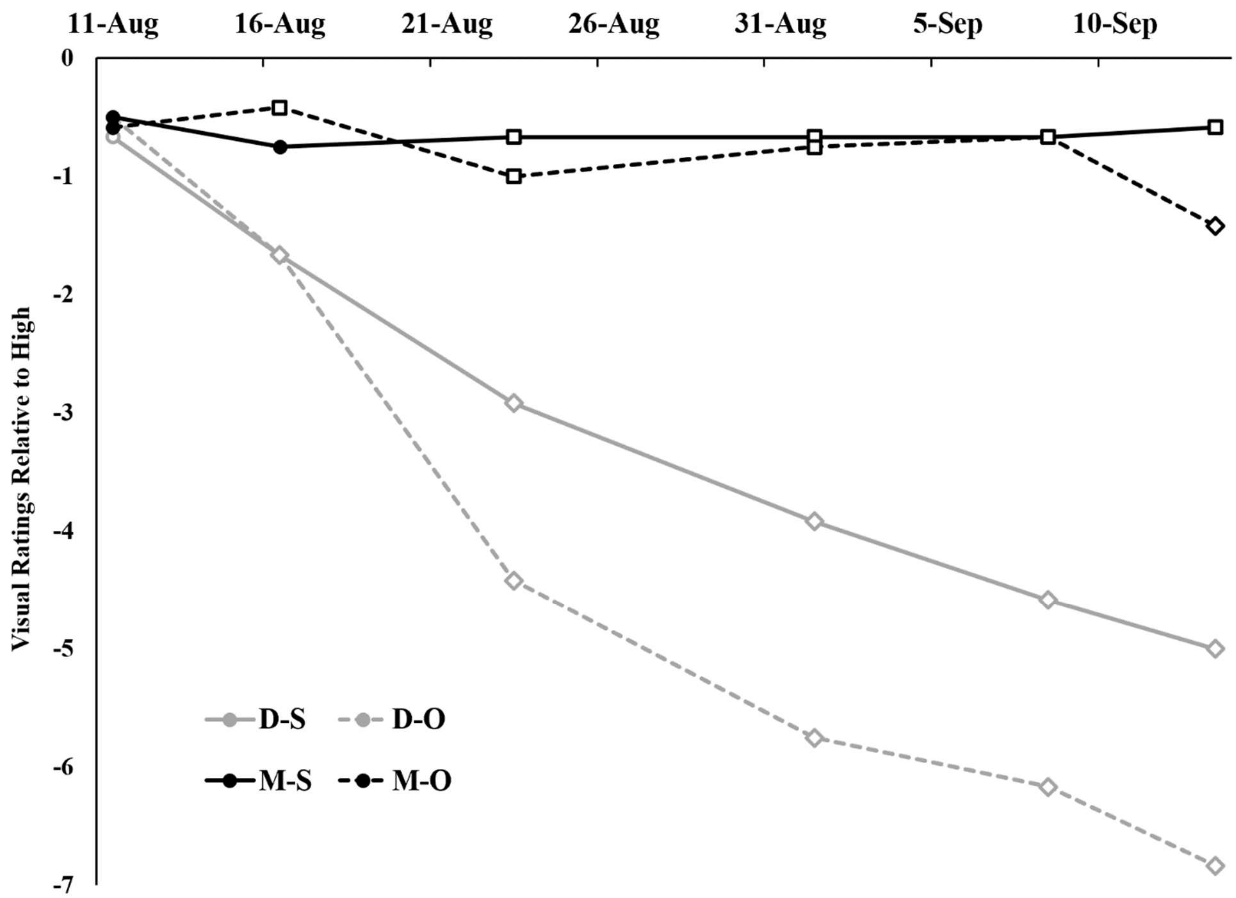

Figure 1-d. Change in visual turf quality ratings at short (-S) and optimum (-O) mowing heights and deficit (D) and moderate (M) irrigation rates relative to the high rate (control) for each grass for a glasshouse study in 2021. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments.

CHAPTER 2

Cynodon dactylon (L.) Pers. × *Cynodon transvaalensis* Burtt Davy and *Poa pratensis* L. Response to Deficit Irrigation in a Semi-Arid, Cool Season Climate

Hanna R. Burgin[1], Glenl A. Wear[2], Neil C. Hansen[1], Bryan G. Hopkins[1]
[1]Department of Plant and Wildlife Sciences, Brigham Young University, Provo, UT
[2]Grounds Department, Brigham Young University, Provo, UT
Master of Science

ABSTRACT

As average global temperatures rise, cool-season C_3 grasses, such as the most commonly grown Kentucky bluegrass (*Poa pratensis* L.; KBG), struggle to tolerate extreme summer heat and require more of increasingly scarce water. Triploid interspecific hybrid Bermudagrass (*Cynodon dactylon* [L.] Pers. × *Cynodon transvaalensis* Burtt Davy; HBG) is a warm-season C_4 grass that may be increasingly more suited for northern ecosystems traditionally classified as transitional or cool-season climates. This C_4 grass has been successfully grown for a decade in Provo, UT, USA, an area in a traditionally cool-season zone, and is being considered for more widespread use in this and other similar regions. The objective of this study is to evaluate two HBG cultivars (‘Tahoma 31’ and ‘Latitude 36’) compared to a blend of KBG cultivars when subjected to deficit, moderate, and high irrigation for impacts on soil moisture and canopy health, temperature, and growth. These grasses were field evaluated during two dry-down periods (3-4 weeks) in 2021 in a randomized complete block, full factorial design with three replications per treatment at conducted in Provo, UT, USA. Although there were no variable impacts of irrigation for plant growth in these short-term dry-down periods, deficit irrigated KBG had increased canopy temperature and decreased NDVI, visual turf quality, and percent cover than all other treatments, including moderate and high KBG. However, the deficit irrigated

HBG cultivars were not impacted. Soil volumetric water content data suggest that KBG used more water than HBG. These data indicate that HBG could provide a water-saving turfgrass alternative to KBG, especially in regions with increasing water scarcity.

INTRODUCTION

The Intermountain West (IMW) of the USA is generally an arid/semi-arid, cool-season region is the area in which the study described herein is based. Weather data shows that this area is experiencing a mega-drought and increasing average temperatures over the last several decades. For example, Salt Lake City, UT, USA, which is just north of the study site and shares a similar climate, has seen an upward trend over the last century (Fig. 1-1). Climate modeling projections suggest that the IMW will experience more frequent droughts and heat waves, reduced snowpack in the mountains, and earlier snowmelt (Carter and Culp, 2010; Harpold et al., 2012; Mote et al., 2005; Pachauri and Meyer, 2014; Saunders and Maxwell, 2005; Wang and Gillies, 2012). Although predictions are complex and uncertain, Saunders and Maxwell (2005) estimate that as early as 2039 the temperature may raise by 1°C, while precipitation levels drop 3%, snowpack levels drop 24%, runoff drop by 14%, and water storage drop by 36%. Such changes will make water supplies more strained for natural, agricultural, and municipal use (Carter and Culp, 2010; Harpold et al., 2012; Saunders and Maxwell, 2005).

In addition, the IMW region has seen tremendous population growth. Between the 1970s and the early 2000s, the population of the Rocky Mountain West region alone grew by nine million people, which lead to significant urban development and the loss of natural ecosystems (Carruthers and Vias, 2005; St. Hilaire et al., 2008). Five megaregional urban centers have developed from this growth in the IMW and it is expected that each of these regions will house over 10 million citizens by 2050, and the Colorado River, which supplies water to many of these major urban centers, is already dry before it reaches the Gulf of California (Carter and Culp, 2010). As populations grow and the IMW region becomes warmer and drier, the need to conserve water is increasingly crucial.

With increased urbanization in the United States, grass is quickly growing as the principle managed land cover. Turfgrass provides many benefits to society in addition to beautifying landscapes. In contrast to synthetic grass surfaces, properly managed grass minimizes injuries to users by creating a surface that allows cushioning and footing stability while moderating temperatures (Christensen et al., 2012; Jastifer et al., 2019; Monteiro, 2017; Petrass et al., 2015; U.S. National Park Service, 2018). Vegetated urban landscapes also support environmental processes through sequestration of carbon, generation of oxygen, degrading xenobiotics, minimizing soil erosion, improving soil health, cleaning dust and pollutants from the atmosphere, recharging groundwater, reducing wildfire threats, providing habitat, reducing chemical leaching and runoff to surface and groundwater (Beard and Green, 1994; Monteiro, 2017; U.S. National Park Service, 2018; Wentz et al., 2016). Turfgrass can directly benefit humans in urban areas by providing low-cost playing surfaces and spaces for entertainment and recreation, improving physical and mental health, and reducing allergens, glare, temperatures, noise pollution, and nuisance animal pests (Monteiro, 2017).

Despite its benefits, grasses have been brought under scrutiny due to high water demand, particularly in regions where water is increasingly scarce (Romero and Dukes, 2014; St. Hilaire et al., 2008; Svedin et al. 2021; Wherley et al., 2014; Wentz et al., 2016). Grass requires a considerable amount of irrigation water, a resource that is increasingly scarce in these regions. Landscape irrigation often comprises 30-70% of a household's annual water use and most homeowners use significantly more water than necessary to irrigate their lawns (Romero and Dukes, 2014; St. Hilaire et al., 2008; Wherley et al., 2014; Wentz et al., 2016). The amount of water required by a grass depends on various factors, which influence its evapotranspiration (ET) rate. Cool-season grasses, those that thrive between 15 and 24°C, have ET rates of 3-8 mm d^{-1} with a maximum of 7-10+ mm d^{-1} (Beard and Beard, 2005; Huang, 2008; Hatfield, 2017). Warm-season grasses, which prefer temperatures between 24 and 32°C, tend to be more water-efficient with general ET rates of 2-5 mm d^{-1} with a maximum of 6-10 mm d^{-1} (Beard and Beard, 2005; Huang, 2008; Hatfield, 2017). The ET rates can vary greatly within a single species, as cultivars may have different physical characteristics that impede or improve their ability to obtain or use water. The rates can also change depending on the surrounding environment (solar intensity, temperature, humidity, wind, soil type, and stand density) and management practices (nitrogen fertilization rates, mowing height and frequency, and traffic pressure) (Carroll et al., 2017; Huang and Fry, 2000; Huang, 2008; Wherley et al., 2014).

As climates become more arid, managers and homeowners need to improve water use efficiency. Implementing drought-tolerant or native plant species in landscapes can conserve water, but these options can be expensive or difficult to obtain (Carter and Culp, 2010; Hatfield, 2017; Huang and Fry, 2000). Fortunately, drought-tolerant grass has received significant attention in the recent past and efficient cultivars are easier to find.

The most commonly used lawn grass in the world, and especially in cool-season zones, is Kentucky bluegrass (*Poa pratensis* L.; KBG) (Christians et al., 2017). However, Kentucky bluegrass is a cool-season C_3 grass which requires a significant amount of water to remain functional, healthy, and visually appealing (Brede, 2000; Bushman et al., 2012; Jazi et al., 2019). This species thrives in the spring and fall when temperatures are moderate. Although some cool-season grasses can thrive under drought conditions, Kentucky bluegrass is generally classified as having moderate to low drought resistance (Aronson et al., 1987; Abraham et al., 2004). It can tolerate hot summer temperatures but may go dormant if water stressed and/or if temperatures become extreme (Jiang and Huang, 2000; Abraham et al., 2008). Such stresses can damage Kentucky bluegrass cell membranes and crucial photosynthetic components, as well as degrade chlorophyll (Abraham et al., 2004; Du et al., 2011; Jiang and Huang, 2000; Wang and Huang, 2004). In order for Kentucky bluegrass to recover from heat and drought it must be given a sufficient amount of irrigation (Wang and Huang, 2004).

Common Bermudagrass (*Cynodon dactylon*) and its triploid interspecific hybrid (*Cynodon dactylon* × *C. transvaalensis* Burtt Davy) are the most common warm-season C_4 lawn grasses and are known for having relatively low water requirements. Hybrid Bermudagrass cultivars are also popular in high traffic environments (such as sports fields) because they can thrive at very low mowing heights, establish or repair themselves quickly, and withstand significant wear (Pinnix and Miller, 2019). While experts still lack a complete understanding as to how Bermudagrass conserves water, proposed methods include the use of a deep, dense, efficient root system (Carrow, 1996; Fu et al., 2004; Garrot Jnr and Mancino, 1994; Husmoen et al., 2012; Zhou et al., 2013), bulliform cells (Bizhani and Salehi, 2014), accumulation of specific metabolites (namely sugars, sugar alcohols, organic acids, and amino acids) (Du et al., 2011), and closing wax-protected stomata quickly in dry periods (Kim, 1987; Huang and Fry, 2000; Zhou et al., 2013). It has also been suggested that Bermudagrass employs different mechanisms depending on the soil depth, as root growth may be limited in shallow urban soils and the grass may resort to stomatal closure (Zhou et al., 2013).

The hybrid cultivar ‘Midlawn’ was able to maintain a good quality over two summers after receiving only enough irrigation to replenish 60% of ET (Fu et al., 2004). Similarly, a few fine-textured, sports-type cultivars were acceptable after receiving equal to only 10-15% of ET (Wherley et al., 2014). Some cultivars are so drought-tolerant that they can recover from a 55 or 90 d drought in less than two weeks (Severmutlu et al., 2011; Steinke et al., 2011).

The ET rates of Bermudagrass tend to be 6-7 mm d^{-1} whereas Kentucky bluegrass can often require more than 10 mm d^{-1} despite being generally grown in cooler climates (Beard and Beard, 2004; Huang, 2008). Researchers found that the Kentucky bluegrass cultivar Brilliant® (PST-B2-42) required irrigation levels that replenished its full ET loss in order to maintain an acceptable grass quality, while other grass species [hybrid Bermudagrass (*C. dactylon* (L.) Pers. × *C. transvaalensis* Davy), zoysiagrass (*Zoysia japonica* Steud.), and tall fescue (*Festuca arundinacea* Schreb.)] could get by with significantly lower water levels (Fu et al., 2004). Jazi et al. (2019) conducted a similar experiment, with perennial ryegrass (*Lolium perenne*) instead of zoysiagrass, and found that Kentucky bluegrass was the most susceptible to water stress of the four species evaluated.

Despite its benefits, hybrid Bermudagrass cultivars have not been used in cool-season climate zones very commonly because most do not do well under prolonged freezing conditions in winter (Anderson and Taliaferro, 2002; Xiang et al., 2019). Some new hybrid cultivars are available that can withstand both cool and arid environments. Their ability to thrive in traditionally cool-season zones is increasing as climate change results in increasing average temperatures (Hatfield, 2017; Xiang et al., 2019). The hybrid Bermudagrass cultivars Hollywood™, Jackpot™, and Southern Star™ have been grown continuously (5 cm mowing height) with virtually no winter kill for over a decade at Brigham Young University in Provo, UT, USA, which is located in a cool-season zone (Bryan Hopkins, personal communication). Hybrid Bermudagrass cultivars with some cold tolerance will potentially allow continued use of lawn grasses but with less water consumption in cool-season regions.

As HBG and KBG have not been compared directly under identical, cool-season conditions, the objective of this study is to evaluate two field grown HBG cultivars compared to a blend of KBG cultivars in all combinations of deficit, moderate, and high irrigation rates evaluated for plant health (NDVI and visual turf quality), canopy temperature, water use, and shoot and root growth.

MATERIALS AND METHODS

Establishment

Two rounds of this study were conducted in an outdoor turfgrass plot at Brigham Young University in Provo, UT (40° 14′ 43″ N, 111° 38′ 29″ W, 1406 m above mean sea level). Prior to these studies, the grass was established as follows.

The study was established on an existing KBG field established in 2016 as sod laid over a constructed soil (45 cm of soil over a compacted subsoil base) from locally sourced quarry sand. The soil was a sandy loam soil (Table 2-1). The HBG was established in randomized blocks in two-thirds of the study area by killing the KBG with two applications of glyphosate, following label directions, in the spring of 2020. The HBG cultivars were established in the randomized blocks in early summer as ‘OKC 1119’ (Latitude 36™) , hereafter referred to as ‘Latitude 36’, in one-third of the plots and ‘OKC 1131’ (Tahoma 31™), hereafter referred to as ‘Tahoma 31’, in one-third of the plots amidst the plots with a blend of Kentucky bluegrass cultivars (‘3-Way Kentucky Bluegrass Blend’ [Arrowhead 39%, Rubio 39%, Blue Note 20%]).

Plots measured 1 x 1 m and each new grass type was separated from the next with a 0.6 m barrier of bare soil. Both HBG cultivars were planted vegetatively. Latitude 36 was obtained as 2.5 cm plugs, which were spaced 30 cm apart and planted to the depth of their roots on 10 June. Tahoma 31 was obtained as sod which was cut into strips ~8 cm long and ~2 cm wide, spaced 31 cm apart and planted to the depth of their roots on 10 July.

Best Management Practices were generally followed for soil, nutrient, water, and cultural management between establishment and the beginning of the study. The grass was mowed at approximately 5 cm during establishment about every 7 d with a rotary mower. The mowing height was gradually transitioned to a lower level with use of a reel mower 30 d prior to the beginning of the trial. During this phase the grass was mowed twice weekly at a height of 3.8 cm. Clippings were recycled in place during mowing. Fertilizer was added at a rate of 49 kg N ha^{-1}during establishment on each of the following dates: 15 November 2019 (ammonium sulfate 30-0-5), 16 July 2020 (Pro Prills 12-8-16-17[S]-3[Fe]; Simplot, Boise, ID, USA), 23 September 2020 (Pro Prills), and 20 April 2021 (25-5-10-3[Fe]-3[S]-0.03[Mn]-0.12[Zn]). GameOn™ (Corteva Agriscience, Wilmington, DE, USA) and SpeedZone® Southern (PBI/Gordon Corporation, Kansas City, MO) herbicides were applied at labeled rates on 22 July and 6 August 2021, respectively. Other than various weeds, there were no notable pest and pathogen pressure problems in the plot area. The grass was watered every day during the first month of establishment and then decreased to once every second day. Weather during the study time frame was mostly typical for this semi-arid region with low humidity (average ~20-30% relative humidity) and hot days and cool nights with minimal precipitation (Fig. 2-1).

Treatments

Treatments consisted of all combinations of the three grass types with three irrigation rates replicated three times and arranged in a randomized complete block, full factorial design (Fig. 2-2). Grass treatments consisted of HBG Latitude 36, HBG Tahoma 31, and KBG blend. Irrigation treatments included Deficit, Moderate, and High.

The study included two separate dry down periods throughout the summer of 2021, which were evaluated as separate studies. The dry down periods were 9 July to 17 August and 1 September to 22 September with ample irrigation for nearly full plant health recovery in between. The deficit irrigated KBG plots struggled to completely recover, although they were mostly so by the beginning of the second round. During the dry down periods, the irrigation levels were adjusted on a weekly basis based on the previous week's average reported ET_o (reference ET) according to an on-site weather station (ATMOS 41, METER Group, Pullman, WA, USA). During the first dry down period, irrigation treatments were initiated at 60, 80, or 100% of average ET_o. After 14 d, it was apparent that there were minimal moisture stress impacts, especially for the HBG cultivars, and, thus, irrigation rates were altered to 35, 70, or 100% until 25 d when the moderate irrigation level was lowered to 50%, as there were still no visual differences. For the remainder of this dry down, as well as for the entire second dry down period, the irrigation values were 35, 50, or 100% of average ET_o. While weekly rates varied, there were 0.569 and 0.246 mm total irrigation applied, ranges of 0.002-0.008 and 0.002-0.007 mm day^{-1}, and averages of 0.005 or 0.004 mm day^{-1} for the first and second studies, respectively. During the first dry down period, the lowest irrigation rate KBG plots appeared to be in severe stress and, thus, received supplemental irrigation of 4.2 mm on d 27 and 31 in order to avoid complete dormancy that would inhibit completion of the second round.

Irrigation was supplied via a buried PVC pipe system at 400 kPa pressure with a controller (ESP-Modular, Rain Bird, Azusa, CA, USA). The sprinkler heads (Pro-Spray PRS40, Hunter Industries, San Marcos, CA, USA) were located at each corner of each plot. Each sprinkler head was calibrated to do a quarter turn and throw the length of the plot (3 m) to assure minimal overlap with adjacent plots. Measurement were taken from the near center of each plot to avoid any contamination from adjacent plots. This system allows each plot to receive a unique irrigation rate (Fig. 2-2).

Measurements

Estimated soil volumetric water content (VWC), electrical conductivity (EC), and temperature were constantly monitored with sensors (GS3; METER Group, Pullman, WA, USA) installed 6 cm deep underneath every plot prior to establishing the KBG (EC and soil temperature data not shown). Estimated soil water potential (θ) was constantly monitored with sensors (MPS-6; METER Group, Pullman, WA, USA) installed at 6, 15, and 30 cm deep intervals underneath select plots (each Tahoma 31 treatment had one set of sensors; Fig. 2-3 and Fig. 2-a in Supplemental Materials) prior to KBG establishment. These data were collected every 1 h (EM50G Remote Loggers; Meter Group, Pullman, WA, USA). The VWC was also measured at the end of each dry down (Theta Probe ML3, Delta-T Devices, Cambridge, England).

The normalized difference vegetation index (NDVI) was measured for the first row of plots closest to the sensors on the south side of the plot area (Fig. 2-2 and Fig. 2-3) using pole mounted Spectral Reflectance (SRS) sensors (METER Group, Pullman, WA, USA). These data were collected every 1 h (EM50G Remote Loggers; Meter Group, Pullman, WA, USA). Additional NDVI measurements were taken every ~7 d in every plot with a handheld sensor passed directly overhead of every plot at mid-day (Trimble Handheld Greenseeker, Trimble

Agriculture, Sunnyvale, CA, USA). Other sensors were employed aboveground to capture canopy temperature (Apogee SI-421, Apogee Instruments, Logan, UT, USA), and local weather data (ATMOS 41, METER Group, Pullman, WA, USA). Canopy temperature was also assessed every ~7 d in every plot with a handheld sensor passed directly overhead of every plot at mid-day (FLIR E6 thermal imaging camera, FLIR, Wilsonville, OR, USA).

Percent cover was evaluated ~7 d in every plot with a smartphone app using a camera passed directly overhead of every plot (Canopeo, Oklahoma State University Department of Plant and Soil Sciences, Stillwater, OK, USA). Visual turf quality ratings (verdure) were evaluated every ~7 days on a scale from 1-9, with 9 being perfect turf quality and 1 being dead.

Rooting depth and shoot and root biomass were measured at the end of the second round of the study on 28 September 2021 by using a Mascaro MPS1-S Soil Profiler Sampler (Turf-Tec, Tallahassee, FL, USA) to obtain samples. Root, shoot, and thatch biomass were determined after drying at 105 °C in a forced air oven until the biomass reached a constant weight. Shoot to root ratio was calculated by dividing the shoot mass by the root mass.

Statistical significance for each measurement was determined by Analysis of Variance with mean separation by the Tukey-Kramer method (JMP software, Cary, NC, USA).

RESULTS

NDVI

With regard to the hand-held NDVI sensor data (see Fig. 2-b in Supplemental Materials for pole mounted sensor data), irrigation rate was significant for the later half and the average for the first round and for the entire second round (Table 2-2). The effect was variable with a significant interaction between grass type and irrigation rate at $P<0.10$ for all of the dates but two as well as the averages. When comparing NDVI relative to the high irrigation rate for each grass type, by the last two dates of the first study and for all but the first date of the second study, plant health, as measured by NDVI, for deficit irrigated KBG-b was lower than all other treatments, including the moderate irrigation for KBG-b (Fig. 2-4). Neither deficit irrigated HBG cultivar showed a significant difference from their high counterparts in either dry down round. There were general differences between grass types as well, although these are a natural result of inherent physiology differences between species and cultivars and are not related to the objectives of this study.

Visual Ratings (Verdure)

For visual turf quality ratings, the irrigation rate was significant for the first and last assessments for the first round and for the entire second round, as well as the averages of both (Table 2-3). Similar to NDVI, the effect was largely variable with significant grass type x irrigation rate interactions (Table 2-3). However, these were only measured during the later half of the second round of the study, as well as the overall average for that round. When comparing verdure relative to the high irrigation rate for each grass type, deficit irrigated KBG-b was significantly lower than all other treatments on the last three dates of the second study, except for moderate KBG-b on day 9 (Fig. 2-5). Even though not significant, there were similar trends in the first study (Table 2-3).

Canopy Temperature

With regard to the hand-held canopy sensor data (see Appendix for pole mounted sensor data), the effects were similar as NDVI and verdure. Irrigation rate was significant for the last reading and and the average for the first round and for the entire second round (Table 2-4). As with NDVI, the effect was variable with a significant interaction of grass type with irrigation rate on the final day of the first study and for the entire second study and its average. When comparing canopy temperature relative to the high irrigation rate for each grass type, deficit irrigated KBG-b was significantly warmer than all other treatments for the last day of the first round (Fig. 2-6). Deficit irrigated KBG-b had higher canopy temperature than all other treatments for the second round besides moderate KBG-b on the first and last date (Fig. 2-6). Canopy temperature for the HBG cultivars were similar regardless of irrigation rate. There were canopy temperature differences across grass types independent of irrigation but, again, these are likely related to fundamental physiological differences not related to the objectives of this study.

Percent Cover (Grass Plant Density)

For percent cover, the irrigation rate was significant (at alpha level of 0.10) for the last two assessments for the first round and for the entire second round, as well as the average of both rounds (Table 2-4). Similar to canopy temperature and plant health, the results were variable by grass type with a significant interaction with irrigation rate on the last date of the first study and for the entire second study, including the average (Table 2-5). When comparing percent cover relative to the high irrigation rate for each grass type, deficit irrigated KBG-b was significantly lower than all other values, including both moderate and high KBG-b for these dates (Fig. 2-7). Note again that the deficit irrigated KB-b started out at lower health than the other treatments due to carry over effects from the first round. However, it is notable that it continued to decline in percent cover with time due to deficit irrigation when the HBG cultivars never had a reduction in canopy density relative to their counterparts receiving high irrigation rates.

Shoot & Root Growth

Neither irrigation nor the irrigation x grass type interaction were significant for any root or shoot measures (Table 2-6). As expected, there were differences across grass types. The shoot, thatch, and total biomass of KBG-b were significantly smaller than either HBG cultivar, with values nearly half the mass (Fig. 2-9). For shoot-to-root ratio, Tahoma 31 was significantly greater than Latitude 36 and KBG-b with an average nearly twice as large. Surprisingly, there were no significant differences for root mass or root depth.

Volumetric Water Content (VWC)

With regard to the hand-held soil VWC sensor data (see Fig. 2-c in Supplemental Materials for buried sensor data), the volumetric water content was significant for irrigation rate x grass type for both rounds (Table 2-7). There were no differences observed between the HBG cultivars at any irrigation level (Fig. 2-8). The VWC for deficit and moderate irrigated KBG-b were significantly lower than when receiving a high rate of irrigation in both rounds of the study. In contrast, the VWC differences for HBG were not always significantly reduced based on irrigation rate, with only deficit irrigated Latitude 36 less than moderate and high for round 1 and less than moderate for round 2 and deficit irrigated Tahoma 31 less than high in round 1. When compared across irrigation levels the deficit irrigated KBG-b had significantly less VWC than the HBG cultivars in round 2 and moderate irrigated KBG-b had lower VWC than Latitude 36 in round 1. These results suggest that KBG-b used more water than HBG.

DISCUSSION

Deficit irrigated KBG had significantly increased canopy temperature and reduced plant health (as measured by NDVI, verdure, and percent canopy cover) while the deficit irrigated

HBG cultivars were not impacted. The NDVI, verdure, and canopy temperature data were similar to those measured in a similarly designed glasshouse study (see Chapter 1). The combined data confirm the hypothesis KBG is more prone to negative impacts of deficit irrigation, while HBG is considerably tolerant with regard to plant health, visual quality, and canopy temperature. Impacts on shoot and root growth were not as clear and need further evaluation. It is also apparent from these field and glasshouse studies that HBG is using less water, although further work is needed to quantify these results.

Overall, the HBG cultivars were not affected by the deficit irrigation conditions. This may be due in part to the shoot physiology of Bermudagrass, as its slow vertical growth and horizontal growth pattern contribute to a lower ET rate and may delay grass dehydration (Kim and Beard, 1988; Huang et al., 2014; Zhang et al., 2019). Because the HBG did not appear affected by the deficit water conditions, they may not have been stressed enough (whether by irrigation amount or length of the study) to produce drought stress responses. Another study subjected 'Tifway' HBG to various lengths of drought and found that this cultivar could recover from five weeks of drought, even when grown in shallow and sandy soil (Monje-Jiménez et al., 2019). In another drought study it was found that root depth and root growth for all six common Bermudagrass cultivars increased as the drought period progressed (Baldwin et al., 2006). Additionally, some grasses, like KBG, require the soil surface to be dry for a period of time in order for significant root growth to be simulated (Huang, 2008). These studies support the idea that the Latitude 36 and Tahoma 31 may not have been drought-stressed enough under the present study's conditions to trigger drought responses.

While there are subtle differences in actual ET (ET_a) rates for different grass species/cultivars, and most HBG cultivars have lower ET rates than KBG cultivars, this study used an ET_o rate based on our local weather station as a baseline for all grasses. A study by Fu et al. (2004) compared types of grass including 'Midlawn' HBG and 'Brilliant' KBG and found that while the KBG required nearly 100% ET_a to maintain acceptable turf quality, the HBG was acceptable at rates of 40-60% ET_a. This suggests that even if ET_a rates specific to each grass type had been employed at the 100%, 70% and 34% levels, differences may not have been seen for HBG in this study.

Other studies determined that some KBG genotypes required deep rooting (such as 60-90 cm), greater root distribution, and low stomatal sensitivity to uptake enough water to withstand severe drought and exhibit cooler temperature canopy temperatures (Bonos and Murphy, 1999; Keeley and Koski, 2002; Huang et al., 2014; Zhou et al., 2014). Stomatal measurements were not taken in the present study, but it was determined that the KBG blend of cultivars had a relatively shallow root system, which may have affected its drought sensitivity. Other research suggests that KBG has a relatively shallow root system and may sacrifice some of its canopy and root systems during drought to preserve its crown and rhizomes (Menegon et al., 2017; Wang and Huang, 2004). However, as there were no observed differences in KBG root measurements in relation to irrigation rate in the present study, the shallow rooting was likely due to other factors.

Although this study supports previous work that KBG is sensitive to drought conditions, this species is not completely drought intolerant. KBG is generally classified as a grass that employs drought escape while HBG uses drought avoidance (Carrow, 1994; Fry and Huang, 2004; Huang et al., 2014). KBG enters dormancy under stress and resumes growth after water becomes available once more, and this ability is largely due to its extensive rhizomes (Wang and Huang, 2004). While the ability of KBG to recover from drought is important, many turfgrass managers and homeowners prefer to have a lawn that looks healthy and performs well, which is generally not the case under dormancy.

When the irrigation studies began, the HBG had only been established for about one year while the KBG-b had been well established for about four years, which may have affected the root and shoot results. The KBG-b was not statistically different than either HBG cultivar in terms of root depth, but the HBG was also recently established and its roots are likely still growing. If this study was to go on longer, differences in shoot and root responses may develop. Studies by Hamblin and Tennant (1987) and Fuentealba et al. (2015) reported that plants, such as grass, with faster root development frequently developed deeper roots, which may imply that HBGs have not stopped growing. Similar studies will be conducted in future years to see if and how these interactions may change.

Additionally, HBG has historically been sensitive to freezing temperatures, but new cultivars are more cold hardy. In another study conducted by these authors, Tahoma 31 and Latitude 36 were tested along with six other Bermudagrass cultivars for cold tolerance. Between 2020-2021, no winter kill was observed for seven of the eight cultivars, and all were fully filled in and green by late spring. So far HBG appears to have sufficient water survival in Provo, UT, and will likely become more suitable as the climate grows warmer.

CONCLUSION

We hypothesized that the HBG cultivars used in this study would perform better under deficit irrigation than KBG-b, and therefore suggest that they may offer a better solution for sports surfaces and landscaping in arid and semi-arid regions. Although there were no variable impacts of irrigation for plant growth in these short-term dry-down periods, these results show that deficit irrigated KBG consistently produced higher canopy temperatures and lower NDVI, visual turf quality, and percent cover than well or moderately watered KBG. However, the deficit irrigated HBG cultivars were not impacted. Soil volumetric water content data suggest that KBG use more water than HBG, which warrants further study.

In order for KBG to recover from drought and heat stress, it is crucial that this grass receive high rates of irrigation. This may not be feasible in arid and semi-arid regions where water is scarce. However, HBG can maintain acceptable turf quality with less irrigation, thrive at very low mowing heights, establish and repair itself quickly, and withstand significant wear. This suggests that HBG is a feasible replacement for KBG in arid and semi-arid regions, especially as more cold-tolerant varieties are released and tested.

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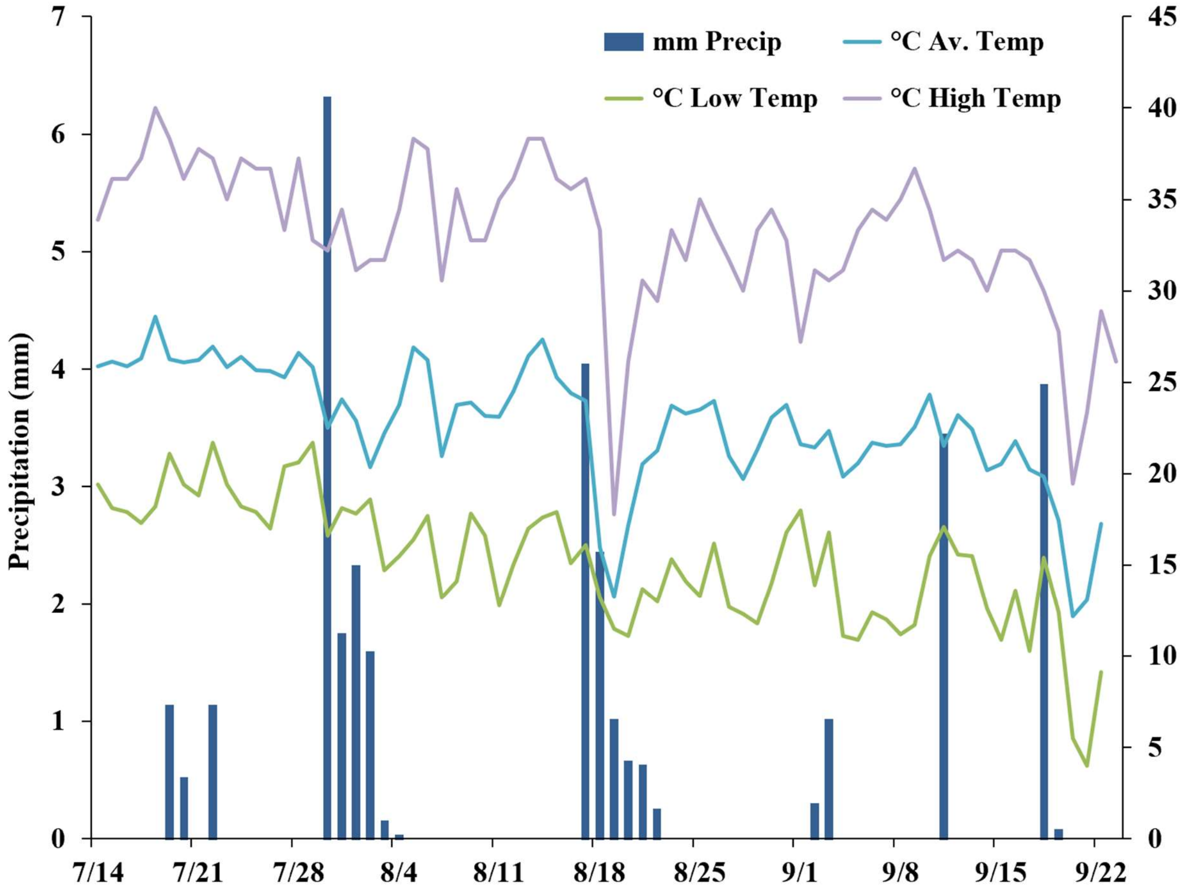

Figure 2-1. Daily precipitation (mm) and high, low, and average air temperature (°C) during the study period in 2021.

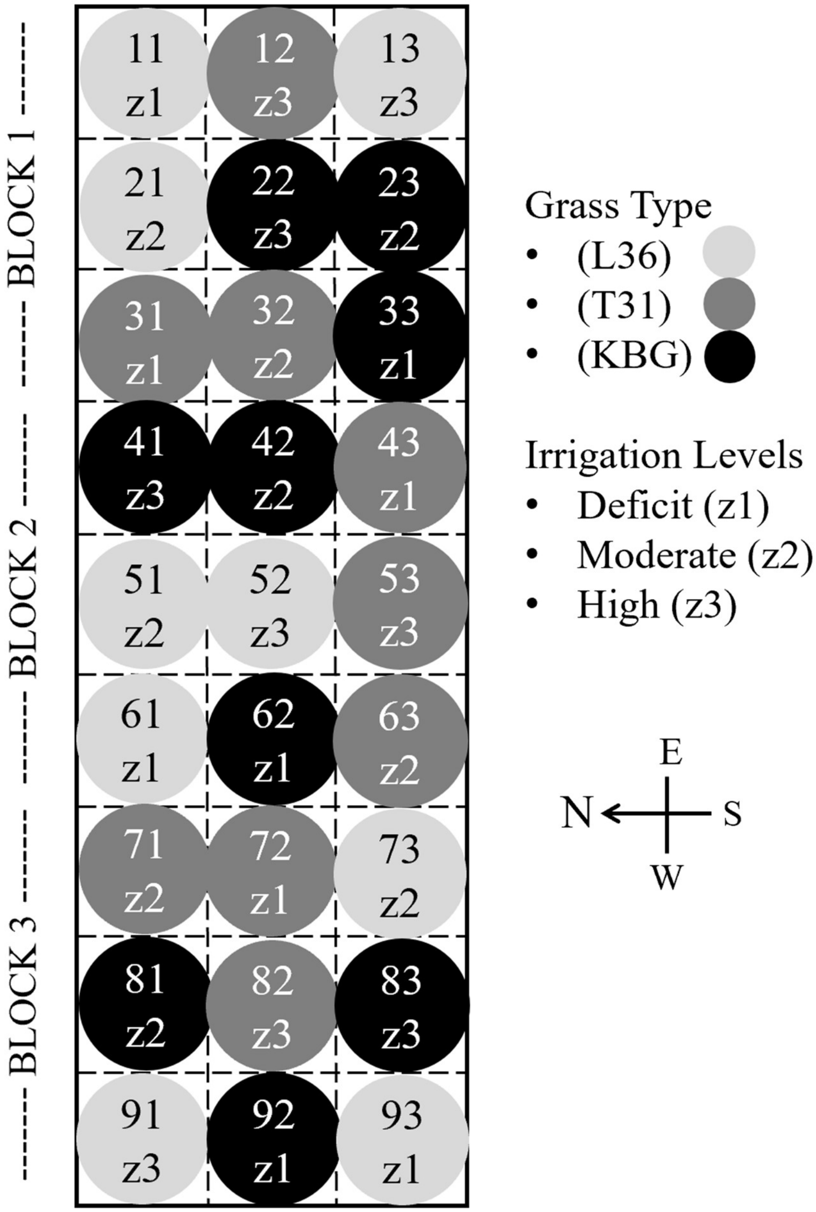

Figure 2-2. Study set-up including three grass types (Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, Kentucky bluegrass) and three irrigation levels (deficit, moderate, high).

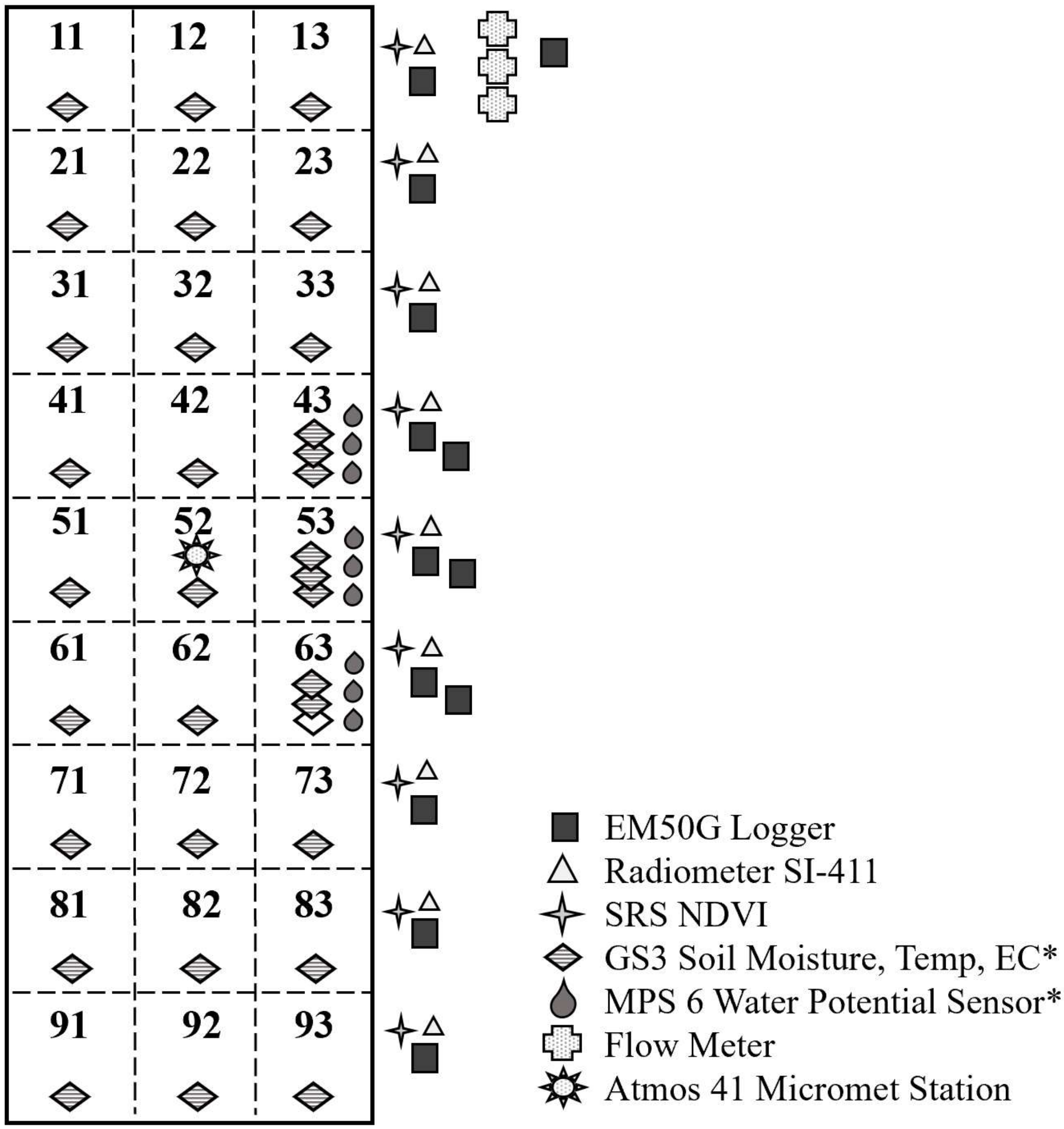

Figure 2-3. Sensor layout for the plots. An asterisk (*) indicates the sensors are buried.

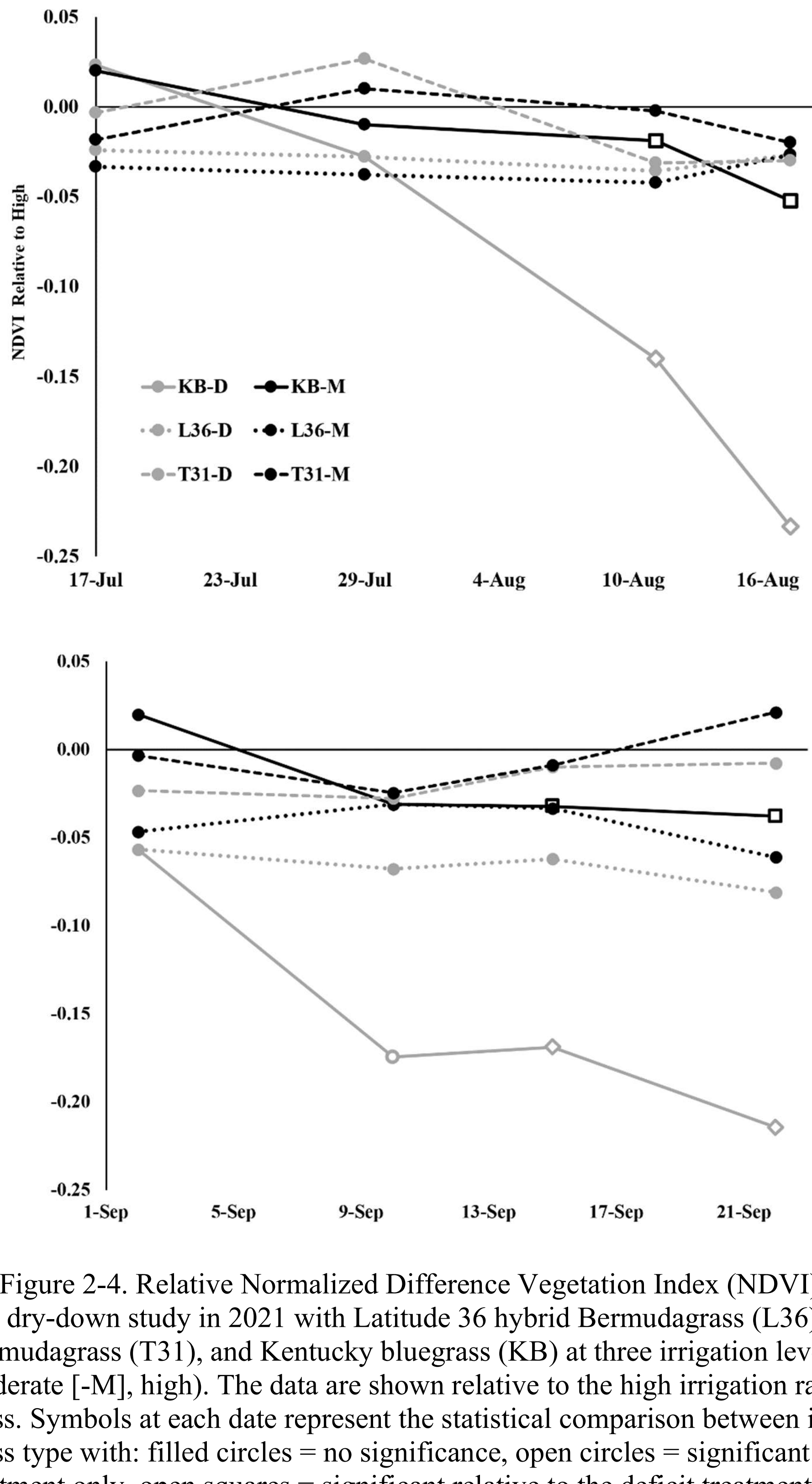

Figure 2-4. Relative Normalized Difference Vegetation Index (NDVI) values for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass (L36), Tahoma 31 hybrid Bermudagrass (T31), and Kentucky bluegrass (KB) at three irrigation levels (deficit [-D], moderate [-M], high). The data are shown relative to the high irrigation rate (control) for each grass. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments. (*P*=0.05)

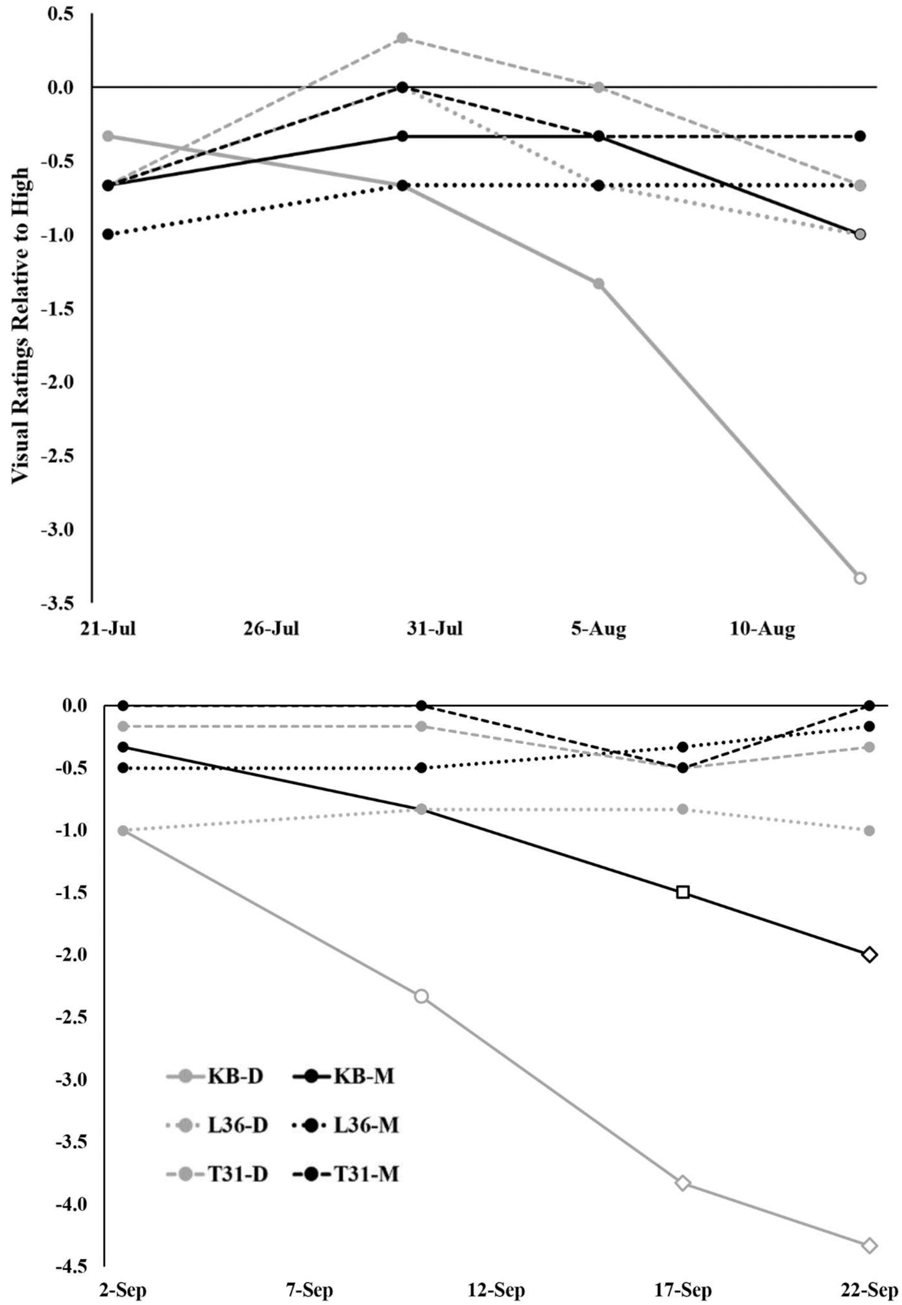

Figure 2-5. Relative visual turf quality (verdure) ratings for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass (L36), Tahoma 31 hybrid Bermudagrass (T31), and Kentucky bluegrass (KB) at three irrigation levels (deficit [-D], moderate [-M], high). The data are shown relative to the high irrigation rate (control) for each grass. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments. (*P*=0.05)

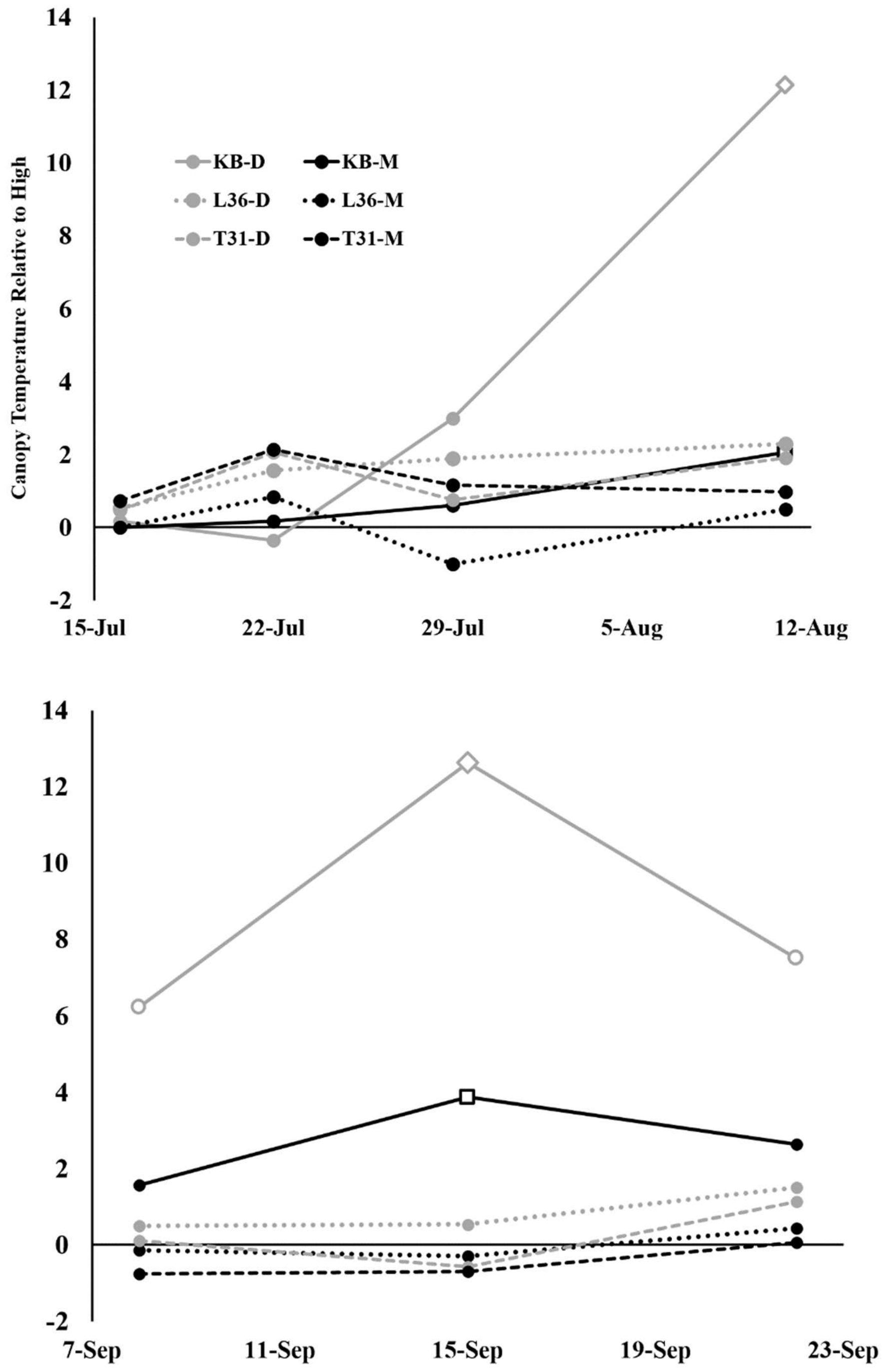

Figure 2-6. Relative canopy temperatures (°C) for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass (L36), Tahoma 31 hybrid Bermudagrass (T31), and Kentucky bluegrass (KB) at three irrigation levels (deficit [-D], moderate [-M], high). The data are shown relative to the high irrigation rate (control) for each grass. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments. (P=0.05)

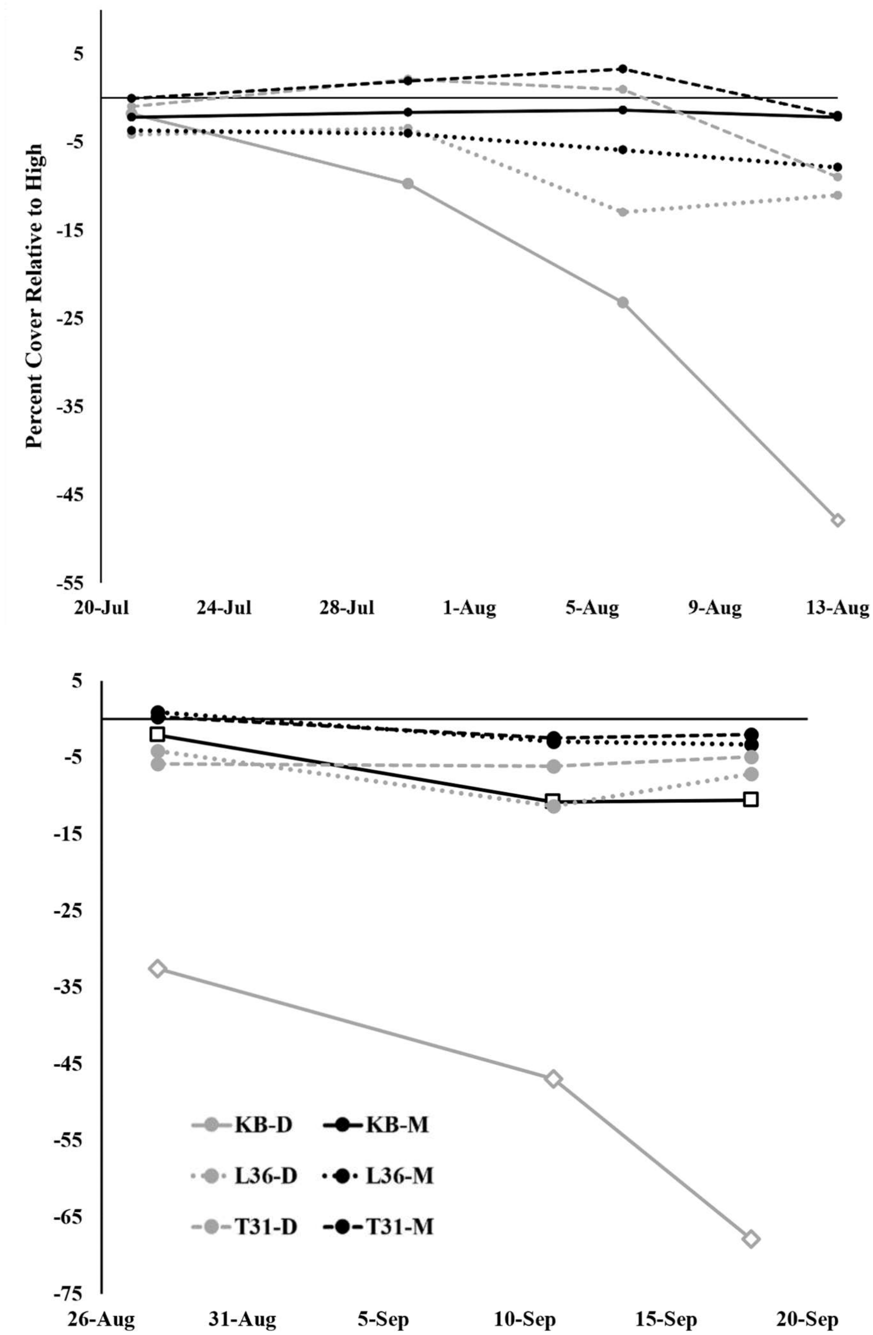

Figure 2-7. Percent cover values for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass (L36), Tahoma 31 hybrid Bermudagrass (T31), and Kentucky bluegrass (KB) at three irrigation levels (deficit [-D], moderate [-M], high). The data are shown relative to the high irrigation rate (control) for each grass. Symbols at each date represent the statistical comparison between irrigation rates within a grass type with: filled circles = no significance, open circles = significant relative to the high treatment only, open squares = significant relative to the deficit treatment only, and open diamonds = significant relative to both other irrigation treatments. (*P*=0.05)

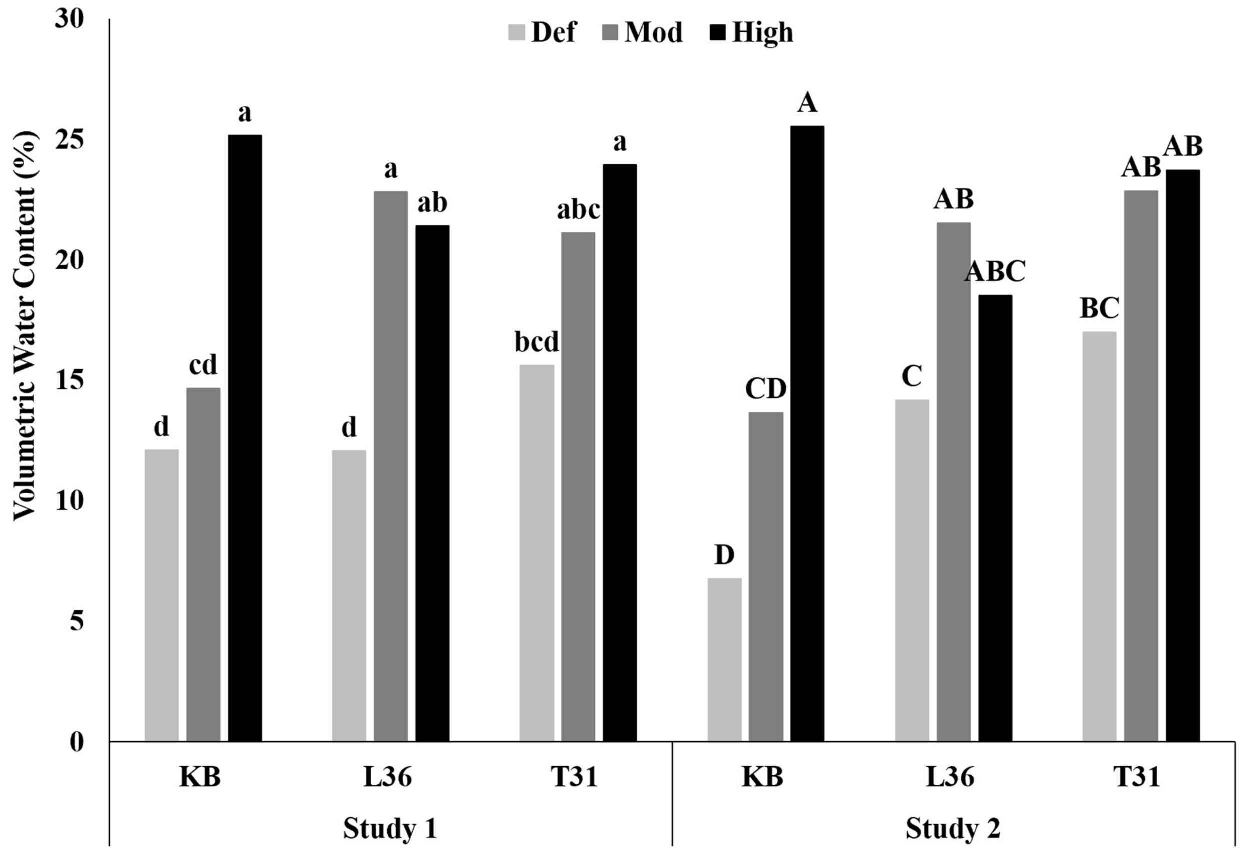

Figure 2-8. Volumetric water content (VWC) values of three grass types (Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, Kentucky bluegrass) at three irrigation levels (deficit, moderate, high). This is from the first and second study, both of which were conducted in 2021. The same letters indicate that no statistically significant difference exists, although the statistics from the first and second studies were run separately.

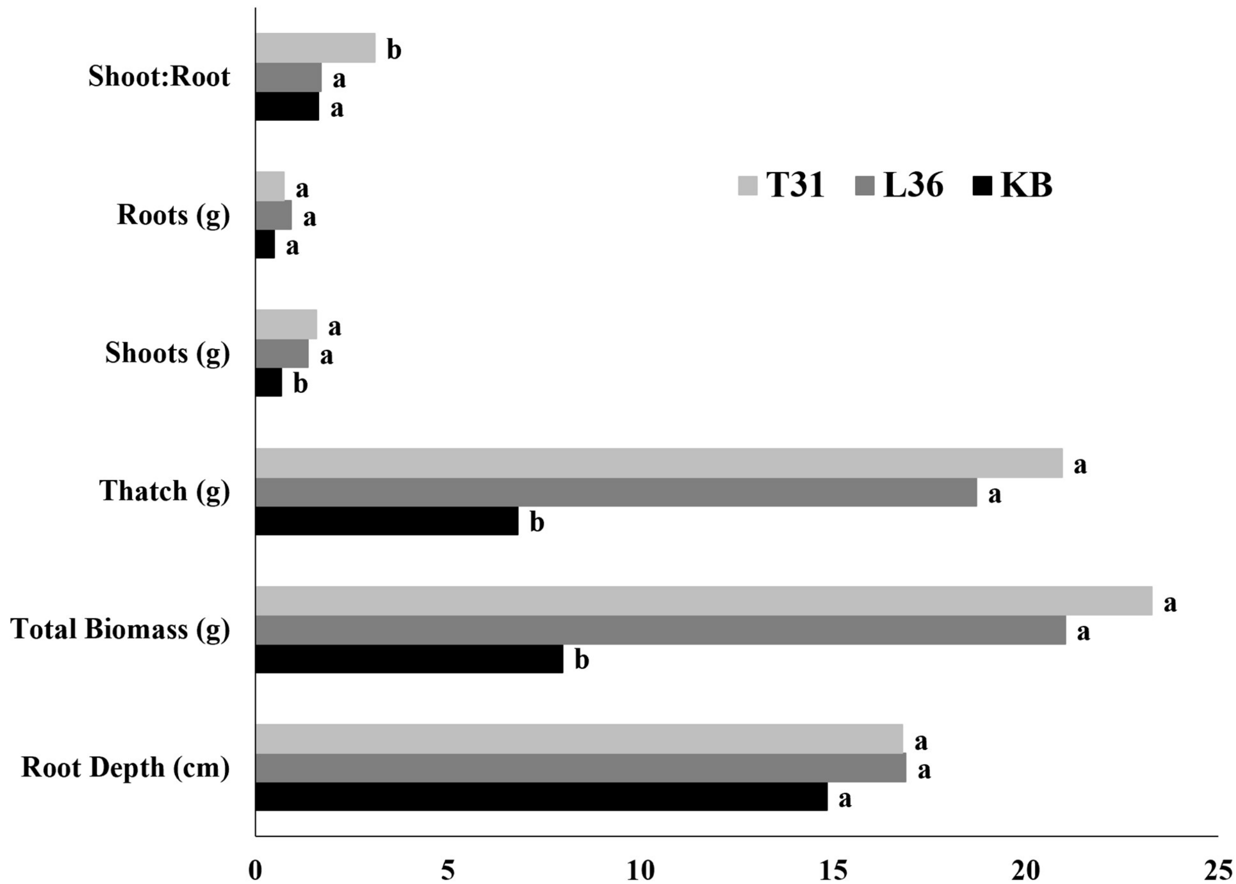

Figure 2-9. Shoot-to-root ratios, root mass (g), shoot mass (g), thatch mass (g), total biomass (g), and root depth (cm) values of three grass types (Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, Kentucky bluegrass) from the end of the study in 2021. The same letters mean that no statistically significant difference exists, although the statistics from each measurement were run separately.

TABLES

Table 2-1. Properties of soil for irrigation prior to fertilization

Property	Value	Method
VWC at field capacity, %	23	Volumetric[1]
Texture	Sandy loam	Hydrometer[2]
Sand, %	67.4	
Clay, %	11.8	
Silt, %	20.7	
Bulk density, g cm^{-3}	1.3	Gravimetric[2]
pH	7.5	Saturated Paste[2]
EC, dS m^{-1}	0.5	″ ″
OM, %	1.5	Walkley-Black Method[2]
NO_3-N, ppm	5	KCl 2M[2]
P, ppm	16	Olsen Bicarbonate[2]
K, ppm	93	″ ″
Zn, ppm	3.7	DTPA Extraction[2]
Mn, ppm	6.0	″ ″
Fe, ppm	38.6	″ ″
Cu, ppm	1.3	″ ″

[1] GS3 Sensor; METER Group, Pullman, WA, USA
[2] Gavlak et al., 1994.

Table 2-2. Normalized Difference Vegetation Index (NDVI) values for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, and Kentucky bluegrass at three irrigation levels (Deficit, Moderate, or High). *P*-values are shown by *italics* with significance with an 0.05 alpha as indicated by **bold-face** type.

	Day of Study and Date									
	1 7/17	13 7/29	26 8/11	32 8/17	Avg.	1 9/2	9 9/10	14 9/15	21 9/22	Avg.
Irrigation Rate	**Kentucky Bluegrass – Blend of cultivars**									
Deficit	0.59	0.62	0.58	0.53	0.58	0.62	0.55	0.56	0.51	0.57
Moderate	0.59	0.64	0.70	0.71	0.66	0.73	0.69	0.70	0.69	0.70
High	0.57	0.65	0.72	0.76	0.67	0.74	0.72	0.73	0.72	0.72
	Hybrid Bermudagrass – Latitude 36									
Deficit	0.73	0.74	0.72	0.74	0.73	0.73	0.65	0.66	0.64	0.67
Moderate	0.72	0.73	0.72	0.74	0.73	0.72	0.69	0.69	0.66	0.69
High	0.75	0.76	0.76	0.77	0.76	0.75	0.72	0.72	0.72	0.73
	Hybrid Bermudagrass – Tahoma 31									
Deficit	0.77	0.77	0.72	0.74	0.75	0.73	0.68	0.69	0.66	0.68
Moderate	0.75	0.75	0.75	0.75	0.76	0.75	0.68	0.69	0.69	0.70
High	0.77	0.74	0.75	0.77	0.76	0.76	0.70	0.70	0.66	0.70
	***P*-values**									
Grass type (G)	***0.030***	***0.049***	***0.050***	***0.002***	*0.062*	*0.168*	*0.126*	***0.029***	***0.015***	*0.063*
Irrigation rate (I)	*0.623*	*0.615*	***0.001***	***0.001***	***0.007***	***0.008***	***0.005***	***0.004***	***0.004***	***0.003***
G x I	*0.381*	*0.340*	***0.022***	***0.003***	***0.032***	*0.094*	*0.124*	***0.043***	***0.041***	*0.059*

Table 2-3. Visual turf quality ratings (ranked 1-9, with 9 being the best) for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, and Kentucky bluegrass at three irrigation levels (Deficit, Moderate, or High). *P*-values are shown by *italics* with significance with an 0.05 alpha as indicated by **bold-face** type.

	Day of Study and Date									
	5 7/21	14 7/30	20 8/5	28 8/13	Avg.	1 9/2	9 9/10	16 9/17	21 9/22	Avg.
Irrigation Rate	**Kentucky Bluegrass – Blend of cultivars**									
Deficit	6.3	6.7	6.7	4.3	6.0	6.8	5.3	4.3	3.8	5.1
Moderate	6.0	7.0	7.7	6.7	6.8	7.5	6.8	6.7	6.2	6.8
High	6.7	7.3	8.0	7.7	7.4	7.8	7.7	8.2	8.2	8.0
	Hybrid Bermudagrass – Latitude 36									
Deficit	7.3	8.0	7.7	7.0	7.5	7.0	7.0	7.2	7.0	7.0
Moderate	7.0	7.3	7.7	7.3	7.3	7.5	7.3	7.7	7.8	7.6
High	8.0	8.0	8.3	8.0	8.1	8.0	7.8	8.0	8.0	8.0
	Hybrid Bermudagrass – Tahoma 31									
Deficit	7.0	8.0	7.7	7.0	7.4	7.5	7.3	6.8	6.7	7.1
Moderate	7.0	7.7	7.3	7.3	7.3	7.7	7.5	6.8	7.0	7.3
High	7.7	7.7	7.7	7.7	7.7	7.7	7.5	7.3	7.0	7.4
	***P*-values**									
Grass type (G)	*0.658*	*0.225*	*0.329*	*0.052*	*0.077*	***0.003***	***0.003***	***<0.001***	***<0.001***	***<0.001***
Irrigation rate (I)	***0.013***	*0.434*	*0.106*	***0.005***	***0.003***	***0.050***	***0.006***	***<0.001***	***<0.001***	***<0.001***
G x I	*0.927*	*0.404*	*0.352*	*0.138*	*0.122*	*0.338*	*0.051*	***0.004***	***<0.001***	***0.002***

Table 2-4. Canopy temperatures (°C) for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, and Kentucky bluegrass at three irrigation levels (Deficit, Moderate, or High). *P*-values are shown by *italics* with significance with an 0.05 alpha as indicated by **bold-face** type.

	Day of Study and Date								
	0 7/16	6 7/22	13 7/29	26 8/11	Avg.	7 9/8	14 9/15	21 9/22	Avg.
Irrigation Rate	**Kentucky Bluegrass – Blend of cultivars**								
Deficit	36.8	33.6	32.2	43.5	36.5	39.4	45.7	35.3	40.1
Moderate	36.6	34.2	29.8	33.4	33.5	34.7	36.9	30.4	34.0
High	36.6	34.0	29.2	31.3	32.8	33.1	33.1	27.8	31.3
	Hybrid Bermudagrass – Latitude 36								
Deficit	36.1	36.5	32.1	35.5	35.1	35.5	35.4	32.4	34.4
Moderate	35.6	35.8	29.2	33.7	33.6	34.9	34.6	31.3	33.6
High	35.6	34.9	30.2	33.2	33.5	35.0	34.9	30.9	33.6
	Hybrid Bermudagrass – Tahoma 31								
Deficit	35.1	35.6	29.8	34.1	33.6	35.0	33.9	32.2	33.7
Moderate	35.4	35.6	30.2	33.2	33.6	34.2	33.8	31.1	33.0
High	34.7	33.5	29.0	32.2	32.3	34.9	34.5	31.1	33.5
	***P*-values**								
Grass type (G)	*0.767*	*0.308*	*0.670*	***0.002***	*0.376*	***0.008***	***<0.001***	***0.006***	***<0.001***
Irrigation rate (I)	*0.715*	*0.431*	*0.156*	***<0.001***	***0.011***	***0.042***	***0.001***	***0.047***	***0.003***
G x I	*0.943*	*0.811*	*0.655*	***0.002***	*0.385*	***0.030***	***0.004***	***0.004***	***0.006***

Table 2-5. Percent cover values for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, and Kentucky bluegrass at three irrigation levels (Deficit, Moderate, or High). *P*-values are shown by *italics* with significance with an 0.05 alpha as indicated by **bold-face** type.

	Day of Study and Date								
	5 7/21	14 7/30	21 8/6	28 8/13	Avg.	-2 9/28	10 9/11	17 9/18	Avg.
Irrigation Rate	**Kentucky Bluegrass – Blend of cultivars**								
Deficit	72.66	64.31	55.27	26.64	54.72	42.40	34.68	20.26	32.45
Moderate	72.26	72.42	77.08	72.34	73.52	72.94	70.86	77.55	73.78
High	74.43	74.03	78.48	74.52	75.37	75.00	81.67	88.11	81.59
	Hybrid Bermudagrass – Latitude 36								
Deficit	91.06	82.82	74.71	67.27	78.97	68.28	71.60	80.27	73.39
Moderate	91.50	82.25	81.77	70.45	81.49	73.29	80.00	84.09	79.13
High	95.21	86.27	87.68	78.32	86.87	72.43	82.95	87.44	80.94
	Hybrid Bermudagrass – Tahoma 31								
Deficit	94.32	82.94	84.51	71.92	83.42	73.01	76.62	77.70	75.78
Moderate	95.21	82.75	86.85	78.89	85.92	79.12	80.25	80.63	80.00
High	95.29	80.85	83.55	80.89	85.15	78.86	82.75	82.65	81.42
	***P*-values**								
Grass type (G)	*0.228*	*0.696*	*0.162*	***0.016***	*0.149*	***0.029***	***0.021***	***<0.001***	***0.001***
Irrigation rate (I)	*0.175*	*0.833*	*0.064*	***<0.001***	***0.024***	***0.035***	*0.061*	***<0.001***	***<0.001***
G x I	*0.774*	*0.937*	*0.355*	***0.002***	*0.187*	***0.003***	***0.004***	***<0.001***	***0.002***

Table 2-6. Shoot, root, and thatch mass, root depth, and shoot-to-root ratio for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, and Kentucky bluegrass at three irrigation levels (Deficit, Moderate, or High). *P*-values are shown by *italics* with significance with an 0.05 alpha as indicated by **bold-face** type.

	Shoots	**Roots**	**Thatch**	**Total Biomass**	**Root Depth**	**Shoot: Root**
	g	g	g	g	cm	
Irrigation Rate	**Kentucky Bluegrass – Blend of cultivars**					
Deficit	0.4	0.7	3.5	4.7	13.7	0.6
Moderate	0.7	0.3	7.1	8.1	17.8	2.5
High	0.9	0.5	9.8	11.2	13.1	1.8
Average	0.7	0.5	6.8	8.0	14.8	1.6
	Hybrid Bermudagrass – Latitude 36					
Deficit	1.1	0.8	18.9	20.8	16.4	1.3
Moderate	1.3	0.5	21.2	22.9	17.5	2.6
High	1.8	1.5	16.1	19.4	16.8	1.2
Average	1.4	0.9	18.7	21.0	16.9	1.7
	Hybrid Bermudagrass – Tahoma 31					
Deficit	1.9	0.4	15.1	17.3	16.2	5.2
Moderate	1.3	1.4	24.3	27.0	18.1	1.0
High	1.6	0.5	23.4	25.5	16.2	3.1
Average	1.6	0.7	20.9	23.3	16.8	3.1
	***P*-values**					
Grass type (G)	***0.008***	*0.443*	***0.004***	***0.002***	*0.315*	***0.033***
Irrigation rate (I)	*0.477*	*0.841*	*0.413*	*0.366*	*0.201*	*0.783*
G x I	*0.586*	*0.193*	*0.758*	*0.792*	*0.850*	*0.849*

Table 2-7. Handheld volumetric water content (VWC) values for final days of two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass, Tahoma 31 hybrid Bermudagrass, and Kentucky bluegrass at three irrigation levels (Deficit, Moderate, or High). *P*-values are shown by *italics* with significance with an 0.05 alpha as indicated by **bold-face** type.

Final Date	17 Aug	23 Sep
	Study 1	Study 2
Irrigation Rate	**Kentucky Bluegrass – Blend of cultivars**	
Deficit	12.1	6.7
Moderate	14.6	13.6
High	25.1	25.5
	Hybrid Bermudagrass – Latitude 36	
Deficit	12.1	14.2
Moderate	22.8	21.5
High	21.4	18.5
	Hybrid Bermudagrass – Tahoma 31	
Deficit	15.6	17.0
Moderate	21.1	22.9
High	24.0	23.7
	***P*-values**	
Grass type (G)	***0.047***	***<0.001***
Irrigation rate (I)	***<0.001***	***<0.001***
G x I	***0.004***	***<0.001***

SUPPLEMENTAL MATERIAL

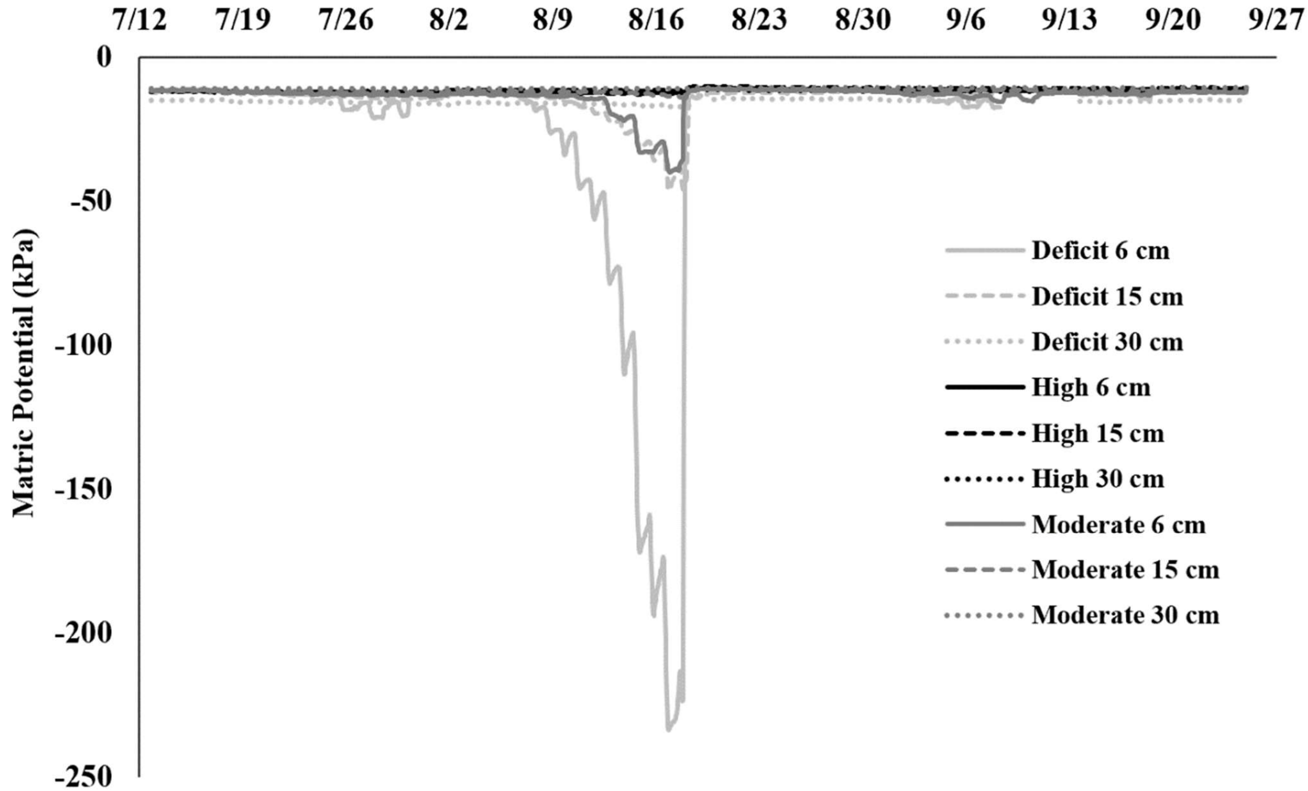

Figure 2-a. Water matric potential values (kPa) for two rounds of a dry-down study in 2021 with Tahoma 31 hybrid Bermudagrass (T31) at three irrigation levels (deficit [-D], moderate [-M], and high [-H]) and three sensor depths (6 cm, 15 cm, and 30 cm).

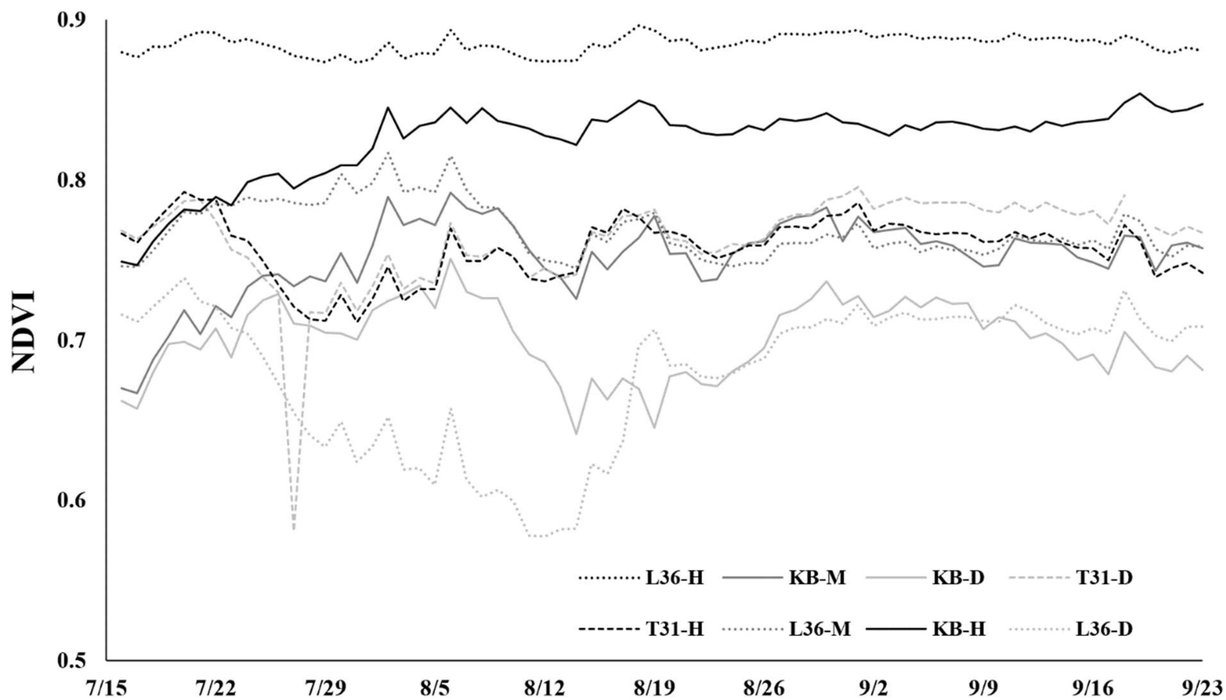

Figure 2-b. Normalized Difference Vegetation Index (NDVI) values for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass (L36), Tahoma 31 hybrid Bermudagrass (T31), and Kentucky bluegrass (KB) at three irrigation levels (deficit [-D], moderate [-M], and high [-H]). The data were lost for T31-M.

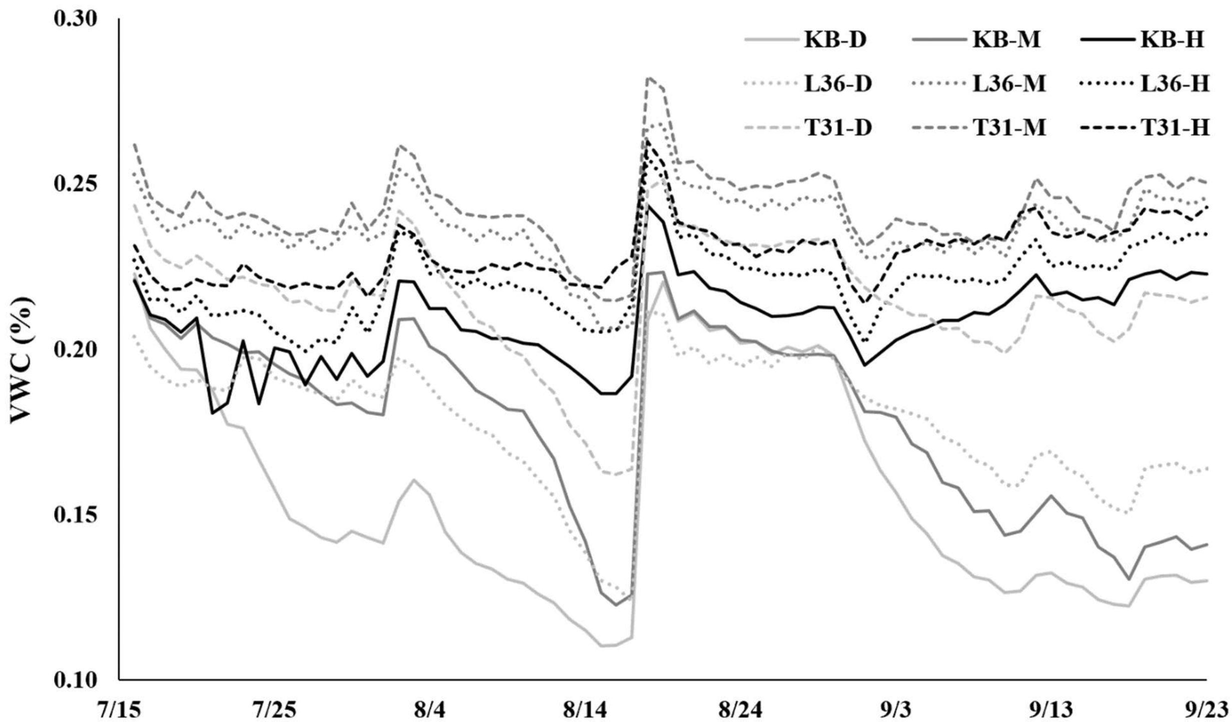

Figure 2-c. Volumetric Water Content (VWC) values for two rounds of a dry-down study in 2021 with Latitude 36 hybrid Bermudagrass (L36), Tahoma 31 hybrid Bermudagrass (T31), and Kentucky bluegrass (KB) at three irrigation levels (deficit [-D], moderate [-M], and high [-H]).