Rooting Characteristics and Responses of Photosynthesis to Irrigation Deficit of Two Hybrid Bluegrasses, Kentucky Bluegrass, and Tall Fescue

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Abbreviations: DOT, days of treatment; ET, evapotranspiration; HBG, hybrid bluegrass; HBG1, Thermal Blue- a HBG; HBG2, Reveille- a HBG; KBG, Kentucky bluegrass; MRE, maximum root extension; P_g, gross photosynthesis; RLD, root length density.

ABSTRACT

Drought stress is common among cool-season turfgrasses during summer in the U.S. transition zone. A two-year field study was conducted near Manhattan, Kansas, USA, to evaluate rooting characteristics and effects of drought on canopy physiology and appearance of 'Apollo' Kentucky bluegrass (*Poa pratensis* L.) (KBG), 'Dynasty' tall fescue (*Festuca arundincea* Schreb.) (TF), and two hybrid bluegrasses (HBG) 'Reveille' and 'Thermal Blue'; HBG are genetic crosses between native Texas bluegrass (*Poa arachnifera* Torr.) and KBG. Rooting characteristics were measured in the field and greenhouse under well-watered conditions to evaluate root contributions to drought avoidance. Two irrigation treatments in the field included: 1) 60% (water-deficit); and 2) 100% (well-watered) evapotranspiration (ET) replacement. Ninety to 96% of all root length (0-80 cm) in the field and 74 to 80% of all root length (0-120 cm) in the greenhouse were in the upper 30 cm among Thermal Blue, Reveille, and KBG while in TF, only 86% and 70% of all root length in the field and greenhouse, respectively, were in the top 30 cm. In the field, tall fescue had 3 to 12 times greater root length in the lower profile (60-80 cm) among turfgrasses. Visual quality and gross photosynthesis (P_g) were greatest in TF among turfgrasses in both irrigation treatments. Reveille used more water from the 0-50 cm profile and performed better than Thermal Blue during water-deficit, but both HBG recovered from water-deficit slightly faster than KBG. Performances in visual quality and P_g generally ranked: TF > Reveille ≥ Thermal Blue = KBG.

Drought stress is common among cool-season turfgrasses during summer months in the U.S. transition zone, which spans between the northern regions where cool-season grasses are adapted and the southern regions where warm-season grasses are adapted (Dunn and Diesburg, 2004). As water for irrigation becomes increasingly limited, water restrictions are becoming more common for turfgrass managers and consequently, the problem of drought stress in cool-season turfgrasses will likely intensify (Reisner, 1993; Snow, 2001).

Kentucky bluegrass (*Poa pratensis* L.) (KBG) is a cool-season turfgrass often used in home and commercial lawns, athletic fields, and golf courses fairways and roughs (Turgeon, 2002). During drought, however, KBG may go dormant and lose its green color, which is an undesirable trait to some turf managers. Tall fescue (*Festuca arundincea* Schreb.) (TF), also a cool-season grass, is sometimes used in golf course roughs and is popular in lawns because of its good drought resistance (Carrow, 1996; Qian et al., 1997). Some turf managers, however, do not like TF because of its bunch-type growth habit and coarser texture compared with KBG. Hybrid bluegrasses (HBG), which are genetic crosses between native Texas bluegrass and Kentucky bluegrass (KBG), may have similar visual quality as KBG but exhibit greater drought and heat resistance than other cool-season grasses (Read et al., 1999). Consequently, new cultivars of HBG are being investigated as potential drought-resistant alternatives compared with current cool-season turfgrasses.

Until recently, limited data have been available regarding the drought resistance of HBG. In a field study in Kansas, USA, differences were negligible in drought resistance among two HBG (‘Thermal Blue’ and ‘Dura Blue’) and a KBG (‘Apollo’) (Bremer et al., 2006). In a growth chamber study, no differences in drought resistance were observed among a HBG (Thermal Blue), a KBG (Apollo) and a TF (‘Dynasty’) although Thermal Blue was more resistant to heat than the other turfgrasses (Su et al., 2007). Considerable variation in drought resistance, however, was observed among thirty cultivars of HBG and their genetic parents in a growth chamber study (Abraham et al., 2004). Therefore, further research is needed to compare drought resistance among HBG in field trials, including new releases of HBG.

Even fewer data are available concerning the rooting characteristics of HBG. Suplick-Ploense and Qian (2005) investigated vertical rooting patterns of HBG (‘Reveille’) and KBG (‘Bensun’s A-34’) and reported that HBG possessed a deeper more extensive root system, a lower inherent ET rate, and exhibited greater drought avoidance than KBG. A deep, extensive root system is an important mechanism of drought avoidance in turfgrasses (White et al., 1993; Carrow, 1996; Qian et al., 1997, Jiang and Huang, 2001). Presumably, greater root density at deeper depths allows plants to extract soil water deeper in the profile (Fry and Huang, 2004).

Therefore, our objectives were to: 1) measure rooting characteristics of two HBG, a KBG, and a TF under well-watered conditions in the field and greenhouse; 2) measure soil water content in the profile, including at different depths and under water deficit, to evaluate patterns of soil water depletion by roots among species; and 3) measure the canopy characteristics of visual quality and photosynthesis in the same species under well-watered and water-deficit conditions.

Materials and Methods

Study Site and Experimental design

This study was conducted from 3 August to 8 October, 2004 and from 27 June to 15 September, 2005 under an automated rainout shelter (12 m x 12 m) at the Rocky Ford Turfgrass Research Center near Manhattan, KS (39.14^{o}N, 96.35^{o}W); Manhattan lies in the U.S. transition zone. The rainout shelter rested north of the study area but automatically covered the research plots as precipitation began and retracted one hour after it ceased. The soil at the site was Chase silt loam (fine, montmorillonitic, mesic, Aquic, Argiudoll).

Plots were arranged in a randomized complete block design with four replications. Thirty two plots (1.36 m x 1.76 m) were bordered by metal edging (10 cm depth) to prevent lateral soil water movement between adjacent plots. Two irrigation treatments included well watered (replacement of 100% of the water lost from plants and soil via evapotranspiration [ET]) and water deficit (replacement of 60% of ET). Water was applied by hand on Monday and Friday twice a week through a fan spray nozzle attached to a hose; a meter (Model 03N31, GPI, Inc., Wichita, KS) was attached to ensure proper application rate. To determine irrigation requirements, evapotranspiration (ET) was calculated by using the Penman-Monteith equation (FAO, 1998) and climatological data obtained at an on-site weather station.

Plot Preparation and Maintenance

Prior to seeding in 2003, the plot area was fumigated with dazomet (tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thione) at 575 kg a.i.ha^{-1} to kill vegetation and weed, insect, and disease pests. Plots were seeded on 17 September 2003 with a hybrid bluegrass (Thermal Blue [HBG1]) at 147 kg ha^{-1}, another hybrid bluegrass (Reveille [HBG2]) at 293 kg ha^{-1} (rate recommended by manufacturer because of lower germination rates), Kentucky bluegrass (Apollo [KBG]) at 147 kg ha^{-1}, and tall fescue (Dynasty [TF]) at 293 kg ha^{-1}. All plots were fertilized with urea at 45 kg N ha^{-1} on 20 April, 73 kg N ha^{-1} on 17 September, and 45 kg N ha^{-1} on 19 November in 2004. In 2005, urea was applied at 54 kg N ha^{-1} on 27 April, 45 kg N ha^{-1} on 19

September, and 45 kg N ha^{-1} on 4 October. Plots were mowed twice a week with a walk-behind rotary mower at 7.6 cm mowing height.

Insecticide applications for controlling billbug grubs and white grubs in 2004 included imidacloprid (1-[(6-chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimine) at 0.44 kg a.i. ha^{-1} on 19 April, bifenthrin (2-methyl [1,1'-biphenyl]3-y1)-methyl 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate) at 0.12 kg a.i. ha^{-1} on 27 May, and halofenozide (Benzoic acid, 4-chloro-, 2-benzoyl-2-(1,1-dimethylethyl)hydrazide) at 1.69 kg a.i. ha^{-1} on 8 July. In 2005, the same insect pests were controlled with imidacloprid at 0.44 kg a.i. ha^{-1} on 18 June and bifenthrin at 0.06 kg a.i. ha^{-1} on 22 June.

Herbicides included dithiopyr (S,S'-dimethyl 2-(difluoro-methyl-4-(2-methylpropyl)-(trifluoromethyl)-3,5-pyridinedicarbothioate) applied at 0.58 kg a.i.ha^{-1} on 27 May in 2004 and 4 May in 2005 to control annual grassy weeds, and carfentrazone-ethyl [X,2-dichloro-5-[4-(difluromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]-4-fluorobenzenepropanic acid] (0.03 kg a.i. ha^{-1}) + 2,4- D, [(2,4-dichlorophenoxy)acetic acid] (1.29 kg a.i. ha^{-1}) + mecoprop-p ((±)-2-(4-chloro-2-methylphenoxy)propanoic acid) (0.27 kg a.i. ha^{-1}) + dicamba (3,6-dichloro-2-methoxybenzoic acid) (0.08 kg a.i.ha^{-1}) were applied to control broadleaf weeds on 27 May and 22 October in 2004 and 4 May and 19 October in 2005.

Fungicide applications for controlling brown patch (*Rhizoctonia solani*) and summer patch (*Magnoporthe poae*) included azoxystrobin (methyl(E)-2-{2-[6-(2-cyanophenoxy)pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) at 0.61 kg a.i. ha^{-1} on 21 April, 24 May, and 22 June and triadimefon (1-(4-Chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4- trizol-1-yl)-2-butanone) at 1.53 kg a.i. ha^{-1} on 23 July in 2005.

Measurement of Rooting Characteristics

Field

Root cores (80 cm x 4.8 cm diam.) were collected on 13 October 2005 from well-watered plots using a direct-push coring machine (LWW; Concord Environmental Equipment, Hawley, MN) equipped with a 4.8-cm-i.d. sampling tube (D10006P; Concord Environmental Equipment) and single-use polyethylene terephthalate copolymer plastic liners (1024151; Concord Environmental Equipment). Two root cores were taken from each plot. After extraction, soil cores were cut into three segments representing the 0-30, 30-60, and 60-80 cm profiles and soaked in water for 3 h. After soil was washed from the roots, methyl blue (5 g L^{-1} water) was applied to enhance the image of finer roots. Root length, average root diameter, and root surface area at different segments were then measured using an image analysis system, WinRHIZO (Regent Instruments Inc. QC, CA). After root characteristics were measured, samples were dried in a forced-air oven for 48 h at 70°C and weighed separately. Root length density (RLD) was calculated as root length divided by the volume of soil inside each respective section of root core. Total RLD, average root diameter, and root surface area (0-80 cm profile) were also calculated by each depth. Root characteristics in the two root cores within each plot were averaged as a sample.

Greenhouse

This research was conducted from 13 December 2004 to 23 February 2005 in a greenhouse at Kansas State University. Sod plugs of Thermal Blue (HBG1), Reveille (HBG2), Apollo (KBG), and Dynasty (TF) were collected from the field with a 3-cm-diam. corer. Six plugs of each species/cultivar were washed to remove the remaining soil, and existing roots were cut from the crown to stimulate new root formation. The plugs were then planted in 24 clear polyethylene tubes (3.5 cm in diam. by 120 cm long) that were filled with 100% calcined clay (Turface, Buffalo grove, IL). Calcined clay inside the tubes was saturated with water before planting grasses. Each tube was inserted into an opaque polyvinyl chloride (PVC) pipe. The method of Qian et al. (1997) was followed to prepare and position the tubes. Briefly, each PVC pipe was 120 cm long and 4 cm inside diam. The bottom was capped by a PVC plug in which holes were drilled to allow for drainage. Twenty-four tubes were arranged on a tube rack at a 20^o angle from vertical in a randomized complete block design with six replications.

Irrigation was applied with a mist system which was automatically turned on 6 times per day for 10 min each. Fertilizer was applied once weekly with irrigation water at 250 ppm N of Peters Peat-lite Special 20-10-20 water-soluble fertilizer (Scotts-Sierra Horticultural Product Co., Marysville, OH). Average day/night air temperature was 24/15°C and supplemental light with incandescent lamps was included for 14-h/day. Grasses were clipped weekly at 6.5 cm.

Maximum root extension (MRE) was determined by measuring the length of the deepest root visible at the calcined clay- clear polyethylene tube interface every two weeks. When MRE reached the bottom of the first tube, the study was halted. Tubes were then cut into four 30-cm long sections. Roots in every section were also washed and measured as previously described.

Volumetric Soil Water Content

In all field plots, volumetric soil water content (θ_v) in the 0 to 50 cm profile was measured weekly in 2004 and 2005 using time domain reflectometry (TDR) (model 6050XI, Soilmoisture Equipment, Santa Barbara, CA); data from 2004 were discarded because of an instrument error. In drought plots, volumetric soil water content (θ_v) was also measured near the surface at 5 cm in 2004 and 2005, which presumably was a region of denser root mass compared to deeper depths (Ervin and Koski, 1998; Turgeon, 2002; Su et al., 2007). These θ_v measurements near the soil surface were used to investigate possible differences in root activity (i.e., water absorption) among HBG1, KBG, and TF during drought. Soil moisture was not measured at 5 cm in HBG2 because of practical limitations in sensor availability and datalogging capacity. The θ_v at 5 cm was measured using the dual-probe heat-pulse (DPHP) technique (Campbell et al., 1991; Tarara and Ham, 1997; Song et al., 1998); DPHP sensors were fabricated in the authors' laboratory as described by Basinger et al. (2003) and Bremer (2003). Measurements of θ_v were logged twice daily at 0600 and 1800 CST. All data acquisition and control were accomplished with a micrologger and accessories (CR10x, two AM16/32's, and one M25T, Campbell Scientific, Logan, UT).

Canopy Characteristics

Turf visual quality was rated on a scale of 1 to 9 (1=poorest quality, 6=minimally acceptable, and 9=highest quality) according to color, texture, density, and uniformity (Emmons, 2000). Quality ratings were recorded weekly in 2004 and 2005 by the same individual during the 2-year study.

Photosynthesis and respiration were measured biweekly on clear days in 2004 and 2005 between 1000 and 1400 CST with a LI-6400 portable gas exchange system (LI-COR Inc., Lincoln, NE) using a custom surface chamber described by Bremer and Ham (2005). Permanent PVC collars (10-cm diam.) were placed randomly at one location in each plot and were driven approximately 5 cm into the soil. The collars and foam gaskets provided an effective seal between the surface chamber and soil during photosynthesis and respiration measurements.

Calculations and Data Analysis

Gross photosynthesis in each plot was estimated from measurements of photosynthesis and respiration according to the method of Bremer and Ham (2005). Briefly, this method involves consecutive measurements with a sunlit and shaded chamber, respectively, at each collar; shaded measurements were obtained by covering the chamber with an opaque cloth that blocked solar radiation from the chamber. Using Equations 5 and 6 from Bremer and Ham (2005), sunlit measurements were used to determine $P_g - (R_c + R_s^{'})$ and shaded chamber measurements to determine $R_c + R_s^{'}$, where P_g is gross photosynthesis, R_c is canopy respiration, and $R_s^{'}$ is residual soil respiration in a pressurized chamber; all values are positive and units are µmol CO_2 $m^{-2}s^{-1}$. Gross photosynthesis was calculated using their equation 8: P_g = sunlit chamber + shaded chamber.

All data were analyzed with the mixed procedure of SAS (SAS Institute Inc., Cary, NC). There were no significant interactions between turfgrass species and irrigation level on any given day after treatment initiation (Days of treatment) for θ_v in the 0-50 cm profile, visual quality, and P_g. Therefore, all differences between means were separated by the SAS PDIFF option (P=0.05). Average values of visual quality and Pg in each year were calculated by averaging each respective variable across all measurement days during the period of treatment.

Results and Discussion

Rooting characteristics and soil moisture in the field

In the 0-30 cm profile, RLD, dry root weight, and root surface area were the greatest in HBG1 and similar among HBG2, KBG, and TF (Table 1). Greater roots in the upper profile apparently resulted in a greater extraction of soil moisture near the surface by HBG1 than in KBG or TF (Fig. 1). At 5 cm in the drought treatment, the pattern of θ_v was consistently lower in HBG1 than in KBG and TF during both years although daily differences in θ_v were not significant among HBG1, KBG, and TF.

In the entire 80-cm profile in the field, HBG1, HBG2, KBG, and TF had 95%, 93%, 90%, and 86% of all root length in the top 30 cm of soil, respectively (Table 1). Therefore, most roots among species were distributed in shallow soil although the percentage was lowest in TF. Conversely, in the lower profiles (i.e., 30-60 cm and 60 to 80 cm) dry root weight ranged from 2.1 to 3.8 times greater and average root diameter was about 1.6 times greater in TF than in the other three turfgrasses. In the deepest part of the measured profile (60-80 cm), RLD ranged from 3 to 12 times greater and root surface area 5 to 20 times greater in TF than the three bluegrasses. Thus, TF had more roots deeper in the profile than HBG1, HBG2, and KBG. Interestingly, the roots deep in the profile (60-80 cm) in TF were only 4% of all root length in the entire profile (0-80 cm). Greater quantities of roots deep in the soil, however, may play an important role in a plant's ability to avoid drought stress even if deep roots are a small percentage of the total root system (Garrot and Mancino, 1994; Carrow 1996).

Root characteristics were similar among HBG1, HBG2, and KBG at lower depths (Table 1). Our results contradicted those of Suplick-Ploense and Qian (2005), who found that HBG2 (Reveille) exhibited greater RLD at each soil depth (0-20, 20-40, and 40-60 cm) and total root mass than a KBG (Bensun's A-34). In our study the total RLD and root surface area in the 0 to 80 cm profile were lower in HBG2 than in KBG. These differing results may be attributable to the different cultivars of KBG used between studies, and perhaps to different soils and climates between sites.

In the 0 to 50 cm profile, θ_v was similar among HBG1, KBG and TF, but θ_v was consistently lower in HBG2 under well-watered and drought conditions (Fig. 2). Lower θ_v indicates that HBG2 (Reveille) extracted more water from the profile than HBG1, KBG, and TF given equal irrigation amounts. Greater soil moisture extraction by HBG2 indicates greater water use in HBG2 than in KBG and TF although presumably TF may have drawn more water from below 50 cm (Table 1). Greater water use in HBG2 than in KBG contradicts observations by Suplick-Plonse (2005) that HBG2 (Reveille) used less water than another KBG (Bensun's A-34). High variability in ET among cultivars of KBG may partially explain contradicting results between studies (Shearman, 1986). These data and others (e.g., Bremer et al., 2006) illustrate a need to investigate water use among a greater number HBG and KBG in the field before concluding that a HBG is more water efficient or drought tolerant than KBG, or visa versa.

Presumably, greater water-extraction in soils is positively related to root characteristics (e.g., greater RLD and root surface area) (Carrow, 1996; Fry and Huang, 2004; Fu et al., 2007). In our study, however, all measured root parameters in the 0-80 cm profile were numerically lowest in HBG2 despite the greater extraction of soil water by HBG2 among turfgrasses (Table 1; Fig. 2). Canopy characteristics that were not investigated in this study may have strongly impacted ET and water use among turfgrasses. For example, Fu and Huang (2003) reported that drought resistance in tall fescue is positively related to leaf thickness, epicuticular wax content, and tissue density but negatively related to stomatal density and leaf width. Differences in green leaf area index and canopy conductance may also affect ET and water use among grasses (Loomis and Conner, 1992; Bremer and Ham, 1999; Bremer et al., 2001). More information is needed on the relationship between physical root characteristics and root activity (e.g., root water potential, root electrolyte leakage, and root life span), and on leaf characteristics and their effects on water use in the particular cultivars used in our study.

Rooting characteristics in the greenhouse

In the first two weeks of the study, roots grew fastest in HBG1 among turfgrasses and at the end of the first month, MRE in HBG1 remained greater than in KBG (Fig. 3). After the first month, however roots grew faster in TF than in HBG1, HBG2, and KBG and differences in MRE diminished among HBG1, HBG2, and KBG (Fig. 3). By the end of the evaluation period (70 days after planting), MRE was 15 to 30% greater in TF than in the other three turfgrasses (Fig.3). Greater MRE in TF may partially explain faster establishment of TF than HBG (Thermal Blue and Dura Blue) and KBG in a field experiment in Kansas, USA (Bremer et al., 2006).

Tall fescue exhibited the greatest dry root weight and average root diameter at each depth (0-30, 3-60, 60-90, and 90-120) (Table 2). Seventy-four to 80% of all root length (0-120 cm deep) was in the upper 30 cm among KBG, HBG1, and HBG2, while only 70% of TF all root length was in the top 30 cm; this was similar to results from our field study. In the upper 30 cm, HBG1 had the greatest RLD and root surface area among turfgrasses, which is also consistent with results from our field study (Table 1).

Below 60 cm, TF also generally had greater RLD, dry root weight, average root diam., and root surface area than the other 3 turfgrasses, the lone exception being a similar RLD to KBG in the 60 – 90 cm layer (Table 2). In the deepest section (90-120 cm), TF was the only grass with measurable root surface area (Table 2). Overall, these results were similar to the field study and indicated TF may be able to extract soil water from deeper depths than HBG1, HBG2, and KBG. A deep extensive root system, which is an important drought avoidance mechanism, has also been observed in TF in other studies (White et al., 1993; Carrow, 1996; Qian et al., 1997, Jiang and Huang, 2001).

Canopy characteristics in the field

Visual quality

In well-watered conditions, visual quality in TF was generally highest among the four turfgrasses during both years (Figs. 4A and 4B). Higher performance in TF than in HBG1 and KBG was also reported in another nearby field study (Bremer et al., 2006); HBG2 was not evaluated in that study. In 2004, visual quality of HBG2 was lower than the other grasses early in the treatment period, but differences diminished among bluegrasses and by 32 DOT, visual quality was similar among HBG1, HBG2, and KBG. In 2005, visual quality was lower in HBG1 than in HBG2 on 25, 31, 37, and 45 DOT (Fig. 4B). Lower visual quality in HBG1 in 2005 was likely caused by summer patch (*Magnaporthe poae*), which affected HBG1 more seriously than HBG2.

In the water-deficit treatment, the visual quality of TF was consistently higher than the other turfgrasses during both years (Fig. 4C, D). The deep root system of TF (Table 1; White et al., 1993; Carrow, 1996; Qian et al., 1997, Jiang and Huang, 2001) likely contributed to its drought avoidance. In 2004, there were no differences in average visual quality among HBG1, HBG2, and KBG in the water-deficit treatment. In 2005, however, visual quality of HBG2 was higher than HBG1 on 25, 31, and 37 DOT and KBG on 25 and 37 DOT (Fig. 4D). This indicated that HBG2 performed better than HBG1 under water deficit, heat stress, and during exposure to summer patch.

Gross Photosynthesis (P_g)

In well-watered plots, P_g was generally greatest in TF among turfgrasses during both years (Figs. 5A and 5B). The P_g in TF averaged 28 to 82% greater than Pg in the other 3 turfgrasses. During both years, average P_g was similar among HBG1, HBG2, and KBG although Pg tended to be greater in KBG than HBG1 and HBG2; P_g in KBG averaged about 28% higher than in HBG2 during both years. Higher P_g in TF among turfgrasses may have been caused in part by higher green leaf area index in TF (Lee, 2008).

In the water-deficit treatment, P_g was greatest in TF among turfgrasses in 2004. In HBG2, P_g was greater than HBG1 on 24 and 31 DOT and than KBG on 24, 31, and 38 DOT (Fig. 5C). In 2004, the average P_g of TF was 39 to 74% greater than that of the other three turfgrasses under the drought treatment. In 2005, P_g was greater in TF than in HBG1 and KBG during the first two weeks. Thereafter, P_g became similar among cultivars/species although the trend of higher P_g in TF apparently continued (Fig. 5D). Late in 2005, P_g decreased among turfgrasses, which was contrary to the upward trend late in 2004. The decline in 2005 was likely caused by a combination of drought stress and corresponding high temperature stress which did not occur in 2004; the drought treatment in 2004 ended in October, when temperatures had cooled compared with 2005, when the drought treatment ended in early September. For example, weekly daytime air temperature (1000-1800 CST) after 28 DOT averaged 26.2 to 32.2°C in 2005, but was only 19.4 to 28.5°C in 2004 (Table 3). In 2005, P_g averaged greater in TF than in HBG1 and KBG, but was statistically similar to HBG2 under the drought treatment.

Recovery after drought

In 2005, after termination of the water-deficit treatment and upon re-watering (on 70 DOT), HBG1 and HBG2 recovered more quickly than KBG from water-deficit and summer stresses. Visual quality was statistically similar among HBG1 (4.0), HBG2 (4.8), and KBG (4.0) at the end of the water-deficit treatment. At the end of the 4-wk recovery period, however, visual quality was higher in HBG1 (8.0) and HBG2 (8.0) than in KBG (7.3). Faster recovery in HBG after drought indicated a slight advantage in HBG1 and HBG2 over KBG as related to their drought resistances.

Conclusions

Under well-watered conditions, most roots were distributed in the shallowest soil layer (0-30 cm) although TF had fewer roots in the upper soil profile among turfgrasses. Tall fescue had a more developed root system at deeper depths, however, and its roots grew faster than the other three turfgrasses. In the upper layer (0-30 cm), HBG1 had the greatest RLD and root surface area among the four grasses although that didn't translate to greater performance in HBG1 during water-deficit, after water near the surface was depleted. In the water-deficit treatment, HBG2 (Reveille) performed better than HBG1 (Thermal Blue) and KBG but apparently used more water from the 0-50 cm profile among turfgrasses, including TF. Both HBG recovered from drought slightly faster than KBG.

In general, TF exhibited the highest visual quality and P_g among turfgrasses under water-deficit and well-watered conditions. Our results were similar to those of Bremer et al. (2006), who reported that TF may be better suited than HBG in areas of the transition zone where soils are deep and if drought resistance is a priority. Further field research is needed to compare the drought resistance of newly released cultivars of HBG with multiple cultivars of KBG and TF, including in areas of the transition zone with different soil types and depths, before concluding that a HBG is more water efficient or drought resistant than KBG or TF, or visa versa. The performances of the turfgrasses in our field study, as evaluated by visual quality and Pg, generally ranked: TF > Reveille ≥ Thermal Blue = KBG.

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List of figures

Table 1. Root length density (RLD), dry root weight, average root diameter, and root surface area in different depths of HBG1 ('Thermal Blue' hybrid bluegrass), HBG2 ('Reveille' hybrid bluegrass), KBG ('Apollo' Kentucky bluegrass), and TF ('Dynasty' tall fescue) under well-watered conditions in the rainout shelter at Manhattan, KS, in 2005.

Soil depth	Species	RLD	Dry root weight	Average root diam.	Root surface area
-- cm --		- cm cm^{-3} -	--- g ---	-- mm --	-- cm^2 --
0-30	HBG1	14.10 a†	0.569 a	0.33 a	785 a
	HBG2	7.28 b	0.321 b	0.29 b	361 b
	KBG	10.35 b	0.401 b	0.31 a	547 b
	TF	8.17 b	0.408 b	0.32 a	454 b
30-60	HBG1	0.63 a	0.011 b	0.20 b	22 a
	HBG2	0.50 a	0.012 b	0.19 b	18 a
	KBG	1.08 a	0.019 b	0.20 b	39 a
	TF	0.97 a	0.036 a	0.29 a	48 a
60-80	HBG1	0.05 b	0.002 b	0.18 b	1 b
	HBG2	0.07 b	0.003 b	0.17 b	2 b
	KBG	0.19 b	0.004 b	0.17 b	4 b
	TF	0.61 a	0.013 a	0.29 a	20 a
0-80 (Total)	HBG1	5.54 a	0.581 a	0.32 a	808 a
	HBG2	2.93 c	0.336 b	0.28 b	381 c
	KBG	4.33 ab	0.423 ab	0.30 b	591 b
	TF	3.58 bc	0.457 ab	0.32 a	522 bc

† Means followed by the same letter within a specific soil depth and a column were not significantly different (P=0.05).

Table 2. Root length density (RLD), dry root weight, average root diameter, and root surface area in different depths of HBG1 ('Thermal Blue' hybrid bluegrass), HBG2 ('Reveille' hybrid bluegrass), KBG ('Apollo' Kentucky bluegrass), and TF ('Dynasty' tall fescue) under well-watered condition in the greenhouse in 2005. Dash (-) indicates amounts <0.001 g in dry root weight, <0.01 cm cm^{-3} in RLD, and < 1 cm^2 in root surface area, respectively.

Soil depth (cm)	**Species**	**RLD ($cm\ cm^{-3}$)**	**Dry root weight (g)**	**Average root diam (mm)**	**Root surface area (cm^2)**
0-30	HBG1	41.75 a[†]	1.040 ab	0.33 b	1250 a
	HBG2	19.17 c	0.778 c	0.34 b	596 c
	KBG	34.46 b	0.892 bc	0.33 b	1014 b
	TF	18.90 c	1.199 a	0.42 a	728 c
30-60	HBG1	9.68 a	0.185 b	0.25 c	218 ab
	HBG2	5.91 b	0.169 b	0.29 b	154 b
	KBG	10.26 a	0.219 b	0.26 c	242 a
	TF	5.76 b	0.324 a	0.40 a	210 ab
60-90	HBG1	0.81 b	0.015 b	0.20 c	16 c
	HBG2	0.83 b	0.018 b	0.23 bc	19 c
	KBG	1.82 a	0.029 b	0.24 b	40 b
	TF	2.10 a	0.100 a	0.40 a	76 a
90-120	HBG1	-	-	0.06 b	-
	HBG2	-	-	0.04 b	-
	KBG	0.01 b	-	0.11 b	-
	TF	0.40 a	0.016 a	0.42 a	15 a
0-120 (Total)	HBG1	13.06 a	1.240 b	0.31 b	1484 a
	HBG2	6.48 b	0.965 c	0.33 b	769 c
	KBG	11.64 a	1.141 bc	0.31 b	1296 a
	TF	6.79 b	1.638 a	0.42 a	1028 b

[†] Means followed by the same letter within a specific soil depth and a column were not significantly different (P=0.05).

Table 3. Weekly average daytime (1000-1800 CST) air temperature on 3 Aug. – 11 Oct., 2004 and 27 June – 4 Sept., 2005 during both years of the study and their difference.

Days of treatment (DOT)	2004 (°C)	2005 (°C)	Difference 2005-2004 (°C)
7 †	26.9	29.2	2.4
14	22.7	29.3	6.6
21	25.8	31.3	5.4
28	28.1	32.2	4.2
35	28.5	28.0	-0.5
42	27.6	30.6	3.0
49	26.8	28.9	2.1
56	25.6	27.2	1.7
63	20.0	26.2	6.2
70	19.4	28.3	8.9

† This value referred to the period from 1 to 7 days.

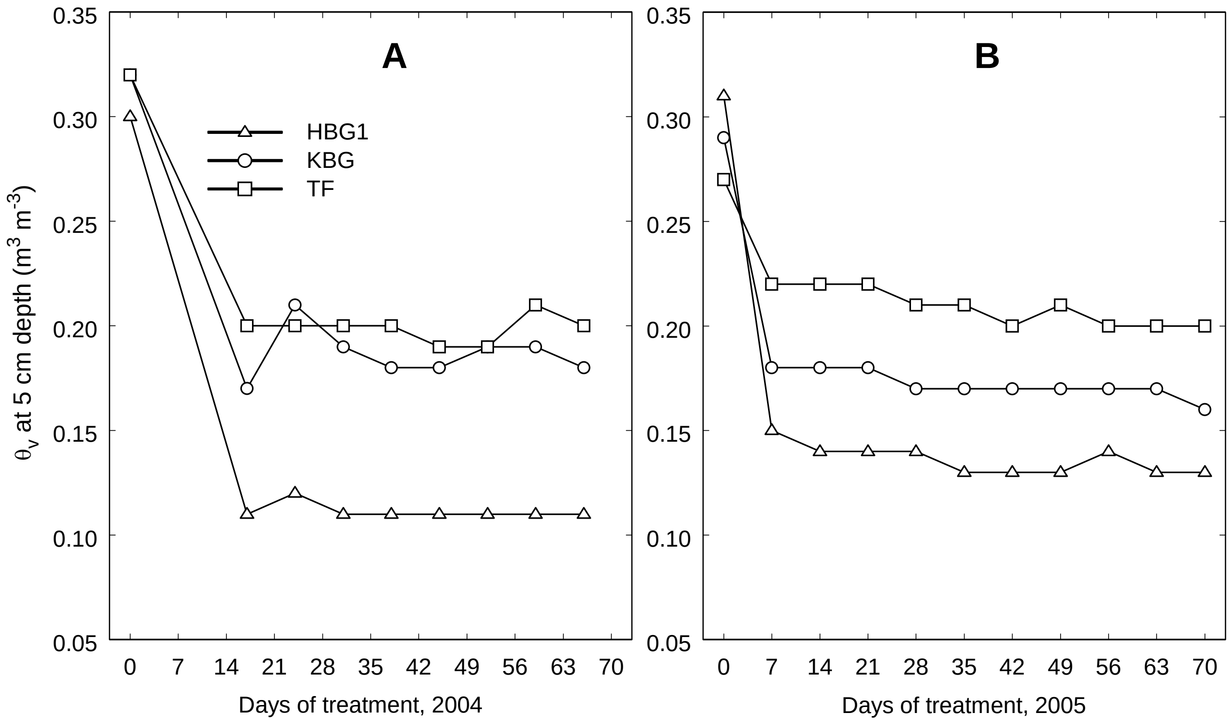
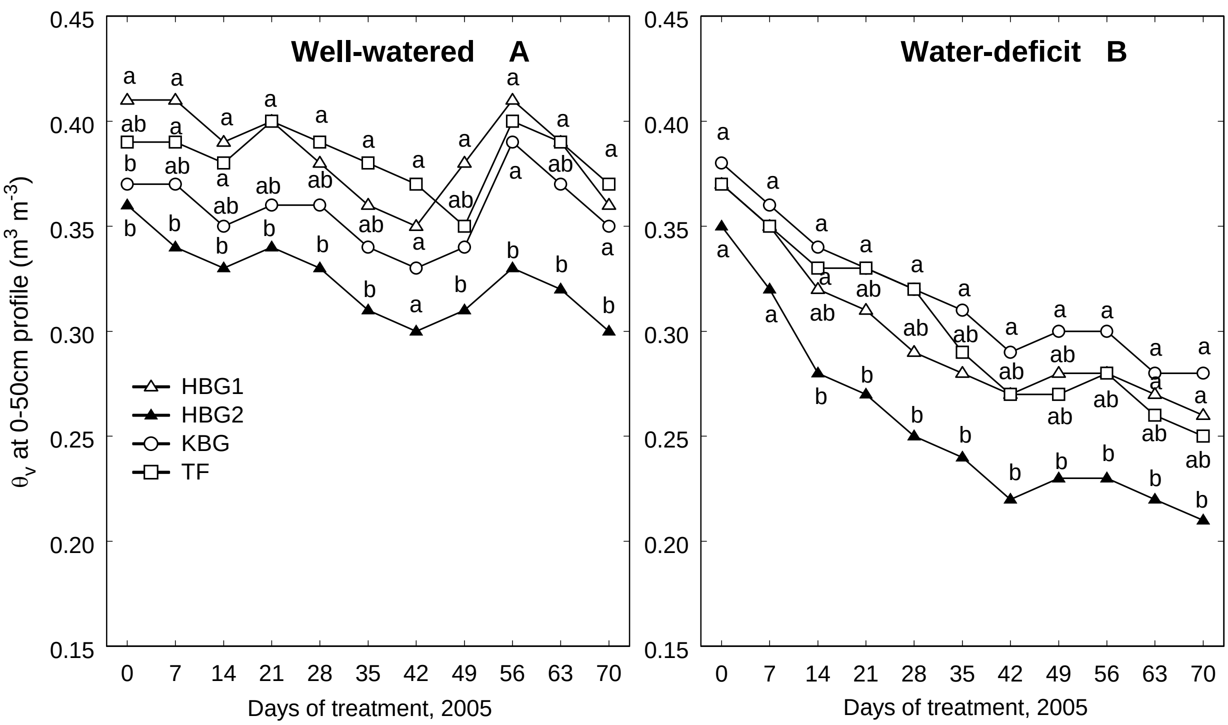

A
B
HBG1
KBG
TF
θv at 5 cm depth (m3 m-3)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0 7 14 21 28 35 42 49 56 63 70
Days of treatment, 2004
Days of treatment, 2005

Figure 1.



Well-watered A
Water-deficit B
HBG1
HBG2
KBG
TF
θv at 0-50cm profile (m3 m-3)
Days of treatment, 2005
Days of treatment, 2005

Figure 2.

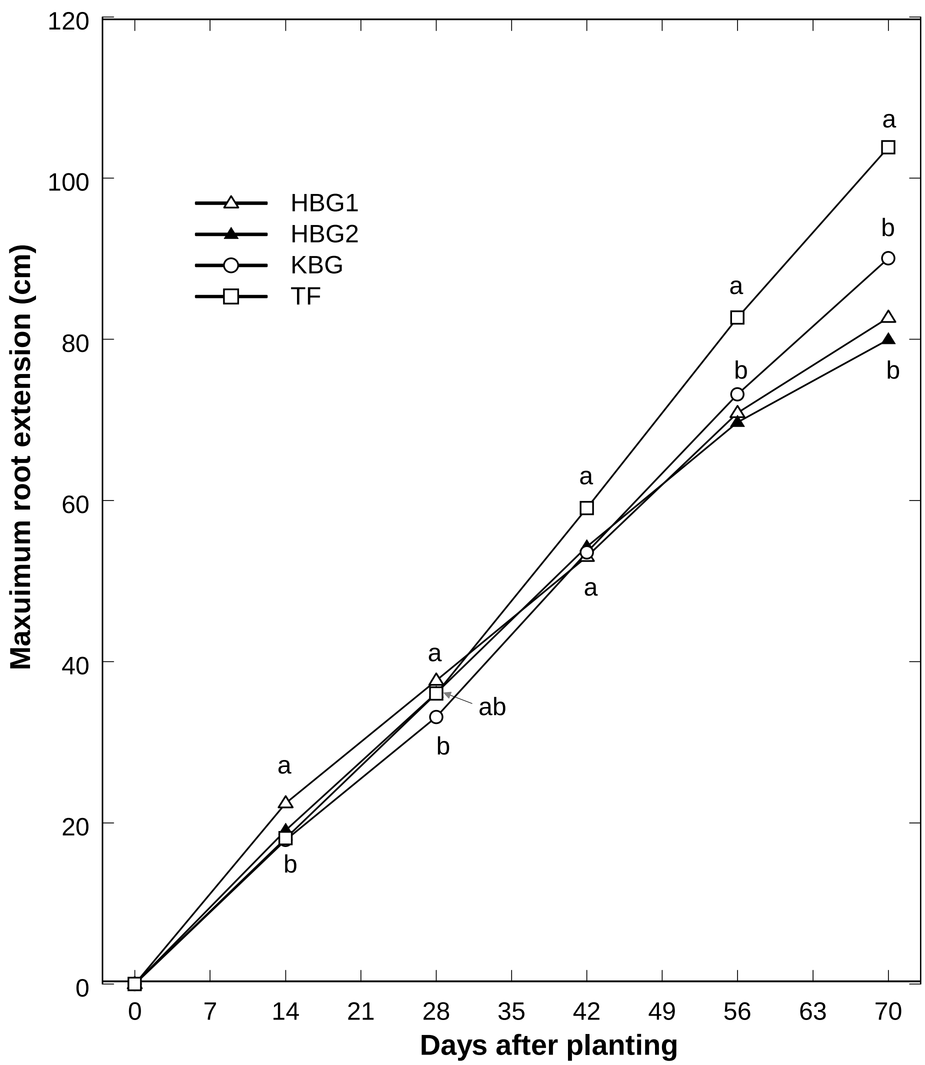

Maxuimum root extension (cm)
Days after planting
HBG1
HBG2
KBG
TF
0
20
40
60
80
100
120
0
7
14
21
28
35
42
49
56
63
70
a
b
a
ab
b
a
a
a
b
a
b
b

Figure 3.

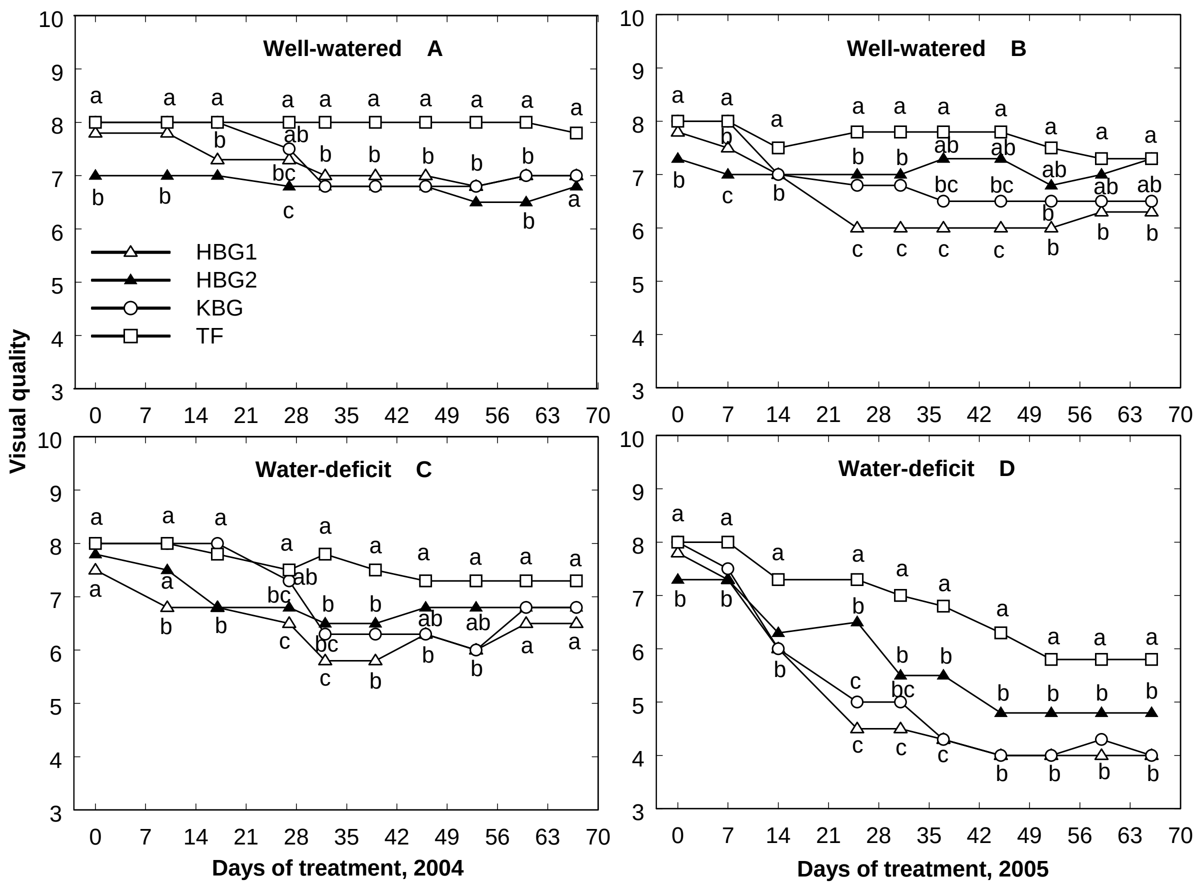

Well-watered A
Well-watered B
Water-deficit C
Water-deficit D
HBG1
HBG2
KBG
TF
Visual quality
Days of treatment, 2004
Days of treatment, 2005

Figure 4

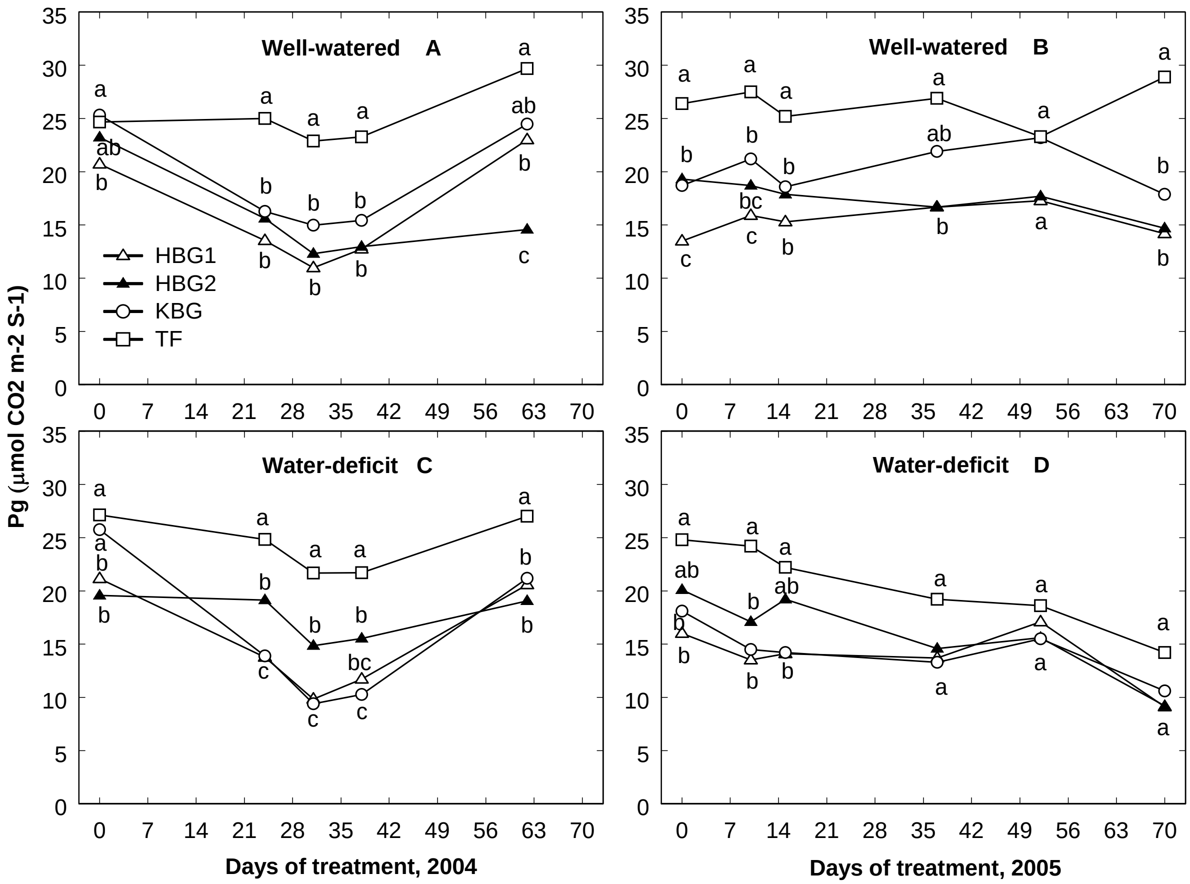

Pg (μmol CO2 m-2 S-1)
Well-watered A
Well-watered B
Water-deficit C
Water-deficit D
HBG1
HBG2
KBG
TF
Days of treatment, 2004
Days of treatment, 2005

Figure 5.