Impacts of Altered Light Spectral Quality on Warm-Season Turfgrass Growth under Greenhouse Conditions

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ABSTRACT

Warm-season turfgrass quality declines under shade due to reduced photosynthesis, increased disease pressure, reduced carbohydrate production, tree root competition, and reduced lateral stem growth. Another factor limiting turfgrass growth and development under tree shade is variable qualities of light filtered by trees. However, effects of various filtered wavelengths on turfgrass performance are lacking and deserve research. Therefore, a greenhouse project investigated the physiological and morphological responses of 'Diamond' zoysiagrass [*Zoysia matrella* (L.) Merr.], 'Sea Isle 2000' seashore paspalum (*Paspalum vaginatum* Swartz.), and 'Tifway' and 'Celebration' bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] to variable light spectral qualities. Light treatments included a control without any shade cloths and four different color shade cloths filtering wavelengths 560 to 720 nm (blue shade cloth), 360 to 520 nm (yellow shade cloth), 360 to 560 nm (red shade cloth), and 360 to 720 nm (black shade cloth). The percent light reduction for each cloth was about 65% relative to the control. Data collected included visual turfgrass quality (TQ), relative clipping yield, relative chlorophyll concentration, relative shoot width, relative root biomass, relative root length density, relative specific root length, and root and shoot total nonstructural carbohydrates. Diamond was the least affected turfgrass by the color shade cloths, while Celebration and Sea Isle 2000 performed similarly. Tifway was the most sensitive turfgrass with the lowest TQ under color shade cloths. Yellow and red shades were least detrimental, while black shade most negatively inhibited parameters measured, followed by blue shade. This study implies different types of shade significantly impact the TQ of warm-season turfgrasses.

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Abbreviations: RCC, relative chlorophyll concentration; RCY, relative clipping yield; R/FR, red/far-red; RLD, root length density; RLS, relative lateral spread; RLW, relative leaf width; RRB, relative root biomass; RRLD, relative root length density; RSRL, relative specific root length; RSW, relative shoot width; SRL, specific root length; TNC, root and shoot total nonstructural carbohydrates; TQ, visual turfgrass quality.

Turfgrass growth and development under shade is inhibited by reduced photosynthesis (Jiang et al., 2004; Miller et al., 2005), increased disease pressure (Beard, 1965; Vargas and Beard, 1981) due to extended morning dew duration (Dudeck and Peacock, 1992; Williams et al., 1996), reduced carbohydrate production (Bunnell et al., 2005b, 2005c), tree root competition (Whitcomb, 1972; Whitcomb and Roberts, 1973), and reduced lateral stem growth (Beard, 1997). Another factor limiting turfgrass growth and development under shade are various types of filtered light. The photosynthetic active radiation available for plant growth is between 400 and 700 nm with ~90% absorbed by the plant and the remainder reflected at the leaf surface or transmitted through the leaf (Taiz and Zeiger, 2006). Blue light occurs from wavelengths 400 to 500 nm; green light, 500 to 600 nm; red light, 600 to 700 nm; and far-red light, 700 to 800 nm (Taiz and Zeiger, 2006). In nature, trees alter spectral quality available for turfgrass development (Bell et al., 2000); however, limited research has investigated the light specific tree species filter in highly maintained turfgrass

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environments. Also, most turfgrass shade research has focused on light quantity using black neutral shade material (Bell and Danneberger, 1999; Koh et al., 2003; Steinke and Stier, 2003; Bunnell et al., 2005a; Baldwin et al., 2008).

Gaskin (1965) demonstrated a green shade cloth (75% light reduction) had different light quality spectrums compared to white oak (*Quercus alba* L.) and maple (*Acer* sp.) tree shade. McBee (1969) noted a post oak (*Q. stellata* Wang.) canopy filtered wavelengths between 600 and 675 nm. McKee (1963) indicated lambsquarter (*Chenopodium album* L.), ragweed (*Ambrosia trifida* L.), and smartweed (*Polygonum pensylvanicum* L.) depleted blue wavelengths, while trees with a high canopy filtered red wavelengths. Bell et al. (2000) noted conifer and deciduous tree shade, red/far-red (R/FR) <1.0, altered spectral quality available for turfgrass growth.

While previous research has demonstrated that shade source alters the type of light available for turfgrass growth, few reports have investigated light quality impacts on turfgrass growth and development. McBee (1969) noted blue light minimized stem elongation, while red light enhanced stem elongation for selected bermudagrass (*Cynodon* spp.) cultivars. McVey et al. (1969) noted blue light enhanced quality and color while reducing clipping fresh weight production and vertical shoot elongation in 'Windsor' Kentucky bluegrass (*Poa pratensis* L.) and 'Tifgreen' bermudagrass. Wherley et al. (2005) subjected 'Plantation' (shade-tolerant) and 'Equinox' (shade-sensitive) tall fescue [*Schedonorus phoenix* (Scop.) Holub.] to deciduous (*Acer* spp. and *Fraxinus* spp.; R/FR, 0.428) and neutral (R/FR, 1.021) shade. Both cultivars grown under deciduous shade had less tillering, thinner leaf blades, and lower chlorophyll concentrations than neutral shade (92% light reduction) grown cultivars. High or low R/FR ratios did not impact root growth.

Changes in spectral light quality influence plant morphogenesis, while a photosynthetic photon flux density reduction (neutral shade) affects growth and production parameters (Stuefer and Huber, 1998). However, physiological and morphological studies of warm-season turfgrasses response to various light spectrums are minimal. Results from this research benefit turfgrass managers in many aspects. First, this study will determine how various spectral qualities of light affect warm-season turfgrasses' performance. This information will allow turfgrass managers to make informed decisions when trees or tree limbs are considered for removal. Second, this research project will further the understanding of why warm-season turfgrasses respond differently when grown under shade. Lastly, few studies have demonstrated tree species alter light spectral quality in a turfgrass setting (McKee, 1963; McBee, 1969; Bell et al., 2000). Taking results from these previous studies and continued research will specify the type of light certain tree species filter. Therefore, this research is the first step in providing a blueprint for golf course design by matching turfgrass cultivars that perform well under specific light filtered by individual tree species. Therefore, the authors hypothesized that different light spectrums, not just light quantity, would alter morphological and physiological status of selected warm-season species to varying degrees and selected turfgrasses would show differences in response to various light treatments. The objective of the research was to investigate relative responses of four warm-season turfgrasses, 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, and 'Tifway' and 'Celebration' bermudagrass commonly used on golf courses, sports fields, and home lawns to red, yellow, blue, and black color shade filters under a greenhouse condition.

MATERIALS AND METHODS

This research included two repeated greenhouse studies in 2007 at the Clemson University, Clemson, SC, Greenhouse Research Complex. Study I was conducted from 18 Apr. 2007 to 13 June 2007. Greenhouse conditions averaged 26/22°C day/night temperature and 60% relative humidity. Study II was conducted from 6 July 2007 to 31 Aug. 2007. Greenhouse conditions averaged day/night temperature of 28/23°C and 70% relative humidity. Temperature and humidity were maintained by an automated computer recording system (Argus Controls, Whiterock, BC). The shade structure consisted of a control (no-shade) and four color shade tarps supported by polyvinyl chloride (PVC) 183 cm in length, 152 cm in width, and 60 cm in height with 2.54-cm-diameter PVC pipes. Shade filters (cloths) were 20 cm above the turfgrass surface. Shade treatments include a control (full sunlight) and four different color shade cloths filtering wavelengths 560 to 720 nm (blue shade cloth), 360 to 520 nm (yellow shade cloth), 360 to 560 nm (red shade cloth), and 360 to 720 (black shade cloth). The percent light reduction for each cloth was adjusted to 65% shade relative to the control.

Turfgrasses selected were Tifway and Celebration bermudagrass, Sea Isle 2000 seashore paspalum, and Diamond zoysiagrass. Plugs (15 cm in diameter) of Tifway and Celebration sod were collected from the 2002 NTEP bermudagrass trials at the Clemson University Research Center and washed free of soil. Sea Isle 2000 and Diamond zoysiagrass were provided by Modern Turf (Rembrant, SC) and the Atlanta Athletic Club (Johns Creek, GA) as sod and then were cut into 15-cm plugs, respectively. All turfgrasses were placed in lysimeters 15-cm diameter by 40-cm-deep lysimeters. The bottom 10 cm was filled with gravels (8–10 mm in diameter) and 30 cm of 85% sand and 15% peat as growth media (v/v) and allowed 4 wk to establish before treatment initiation. Roots were trimmed uniformly below the thatch layer for each turfgrass before transplanting in lysimeter. Turfgrasses in lysimeters were mowed every other day at 1.3 cm using a handheld 7.2 V cordless shear (model ssc1000, Black and Decker, Towson, MD) with clipping removal and watered daily (if necessary) to prevent wilt. During the 4-wk establishment period before shade treatment initiation, turfgrasses were fertilized with 19.4 kg N ha^{-1} wk^{-1} using a combination of 10 N–1.3 P–4.2 K and 5 N–0 P–5.8 K liquid fertilizers (50:50 in the quantity of N) (Progressive Turf, LLC, Ball Ground, GA). Following shade treatment initiation, turfgrasses were fertilized with 9.7 kg N ha^{-1} wk^{-1} using the same liquid fertilizers. All fertilizer was applied with a CO_2–pressurized backpack sprayer calibrated at 1010 L ha^{-1}. No pesticides, insecticides, or herbicides were used during the study period. Lysimeters and shade structures were moved every 2 wk to minimize potential greenhouse location effects.

Data collection included canopy and soil temperature, visual turf quality (TQ), relative clipping yield (RCY), relative lateral spread (RLS), relative chlorophyll concentration (RCC), relative leaf width (RLW), relative root biomass (RRB), relative root density, relative specific root length (RSRL), and root and shoot total nonstructural carbohydrates (TNC).

Canopy and soil temperature were recorded on a clear, cloudless day at solar noon using a thermometer (model 1455 and model 9840, Taylor, Oakbrook, IL) for each lysimeter at a depth of 5 cm. Light quality and photon flux density (μmol m^{-2} s^{-1}) were measured on a clear, cloudless day at solar noon using a spectroradiameter (Model LI-1800; LiCor, Inc., Lincoln, NE) and a quantum radiometer (Model LI-250, LiCor, Inc.), respectively.

Visual turfgrass quality was rated weekly based on color, density, texture, and uniformity of the turfgrass surface. Quality was visually evaluated from 1 to 9: 1 = brown, dead turfgrass, 6 = minimal acceptable turfgrass, 9 = ideal green, healthy turfgrass.

Plants were not mowed 48 h before clipping collection at 2, 4, and 6 wk. Clippings after mowing were collected on poster board, placed in paper bag, oven dried at 80°C for 48 h, and weighed.

Lateral spread (g) was collected at weeks 2, 4, and 6. Stolons were allowed to extend to the exterior of the lysimeter unmowed for 2-wk periods. Every 2 wk, stolon growth exterior of the lysimeter was collected with a pair of scissors. The collected biomass was then oven dried at 80°C for 48 h and weighed.

Shoot width (mm) was measured at weeks 3 and 6. Five fully expanded leaves from each lysimeter were randomly selected. For each leaf, width across the leaf blade was measured 1.5 mm from the base of each individual leaf using a Buffalo stainless steel digital caliper (Buffalo SSDC6).

Clipping chlorophyll (mg g^{-1}) was collected at weeks 3 and 6. Fresh clippings were collected from each lysimeter. Samples were immediately placed in a plastic bag inside a covered bucket to prevent sunlight degradation. Then 0.1 g of clippings was placed in a glass test tube (1.0 cm in width and 14.8 cm in length) with 10 mL of dimethyl sulfoxide (Hiscox and Israelstam, 1979). Samples were incubated in 65°C water on a hot plate (PC-600, Corning, Corning, NY) for 1.5 h and continuously shaken. Upon completion, remaining extract (2 mL) was transferred into cuvettes. Absorbance values were recorded at 663 nm and 645 nm wavelengths using a spectrophotometer (Genesys 20, ThermoSpectronic, Rochester, NY). Blanks without plant tissues were run initially and also after every sixth sample as an internal control to eliminate background errors. The following formula was used to calculate total shoot chlorophyll: (mg g^{-1}) = (8.02 D_{663} + 20.2 D_{645}) × 0.1 (Arnon, 1949).

Relative root biomass, RRLD, and RSRL were measured at week 8. Roots were extracted from lysimeter and washed free through 1-mm sieve. Roots were clipped from shoot base. Before quantifying root biomass, a root measuring software, WinRhizo Pro (Regent Instruments Inc., Quebec, QC), analyzed scanned root images for RRLD and RSRL. WinRhizo provides a computerized method of measuring root length density, total root length (mm) per volume of soil (cm^3), as described by Tennant (1975). For specific root length, a ratio of root length to root dry weight was calculated to determine the amount of root length per milligram of dry weight (cm mg^{-1}). For total root biomass, roots were placed in an oven (80°C) for 48 h, then weighed. Roots were placed in a muffle furnace (Benchtop Muffle Furnace LMF-A550, Omega Engineering, Inc., Stamford, CT) at 525°C for 3 h to provide ash organic weight (Snyder and Cisar, 2000). The remaining ash weight was weighed and then subtracted from the original dry weight, which determined total root biomass (g m^{-2}).

Root TNC (mg g^{-1}) was collected at week 8, while shoot TNC (mg g^{-1}) was collected at weeks 4 and 8 for both experimental runs. Root tissue with rhizome being removed was harvested using a bulk density sampler, which extracted 206 cm^3 (2.54 cm diameter and 10.2 cm in depth) cores before sunrise to minimize potential diurnal fluctuations (Westhafer et al., 1982). Root and shoot TNC was analyzed using Nelson's assay (Nelson, 1944), which determines glucose and fructose in plant tissue (Nelson, 1944; Somogyi, 1952). For detailed methodology, consult Waltz and Whitwell (2005).

The experiment was designed as a restricted split-plot design with three replications and repeated in two experimental runs (Bunnell et al., 2005c). The various light environments were considered blocks, while each turfgrass species was randomized within each block. All statistical computations were conducted using analysis of variance (ANOVA) within the Statistical Analysis System (version 9.1, SAS Institute, Cary, NC). Means were separated by Fisher's least significant difference (LSD) test with an alpha of 0.05. All relative values were based on the control (without shade cloths) and calculated, for example, as the relative clipping yield [(clipping yield under a shade type/clipping yield under full-sunlight) × 100]. Relative values for other parameters were calculated in a similar manner. For root and shoot TNC and RSRL, no significant treatment by species interactions occurred, therefore, main effect means are presented. Data were pooled for both repeated experimental runs as no significant experimental run by treatment interaction occurred.

RESULTS AND DISCUSSION

Canopy and soil temperatures under each shade cloth were reduced 15°C (46°C in the control, 31°C in shade) and 2°C (31°C in the control, 29°C in shade), respectively. Light intensity under each shade material was adjusted to reduce by 55% by using variable layers of the shade cloths (1974 mmol m^{-2} s^{-1} full-sunlight, 895 mmol m^{-2} s^{-1}) compared to the control. The greenhouse glass filtered an additional 10% light and therefore, the overall light reduction under the shade filters was about 65%.

Turfgrasses performance significantly varied under the control (Table 1). Tifway produced 50, 32, and 44% greater clipping yield at weeks 2, 4, and 6, respectively, than Celebration. By week 6, Diamond produced greatest clipping yield (about 85%) compared to other turfgrasses. Celebration increased lateral spread about 87% at weeks 2, 4, and 6 compared to Tifway, while Sea Isle 2000 and Celebration lateral spread were similar. By week 6, Sea Isle 2000 and Celebration had ~81% greater lateral spread than Diamond and Tifway. At weeks 4 and 8, Diamond's leaf blade was about 1.5, 1.1, and 0.7 times thinner than Sea Isle 2000, Celebration, and Tifway, respectively. Both bermudagrass

Table 1. Clipping yield, lateral spread, shoot width, chlorophyll concentration, root mass, and root length density of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass grown at the Clemson University Greenhouse Research Complex.

Turfgrass	Clipping yield			Lateral spread			Shoot width		Chlorophyll		Root mass	Root length density
	Wk 2	Wk 4	Wk 6	Wk 2	Wk 4	Wk 6	Wk 4	Wk 8	Wk 3	Wk 6	Wk 8	Wk 8
	g m^{-2}			g			mm		mg g^{-1}		g m^{-2}	mm cm^{-3}
Diamond	1.05b†	1.44a	1.83a	0.48ab	0.40b	0.37b	0.39d	0.48d	1.76b	1.71c	1.05c	2.6d
Sea Isle 2000	0.83b	1.00b	0.89c	0.54ab	0.53a	0.58a	0.94a	1.25a	1.87b	2.21b	4.78a	10.7a
Celebration	0.89b	1.05b	0.89c	0.64a	0.61a	0.59a	0.85b	0.93b	2.74a	2.97a	2.61b	6.5b
Tifway	1.33a	1.39a	1.28b	0.40b	0.31b	0.29b	0.65c	0.81c	2.34a	2.62ab	1.22c	3.8c
	Analysis of variance											
Turfgrass (T)	**	*	**	*	***	***	***	***	***	***	***	***

*Significant at $P \leq 0.05$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$.

†Values in a column followed by the same letter are not significantly different at $P \leq 0.05$ by protected LSD.

cultivars produced about 44% and about 36% greater chlorophyll concentrations at week 3 compared to Diamond and Sea Isle 2000, respectively. Also, Celebration's chlorophyll concentration was 74 and 34% greater than Diamond and Sea Isle 2000, respectively, by week 6. Sea Isle 2000 produced 0.8, 3.5, and 2.9 times greater root biomass than Celebration, Diamond, and Tifway, respectively. Meanwhile, Celebration root biomass was about 1.3 times greater than Diamond and Tifway. Sea Isle 2000 (10.7 mm cm^{-3}) had the greatest RLD, followed by Celebration (6.5 mm cm^{-3}), Tifway (3.8 mm cm^{-3}), and Diamond (2.6 mm cm^{-3}).

All turfgrass TQs were above the acceptable threshold of 6 under full sunlight (Table 2). However, following 1 wk of shade, Tifway TQ was below the acceptable threshold of 6. Black shade decreased Celebration TQ by about 0.6 rating units compared to other shades. Shade-grown Diamond and Sea Isle 2000 showed no significant TQ decreases compared to control. Comparing turfgrasses, Diamond and Sea Isle 2000 had greater TQ scores than the bermudagrass cultivars for most shade treatments. However, Celebration TQ was greater than Tifway by 1.0 rating unit under yellow and blue shade.

By week 4, all turfgrasses TQ declined under shade (Table 2). Within each turfgrass, black shade consistently reduced TQ compared to other shade types. Yellow, red, and blue shade minimally impacted Diamond, Sea Isle 2000, and Celebration TQ; however, Tifway TQ under blue (3.3) and black (3.3) shade was similar. Comparing turfgrasses, Celebration TQ was about 1.7 rating units greater than Tifway under all shade treatments. Meanwhile, Sea Isle 2000 TQ was 0.8 rating units greater than Celebration under blue and black shade. Only Diamond's TQ was above 6 under black shade.

At the conclusion of the study, Diamond remained above the acceptable TQ threshold, however, all shade types reduced TQ by about 1.5 rating units compared to full sunlight (Table 2). Unlike week 4, blue shade

Table 2. Turfgrass visual quality of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by control and various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.†

Treatment‡	Diamond	Sea Isle 2000	Celebration	Tifway	Analysis of variance in turfgrasses
	Week 1				
Control	8.2	7.8	7.8a§	7.3a	NS¶
Yellow	7.8 A#	7.7 A	7.0b B	6.0b C	***
Red	8.0 A	7.2 B	6.8bc BC	6.3b C	***
Blue	8.0 A	7.5 B	7.0b C	6.0b D	***
Black	7.8 A	7.2 B	6.3c C	5.8b C	***
	Analysis of variance				
Light	NS	NS	***	***	
	Week 4				
Control	8.3a A	8.2a A	7.8a AB	7.5a B	*
Yellow	7.3bc A	6.8b A	6.2b B	4.7b C	***
Red	7.7b A	6.5b B	6.3b B	5.0b C	***
Blue	7.5b A	6.5b B	5.7b C	3.3c D	***
Black	6.8c A	5.5c B	4.7c C	3.3c D	***
	Analysis of variance				
Light	***	***	***	***	
	Week 8				
Control	8.2a	7.8a	7.5a	7.7a	NS
Yellow	7.2b A	5.7bc B	5.0b C	3.7b D	***
Red	7.3b A	5.8b B	5.5b B	4.0b C	***
Blue	6.5c A	5.2c B	4.0c C	2.5c D	***
Black	6.0c A	4.2d B	2.8d C	1.5d D	***
	Analysis of variance				
Light	***	***	***	***	

*Significant at $P \leq 0.05$.

***Significant at $P \leq 0.001$.

†Turfgrass quality based on a scale of 1–9, 1 = brown/dead turfgrass, 6 = minimally acceptable turfgrass, 9 = healthy/green turfgrass.

‡Control, no filter under a greenhouse condition; yellow, filters < 520 nm; red, filters < 560 nm; blue, filters > 560 nm; black, filters all wavelengths.

§Values within a column within each week followed by the same lowercase letter are not significantly different at $P \leq 0.05$ by protected LSD.

¶NS, nonsignificant.

#Values within a row followed by the same uppercase letter are not significantly different at $P \leq 0.05$ by protected LSD.

reduced Diamond, Celebration, and Tifway TQ by about 0.8, 1.3, and 1.4 rating units, respectively, compared to yellow and red shade. The most shade-sensitive turfgrass was Tifway since TQ scores were ≤4 under all shade treatments. Comparing turfgrasses, Sea Isle 2000 TQ was greater than Celebration by 0.7, 1.2, and 1.4 rating units under yellow, blue, and black shade, respectively. Also, Celebration's TQ was about 1.4 rating units greater than Tifway under all shade types. Diamond's TQ was greater than Sea Isle 2000, Celebration, and Tifway by 1.8, 3.2, and 4.5 rating units, respectively, under black shade.

At week 2, under black shade, Celebration and Tifway RCY was about 0.6 and 1.6 times lower, respectively, compared to yellow, red, and blue shade (Table 3). Yellow shade increased Diamond and Sea Isle 2000 RCY about 75 and 70%, respectively, compared to blue and black shade. Comparing turfgrasses, Celebration produced 30 and 65% greater RCY than Diamond under red and blue shade, respectively. Meanwhile, Tifway RCY was about 0.7 and 1.3 times lower under yellow and black shade, respectively, compared to other turfgrasses.

At week 4, no RCY differences were detected between turfgrasses under shade (Table 3). Tifway RCY under black shade was about 1.5 times lower than yellow, red, and blue shade. Also, yellow shade–grown Diamond RCY was 0.3, 0.7, and 1.4 times greater than red, blue, and black shade, respectively. Similarly, under black shade, Sea Isle 2000 and Celebration RCY was 2.1 and 1.7 times lower, respectively, than yellow shade.

By week 6, RCY differences between yellow and red shade and between red and blue shade were not detected (Table 3). However, blue shade reduced Tifway RCY 76% compared to yellow shade. Diamond, Sea Isle 2000, and Celebration RCY under black shade was about 1.1, 1.2, and 1.5 times lower, respectively, compared to other shade types. Comparing turfgrass, Diamond RCY was about 42% lower than Sea Isle 2000 under yellow and red shade. Meanwhile, Celebration had 49, 73, and 98% greater RCY under yellow, red, and blue shade, respectively, compared to Tifway.

At week 2, shade type did not impact Diamond's RLS (Table 4). For all other turfgrasses, RLS differences were not detected between yellow and red shade or between red and blue shade. Celebration and Tifway RLS under black shade was 0.6 and 1.6 times lower, respectively, than yellow, red, and blue shade. Blue shade reduced Sea Isle 2000 RLS 40% compared to yellow shade. Comparing turfgrasses, Celebration's RLS under red and black shade was 0.6 and 1.3 times greater, respectively, than Tifway. Meanwhile, Celebration and Sea Isle 2000 RLS were similar. Diamond's RLS was 47 and 67% greater than Celebration under yellow and black shade, respectively. Similarly, Tifway's RLS under yellow, red, and black shade was 0.8, 0.6, and 2.8 times lower, respectively, than Diamond.

At week 4, yellow shade–grown Diamond had greater RLS than red (52%), blue (80%), and black (106%) shade (Table 4). Blue shade reduced Sea Isle 2000 and Tifway RLS 59 and 88%, respectively, compared to red shade. Blue and black shade impacted RLS similarly for Diamond, Sea Isle 2000, and Tifway, however, Celebration RLS under black shade was 1.6 times lower than blue shade. Comparing turfgrasses, Celebration increased RLS 55% under yellow shade than Tifway. Diamond's RLS under blue and black shade was 0.6 and 1.7 times greater, respectively, than Sea Isle 2000, Celebration, and Tifway. Similar to week 2, RLS variation between Sea Isle 2000 and Celebration did not occur.

At week 6, Sea Isle 2000 and Celebration RLS was 1.2 and 2.7 times lower under black shade, respectively, compared to blue shade (Table 4). Red shade reduced Sea Isle 2000 RLS 35% compared to yellow shade.

Table 3. Relative clipping yield (%) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.

Treatment†	Diamond	Sea Isle 2000	Celebration	Tifway	Analysis of variance in turfgrasses
			Week 2		
Yellow	119.8a‡ A§	126.8a A	143.9a A	76.5a B	**
Red	101.1a B	97.8ab B	131.4a A	88.2a B	*
Blue	69.3b B	91.0b AB	114.3a A	76.3a B	*
Black	67.9b A	63.2b A	79.7b A	31.1b B	***
			Analysis of variance		
Light	***	**	*	*	
			Week 4		
Yellow	100.9a	105.9a	110.7a	82.4a	NS¶
Red	77.1b	90.2ab	100.1ab	70.4a	NS
Blue	61.2bc	65.8b	71.9bc	70.7a	NS
Black	42.7c	33.7c	41.2c	29.3b	NS
			Analysis of variance		
Light	***	***	**	**	
			Week 6		
Yellow	69.8a B	102.7a A	99.9a A	67.1a B	*
Red	63.7a B	86.4a A	94.9a A	54.7ab B	**
Blue	60.7a AB	74.5a A	75.7a A	38.2bc B	*
Black	31.3b	39.7b	36.7b	21.4c	NS
			Analysis of variance		
Light	**	**	***	***	

*Significant at $P \le 0.05$.

**Significant at $P \le 0.01$.

***Significant at $P \le 0.001$.

†Yellow, filters <520 nm; red, filters <560 nm; blue, filters >560 nm; black, filters all wavelengths.

‡Values within a column within each week followed by the same lowercase letter are not significantly different at $P \le 0.05$ by protected LSD.

§Values within a row followed by the same uppercase letter are not significantly different at $P \le 0.05$ by protected LSD.

¶NS, nonsignificant.

Diamond, Sea Isle 2000, Celebration, and Tifway RLS under red shade was 0.8, 1.9, 3.6, and 4.3 times greater, respectively, than black shade. Comparing turfgrasses, blue shade increased Celebration RLS 72% compared to Tifway. Sea Isle 2000, Celebration, and Tifway performed similarly, regardless of shade type. However, Diamond had 1.5 and 2.2 times RLS spread than Celebration and Tifway, respectively, under all shade types.

Shade types did not impact RLW at week 4 (Table 5). Also, few RLW differences were noted between turfgrasses. However, black shade-grown Sea Isle 2000 (23%), Celebration (29%), and Tifway (36%) had RLW reductions compared to Diamond.

Diamond and Sea Isle 2000 RLW was not impacted by shade types at week 8 (Table 5). Black shade reduced Celebration RLW 38 and 25% compared to red and blue shade, respectively. For Tifway, yellow shade increased RLW 25% compared to other shade types. No RLW differences were noted between turfgrasses by week 8.

By week 3, blue shade increased Diamond RCC 46 and 32% compared to yellow and red shade, respectively (Table 6). Meanwhile, blue and black shade reduced Sea Isle 2000 RCC 20 and 33%, respectively, compared to yellow shade. Black shade reduced Celebration and Tifway RCC about 30 and 59%, respectively, compared to yellow, red, or blue shade. Comparing turfgrasses, Diamond had 37% less RCC than Sea Isle 2000, Celebration, and Tifway under yellow shade. However, Diamond had 27% greater RCC than Sea Isle 2000 and Tifway under blue shade. Under black shade, Sea Isle 2000 and Celebration had 31% greater RCC than Tifway.

Few RCC differences were noted among turfgrasses by week 6 (Table 6). Black shade reduced Tifway RCC 43, 34, and 27% compared to yellow, red, and blue shade, respectively. Comparing turfgrasses, Diamond had 49, 57, and 80% greater RCC than Sea Isle 2000, Celebration, and Tifway, respectively.

Different shade types did not impact root TNC; however, control increased root TNC about 10% compared to other light treatments (Table 7). Sea Isle 2000 had greatest root TNC (36.5 mg g^{-1}), while Diamond (34.1 mg g^{-1}) and Tifway (33.8 mg g^{-1}) had lowest root TNC.

The control increased shoot TNC 16 and 14% at weeks 4 and 8, respectively, compared to all shade types (Table 7). At week 4, yellow shade shoot TNC was 15% greater than black shade, while yellow and red shade increased shoot TNC 11% compared to black shade by week 8. At week 8, Sea Isle 2000 had 12% greater shoot TNC than Tifway and Celebration.

The control had the lowest (8.4 cm mg^{-1}) RSRL, while blue shade increased RSRL 48% compared to other shade types (Table 7). Diamond and Celebration had similar RSRL, while Tifway RSRL was about 1.0 times greater than Sea Isle 2000.

Table 4. Relative lateral spread (%) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.

Treatment†	Diamond	Sea Isle 2000	Celebration	Tifway	Analysis of variance in turfgrasses
			Week 2		
Yellow	101.7 A‡	93.4a§ AB	69.2a BC	57.7a C	**
Red	76.8 A	90.9ab A	76.9a A	47.1a B	*
Blue	66.4	66.9bc	72.5a	48.0a	NS¶
Black	73.9 A	52.8c AB	44.3b B	19.4b C	**
			Analysis of variance		
Light	ns	**	**	**	
			Week 4		
Yellow	97.1a A	80.7a AB	65.9a B	42.4ab C	***
Red	63.7b	61.0b	46.3b	52.2a	NS
Blue	53.9b A	38.4c B	39.0b B	27.7bc B	**
Black	47.1b A	24.6c B	15.1c B	15.5c B	***
			Analysis of variance		
Light	**	***	***	**	
			Week 6		
Yellow	99.0a A	73.3a AB	49.7a B	52.9a B	**
Red	73.8ab A	54.4b AB	40.9ab B	36.3a B	*
Blue	56.9bc A	39.8b B	32.9b B	19.1b C	***
Black	40.8c A	18.5c B	8.9c B	6.8b B	***
			Analysis of variance		
Light	**	***	***	***	

*Significant at $P \leq 0.05$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$.

†Yellow, filters <520 nm; red, filters <560 nm; blue, filters >560 nm; black, filters all wavelengths.

‡Values within a column within each week followed by the same uppercase letter are not significantly different at $P \leq 0.05$ by protected LSD.

§Values within a row followed by the same lowercase letter are not significantly different at $P \leq 0.05$ by protected LSD.

¶NS, nonsignificant.

Diamond's RRB under red shade was 3.6 and 1.5 times greater than blue and black shade, respectively (Table 8). Comparing turfgrasses, Diamond and Sea Isle 2000 performed similarly under yellow and red shade; however, Sea Isle 2000 had 1.9 and 4.7 times greater RRB than Diamond and Tifway, respectively, under blue shade.

Under different shade types, no RRLD differences were noted between turfgrasses (Table 8). However, different light environments impacted RRLD for each turfgrass, except Celebration. Diamond RRLD under red shade was 1.4 times greater than blue and black shade. Similarly, red shade increased Sea Isle 2000 RRLD about 30% compared to blue and black shade. However, Tifway RRLD under blue shade was about 3.0 times lower than yellow and red shade.

Few previous reports have investigated the morphological and physiological responses of warm-season turfgrasses to different light spectral qualities. Also, Diamond,

Table 5. Relative leaf width (%) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.

Treatment†	Diamond	Sea Isle 2000	Celebration	Tifway	Analysis of variance in turfgrasses
			Week 4		
Yellow	88.4	84.3	90.3	77.7	NS‡
Red	87.7	104.4	136.8	75.4	NS
Blue	84.7	72.3	82.3	65.3	NS
Black	100.1 A§	81.2 B	77.4 B	73.4 B	*
			Analysis of variance		
Light	NS	NS	NS	NS	
			Week 8		
Yellow	86.8	84.9	72.4ab¶	89.2a	NS
Red	89.8	82.3	84.6a	75.5b	NS
Blue	83.3	76.5	76.6a	72.3b	NS
Black	81.3	73.9	61.5b	65.9b	NS
			Analysis of variance		
Light	NS	NS	**	**	

*Significant at $P \le 0.05$.

**Significant at $P \le 0.01$.

†Yellow, filters <520 nm; red, filters <560 nm; blue, filters >560 nm; black, filters all wavelengths.

‡NS, nonsignificant.

§Values within a row within each week followed by the same uppercase letter are not significantly different at $P \le 0.05$ by protected LSD.

¶Values within a column followed by the same lowercase letter are not significantly different at $P \le 0.05$ by protected LSD.

Table 6. Relative chlorophyll concentration (RCC in %) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.

Treatment†	Diamond	Sea Isle 2000	Celebration	Tifway	Analysis of variance of turfgrasses
			Week 3		
Yellow	64.7c‡ B§	87.8a A	91.2a A	87.2a A	**
Red	71.2bc	77.0ab	85.9a	78.3a	NS¶
Blue	94.2a A	73.4b B	84.4a AB	75.4a B	*
Black	81.7ab A	66.0b B	66.9b B	50.6b C	**
			Analysis of variance		
Turfgrasses	**	**	*	*	
			Week 6		
Yellow	110.1	92.7	90.3	89.4a	NS
Red	99.8	82.6	85.1	83.9a	NS
Blue	100.1	80.2	87.4	79.1a	NS
Black	112.1 A	75.3 B	71.6 B	62.4b B	*
			Analysis of variance		
Turfgrasses	NS	NS	NS	**	

*Significant at $P \le 0.05$.

**Significant at $P \le 0.01$.

†Yellow, filters <520 nm; red, filters <560 nm; blue, filters >560 nm; black, filters all wavelengths.

‡Values within a column within each week followed by the same lowercase letter are not significantly different at $P \le 0.05$ by protected LSD.

§Values within a row followed by the same uppercase letter are not significantly different at $P \le 0.05$ by protected LSD.

¶NS, nonsignificant.

Sea Isle 2000, and Celebration are turfgrasses gaining popularity; however, direct comparisons of their performance in full-sunlight and shade have not been reported.

In this study, under control and shade, turfgrasses performance varied significantly. Diamond zoysiagrass was the least shade-affected turfgrass. Turfgrass quality scores were consistently higher, chlorophyll concentration decreases compared to control were minimal, and Diamond's lateral spread growth was least impacted by shade compared to other turfgrasses. Bunnell et al. (2005b) also indicated zoysiagrass was more shade tolerant than two bermudagrass cultivars. Also, Diamond zoysiagrass can maintain acceptable TQ under 75 to 81% shade (Qian et al., 1998; Qian and Engelke, 1999). Previous studies have also indicated seashore paspalum cultivars are more shade tolerant than the bermudagrass cultivars 'TifSport' and TifEagle (Jiang et al., 2004; 2005). Similar results were noted in this study as Sea Isle 2000 consistently outperformed Tifway in shade; however, data collected indicates Celebration possesses a similar shade tolerance to Sea Isle 2000. Regardless, both cultivars TQ scores were below 6 by week 8 of shade stress.

Previous reports indicate Celebration bermudagrass is more shade tolerant than Tifway bermudagrass (Bunnell et al., 2005b; Baldwin et al., 2008). While plants have evolved mechanisms to adapt to natural variations in the environment, including photosynthesis, these adaptive changes are poorly understood regarding bermudagrass shade tolerance. A reason for this enhanced shade adaptation appears to be a morphological advantage exhibited by Celebration. Typically, inhibited lateral stem growth negatively impacts warm-season turfgrass development when sunlight is intercepted (Beard, 1997). Also, a shaded cool-season turfgrass, tall fescue, shifted biomass production from roots to shoots, which led to thinner and less dense leaf blades compared to full sunlight (Allard et al., 1991). In this study, under control, Celebration clipping yield was consistently lower than Tifway, while Celebration lateral spread was greater than Tifway. Similar trends were noted under shade. Karcher et al. (2005) also reported Celebration recovery from divot stress was quicker than Tifway bermudagrass. Clipping yield and lateral spread data indicates Celebration minimizes vertical shoot growth and continues energy constituent allocation for continued lateral shoot growth under shade. This morphological adaptation is possibly related to plant hormone manipulation, in particular, gibberellic acid, photoreceptor activity (phytochrome/chromophore), anatomical alterations, or efficient utilization of short bursts of solar energy (sunflecks). All of these possibilities would lead to increased CO_2 fixation capacity at reduced light intensities (Taiz and Zeiger, 2006).

Boardman (1977) indicated shade plants can increase solar energy collection by altering chloroplast arrangement. Few published reports have compared shade-sensitive and shade-tolerant turfgrass cultivars anatomical differences under shade. Wilkinson and Beard (1975) reported shade-tolerant 'Pennlawn' red fescue (*Festuca rubra* L.) grown under shade developed a thicker cuticle layer, enhanced vascular support tissue, and maintained a distinct chloroplast structure compared to shade-sensitive 'Merion' Kentucky bluegrass (*Poa pratensis* L.). However, Wherley et al. (2005) noted morphological or anatomical differences between shade-tolerant and shade-sensitive tall fescue cultivars grown under shade such as tiller numbers, width of leaves, and chlorophyll concentration changes. Future studies investigating the anatomical development of Celebration may provide clues to its apparent relative shade tolerance.

Efficient conversion of sunflecks into carbohydrate production supporting lateral stem growth may also enhance Celebration's relative shade tolerance. The unique anatomical organization of C_4 plants enhances adaptation to warm and dry climatic regions because CO_2 levels remain elevated near ribulose bisphosphate carboxylase/oxygenase (Rubisco). However, this unique anatomical organization may reduce C_4 plants' ability to adapt to variable environments, such as low light, because C_4 photosynthesis requires coordinated changes between mesophyll and bundle sheath tissues (Sage and McKown, 2006). Specifically, C_4 plants cannot readily adapt to sunflecks (typically occur in heavily shaded environments) due to distance between mesophyll CO_2 fixation reactions and bundle sheath Calvin cycle metabolites (Horton and Neufeld, 1998). Future studies determining the importance of sunfleck contribution to C_4 turfgrass photosynthesis is warranted.

Previous studies have reported root growth reductions of warm-season turfgrasses under shade (Qian et al., 1998; Qian and Engelke, 1999; Baldwin et al., 2008), however, to the authors' knowledge, this is the first project to examine RLD and SRL under a different light-shaded microenvironment. Relative to control, shade, regardless of type, reduced root biomass and RLD for all turfgrasses. A high RLD is correlated with nitrate leaching reductions for turfgrasses (Bowman et al., 2002). Therefore, N rates for turfgrasses under shade should be reduced because these areas are more prone to N leaching due to root morphology alterations. Under control, Sea Isle 2000 produced greatest root biomass and RRLD. Therefore, this grass may be a preferred turfgrass of choice adjacent to environmentally sensitive areas, such as water features, due to potential efficiency for nitrate uptake. Main effect means indicated control had lowest SRL. A high SRL indicates a thin, highly branched root system, while a low RSRL indicates a short, stubby root system. Therefore, shade not only reduces root biomass and RRLD, but creates a thinner, highly branched root system.

Light quality impacting turfgrass growth and development remains poorly understood. In other plant disciplines, spectral shade increases individual leaf area and plant biomass compared to neutral shade (typically used in turfgrass research) (Stuefer and Huber, 1998). Increased aboveground biomass for shade-sensitive turfgrasses is detrimental due to increased tissue removal from mowing. Overall, in this study, yellow and red shade was least detrimental, followed by blue shade, while black shade resulted in poorest performance of all turfgrasses. Similar results have been noted in other plant species. Kim et al. (2004) noted red shade increased chrysanthemum [*Dendranthema grandiflorum* (Ramat.) Kitamura] net photosynthetic rates compared to blue shade; however, Lee et al. (2007) reported similar photosynthetic rates under blue and red shade. Compared to red shade, Kim et al. (2004) reported chrysanthemums grown under blue shade had fewer stomata; however, no stomata frequency differences occurred between red and blue shade in Ashwagandha [*Withania somnifera* (L.) Dunal.] or grape (*Vitis* spp.) (Lee et al., 2007; Poudel et al., 2008). Presumably, more stomata would increase photosynthetic rates; however, no definitive trend has emerged in the literature regarding this issue. Conflicting

Table 7. Root and shoot total nonstructural carbohydrates (TNC, mg g^{-1}) and specific root length (cm mg^{-1}) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by control and various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.

	Root TNC	Shoot TNC		Specific root length
	Week 8	Week 4	Week 8	Week 8
	mg g^{-1}			cm mg^{-1}
Treatment†				
Control	37.4a‡	55.6a	59.4a	8.4c
Yellow	33.2b	50.5b	54.3b	11.5bc
Red	34.8b	48.3bc	54.6b	12.4bc
Blue	33.8b	49.0bc	50.9bc	18.5a
Black	34.9b	44.1c	49.3c	13.9b
Turfgrass				
Diamond	34.1b	48.6	54.6ab	12.9b
Sea Isle 2000	36.5a	47.7	57.5a	8.8c
Celebration	34.9ab	51.1	51.4b	12.6b
Tifway	33.8b	50.7	51.3b	17.7a
		Analysis of variance		
Light (L)	**	***	***	***
Turfgrasses (T)	*	NS§	**	***
L × T	NS	NS	NS	NS

*Significant at $P \leq 0.05$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$.

†Control, no filters under a greenhouse condition; yellow, filters <520 nm; red, filters <560 nm; blue, filters >560 nm; black, filters all wavelengths.

‡Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by protected LSD.

§NS, nonsignificant.

Table 8. Relative root biomass (%) and relative root length density (%) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by control and various types of filtered light (about 65% reduction) at the Clemson University Greenhouse Research Complex.

	Relative root biomass Week 8				Analysis of variance in turfgrasses (G)
Treatment†	Diamond	Sea Isle 2000	Celebration	Tifway	
Yellow	54ab‡ A§	45 A	21 B	22 B	***
Red	64a A	48 AB	22 B	13 B	*
Blue	14c B	40 A	27 AB	7 B	*
Black	26bc	25	12	14	NS¶
	Analysis of variance				
Light (l)	*	NS	NS	NS	
	Relative Root Length Density Week 8				
Treatment	Diamond	Sea Isle 2000	Celebration	Tifway	
Yellow	65.7ab	46.1ab	37.9	82.9a	NS
Red	82.4a	48.8a	38.2	76.6a	NS
Blue	31.6b	39.3bc	35.8	19.9b	NS
Black	38.7b	36.1c	18.4	36.7ab	NS
	Analysis of variance				
Light (l)	**	*	NS	**	

*Significant at $P \leq 0.05$.

**Significant at $P \leq 0.01$.

***Significant at $P \leq 0.001$.

†Yellow, filters <520 nm; red, filters <560 nm; blue, filters >560 nm; black, filters all wavelengths.

‡Values within a column within each parameter followed by the same lowercase letter are not significantly different at $P \leq 0.05$ by protected LSD.

§Values within a row followed by the same uppercase letter are not significantly different at $P \leq 0.05$ by protected LSD.

¶NS, nonsignificant.

reports are possibly due to comparison of different plant species between studies, type of shade between studies varying slightly, or different plant species responding differently to variations in the light environment.

Compared to blue shade, yellow shade increased clipping yield (i.e., plant height) in this study. Also, chlorophyll concentrations remained similar between different shade types; however, blue shade increased Diamond chlorophyll concentration 32 and 46% (week 3) compared to red and yellow shade, respectively. Similar results have been noted in other studies. In chrysanthemums plants, filtering wavelengths <500 nm produced tallest plants (Khattak and Pearson, 2006), while grape genotypes grown under about 600 to 680 nm light had lowest chlorophyll content, but greatest plant height compared to about 430 to 510 nm light (Poudel et al., 2008). Similarly, Lee et al. (2007) suggested light with a peak emission of 440 nm produced 54% greater chlorophyll, but 8% less plant dry weight than light with a peak emission of 650 nm for Ashwagandha. In another study, red shade increased lettuce (*Lactuca sativa* L.) shoot growth by a factor of 3.8 compared to blue light (Hunter and Burritt, 2004). Kim et al. (2004) reported chrysanthemums exposed to 650 nm light increased plant dry weight 40% compared to plants grown under 440 nm light; however, chlorophyll concentrations were not impacted by either type of light. McVey et al. (1969) also reported blue shade resulted in reduced turfgrass shoot biomass production. It appears plant light receptors, such as cryptochrome and phytochrome, function prominently in controlling aboveground biomass production.

In summary, this study has demonstrated that both quantity and quality of light impacts growth and development of various turfgrass species. Also, turfgrass species' growth responses varied under reduced light. Overall, black shade most negatively inhibited parameters measured followed by blue shade, while yellow and red shade was least detrimental. For turfgrasses, Diamond was the least affected by light quality, while Tifway was the most shade sensitive. Celebration and Sea Isle 2000 performed similarly. Future studies continuing light quality research for other warm-season turfgrass cultivars are warranted, as well as field studies confirming these greenhouse results. This study implies different types of shade significantly impact the performance of warm-season turfgrasses.

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