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Research conducted at the Clemson University greenhouse research complex determined the impact various spectral qualities of light had on morphological and physiological responses of 'Diamond' zoysiagrass (*Zoysia matrella* (L.) Merr), 'Sea Isle 2000' seashore paspalum (*Paspalum vaginatum* Swartz.), and 'Tifway' and 'Celebration' bermudagrass (*Cynodon dactylon* X *C. transvaalensis).* This study implies different types of shade significantly impact the performance of warm-season turfgrasses.

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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 350 projects at a cost of $29 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

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Altered Light Spectral Qualities Impact on Warm-season Turfgrass Growth and Development

Christian Baldwin and Haibo Liu

SUMMARY

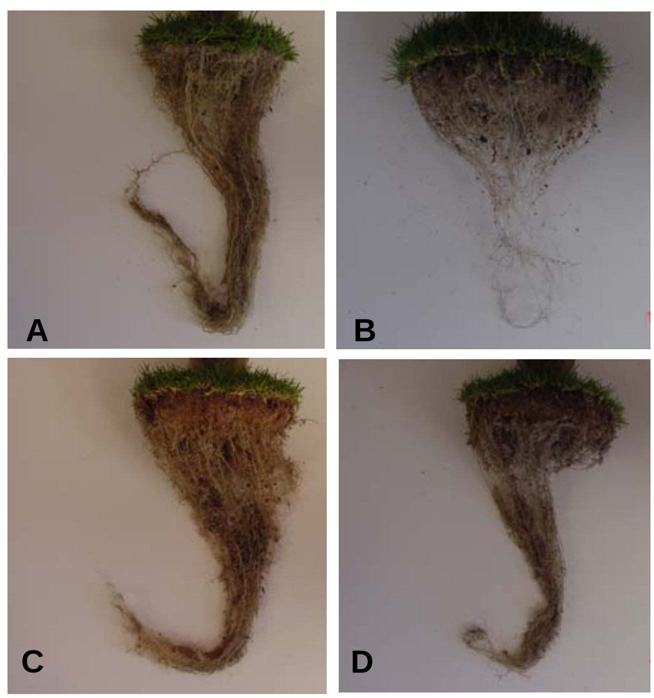
Research conducted at the Clemson University greenhouse research complex determined the impact various spectral qualities of light had on morphological and physiological responses of 'Diamond' zoysiagrass (*Zoysia matrella* (L.) Merr), 'Sea Isle 2000' seashore paspalum (*Paspalum vaginatum* Swartz.), and 'Tifway' and 'Celebration' bermudagrass (*Cynodon dactylon* X *C. transvaalensis).* The study found:

- 'Diamond' was the most shade tolerant turfgrass, while 'Celebration' and 'Sea Isle 2000' performed similarly. The least shade tolerant turfgrass was 'Tifway'.
- Yellow and red shade was least detrimental, while black shade most negatively inhibited parameters measured, followed by blue shade.
- Under full-sunlight, 'Sea Isle 2000' produced 3.5, 0.8, and 2.9 times greater root biomass and 3.1, 0.6, and 1.8 times greater root length density (RLD) than 'Diamond', 'Celebration', and 'Tifway', respectively.
- Relative to full sunlight, all shade types reduced root biomass and root length density (RLD) for all warm-season turfgrasses. A high RLD has been correlated with nitrate leaching reductions in previous research. Therefore, nitrogen rates should be reduced in shaded areas because a turfgrass root system is less efficient at nitrate uptake, thus more prone to nitrate leaching.
- This study implies different types of shade significantly impact the performance of warm-season turfgrasses.

Turfgrass growth and development under shade is inhibited by reduced photosynthesis, increased disease pressure, reduced carbohydrate production, tree root competition, and reduced lateral stem growth. Another factor limiting turfgrass growth and development under shade is various types of filtered light. The photosynthetic active radiation (PAR) 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 (27).

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 (27). In nature, trees alter spectral quality available for turfgrass development (5), however, limited research has investigated the light specific tree species filter in highly maintained turfgrass environments. Also, most shade research has focused on light quantity using black neutral shade material (2, 4, 7, 14, 25).

While previous research has demonstrated that shade source alters the type of light available for turfgrass growth (5, 9, 16, 17), few reports have investigated light quality impacts on turf-



Under full-sunlight, 'Diamond' zoysiagrass (A) produced 3.5, 0.8, and 2.9 times greater root biomass and 3.1, 0.6, and 1.8 times greater root length density (RLD) than 'Sea Isle 2000' seashore paspalum (B), and 'Celebration' (C) and 'Tifway' (D) bermudagrass, respectively.

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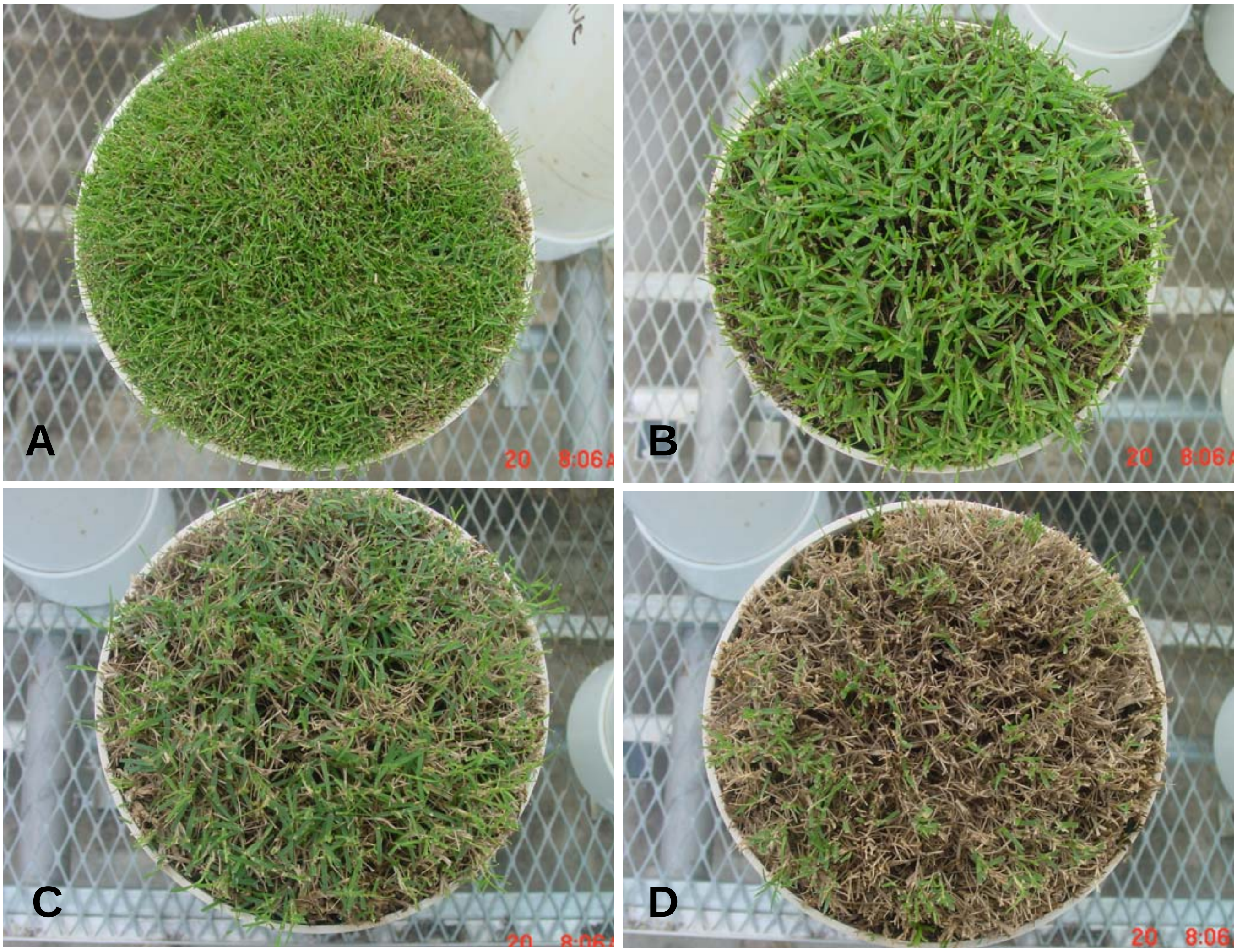

This study implies different types of shade significantly impact the performance of warm-season turfgrasses. Shown above are 'Diamond' zoysiagrass (A), 'Sea Isle 2000' seashore paspalum (B), 'Celebration' (C) and 'Tifway' (D) bermudagrass after 6 weeks of blue shade illustrating the differences between species and cultivars of warm-season grasses.

grass growth and development. McBee (16) noted blue light minimized stem elongation, while red light enhanced stem elongation for selected bermudagrass (*Cynodon spp.*) cultivars. McVey et al. (18) noted blue light reduced clipping fresh weight production and vertical shoot elongation in 'Windsor' Kentucky bluegrass (*Poa pratensis* L.) and 'Tifgreen' bermudagrass.

Wherley et al. (30) subjected 'Plantation' (shade tolerant) and 'Equinox' (shade sensitive) tall fescue (*Festuca arundinacea* Schreb.) to deciduous (*Acer spp.* and F*raxinus spp.*, R:FR - 0.428) and neutral (R:FR - 1.021) shade. Both cultivars grown under deciduous shade produced significantly less tillering, greater leaf width, higher chlorophyll concentrations, and greater leaf thickness 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 (PPFD) reduction (neutral shade) affects growth and production parameters (26). However, physiological and morphological studies of warm-season turfgrasses in response to various light spectrums are lacking. 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. Secondly, this research project will further the understanding of

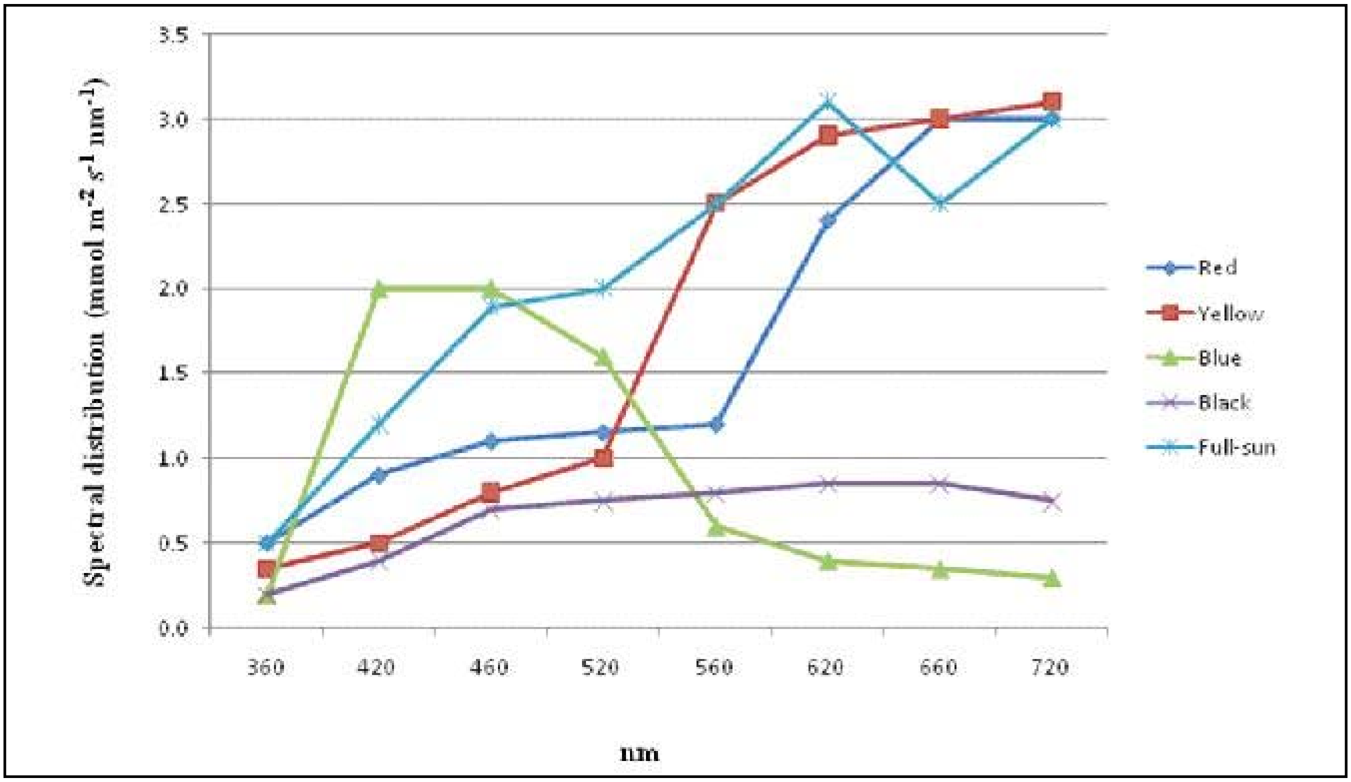

Figure 1. Portion of light spectrum filtered by the shading material selected for a greenhouse experiment

why warm-season turfgrasses respond differently when grown under shade.

Lastly, few studies have demonstrated how tree species alter light spectral quality in a turfgrass setting (5, 16, 17). 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. We hypothesize that different light spectrums, not just light quantity, alter morphological and physiological status of selected warm-season species to varying degrees and selected turfgrasses show genetic differences in response to various light treatments.

Materials and Methods

This research included two repeated studies at the Clemson University, Clemson, SC, Greenhouse Research Complex. Study I was conducted from April 18, 2007 - June 13, 2007, while study II was conducted from July 6, 2007 - August 31, 2007. Greenhouse conditions averaged 27°C / 23°C day/night temperature and 65% relative humidity for both studies.

Shade treatments include a control (full sunlight) and four different color shade cloths filtering wavelengths 560 - 720 nm (blue shade cloth), 360 - 520 nm (yellow shade cloth), 360 - 560 nm (red shade cloth), and 360-720 (black shade cloth) (Figure 1). Red to far red ratio (R:FR) for each cloth was approximately 1.171, while percent light reduction for each treatment was approximately 65%.

Turfgrasses selected were 'Tifway' and 'Celebration' bermudagrass (*Cynodon dactylon* X *C. transvaalensis*), 'Sea Isle 2000' seashore paspalum (*Paspalum vaginatum* Swartz.), and 'Diamond' zoysiagrass (*Zoysia matrella* (L.) Merr). Plugs (15-cm) 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), respectively.

All turfgrasses were placed in lysimeters 15 cm in diameter and 40 cm in height filled with

10 cm of gravel (8 mm to 10 mm in diameter) and 30 cm of 85% sand and 15% peat as growth media (v:v) and allowed to establish for four weeks prior to treatment initiation. Prior to transferring turfgrasses in lysimeters, roots were clipped similarly below the thatch base for each turfgrass. Lysimeters were mowed every other day at 1.3 cm using a handheld cordless shear with clipping removed and watered daily (if necessary) to prevent wilt.

During the four-week establishment period prior to shade-treatment initiation, 19.4 kg N ha^{-1} was provided weekly using a combination of 10N-1.3P-4.2K and 5N-0P-5.8K liquid fertilizers (Progressive Turf, LLC., Ball Ground, GA). Following shade treatment initiation, turfgrasses were fertilized with 9.7 kg N ha^{-1} weekly with a CO_2-pressurized backpack sprayer calibrated at 107 gal. acre^{-1}. Lysimeters and shade structures were moved every two weeks to minimize potential greenhouse location effects.

Data collection included canopy and soil temperature, light quality and quantity, visual turfgrass quality (TQ), clipping yield, lateral spread, total shoot chlorophyll, shoot width, total root biomass, root length density (RLD), and root and shoot total non-structural carbohydrates (TNC).

All microenvironmental parameters were collected on a clear, cloudless day at solar noon. Canopy and soil temperature were recorded using an indoor/outdoor thermometer (model #1455 and model #9840, Taylor, Oakbrook, IL). Light quality and photon flux density (mol m^{-2} s^{-1}) were measured using a spectroradiometer (Model LI-1800; LiCor, Inc., Lincoln, NE) and a quantum radiometer (Model LI-250, LiCor, Lincoln, NE), respectively.

Visual turfgrass quality (TQ) was rated every two weeks 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.

Clipping yield (g) was collected at weeks 2, 4, and 6 following 48 hrs of growth since the last clipping. Lysimeters were tilted at a 45° angle and mowed with a handheld cordless shear 1.3 cm above the surface. Clippings fell onto poster board (122 cm by 122 cm) and then placed into a brown bag. Clippings were oven-dried at 80°C for 48 hr and weighed to quantify shoot production.

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

Shoot chlorophyll (mg g^{-1}) was collected at weeks 3 and 6. Fresh clippings (0.1 g) were collected and placed in 10 mL of dimethyl sulfoxide (DMSO), eliminating the need for shoot tissue grinding to extract chlorophyll (10). Samples were incubated in 65° C water for 1.5 hr and continuously shaken. Absorbance values were recorded at 663 nm and 645 nm wavelengths using a spectrophotometer (Genesys 20, ThermoSpectronic, Rochester, NY) and total shoot chlorophyll was calculated using the methods of Arnon (1).

Total root biomass and root length density (RLD) were measured at week 8. Roots were extracted from the entire lysimeter at washed free of soil using a 1-mm sieve. Once all soil was completely removed using tap water, roots were clipped from the shoot tissue base. Prior to quantifying root biomass, a root measuring software, WinRhizo Pro (Regent Instruments Inc., Quebec, Qc, Canada), analyzed scanned root images for RLD. WinRhizo provides a computerized method of measuring RLD, total root length (mm) per volume of soil (cm^3) as described by Tennant (28).

For total root biomass, roots were placed in an oven (80° C) for 48 hr, then weighed. Following oven drying, roots were placed in a muffle furnace (Benchtop Muffle Furnace LMF-A550, Omega Engineering, Inc., Stamford, CT) at 525° C for three hrs to provide ash-free weight (23). Samples were weighed and then subtracted from the original dry weight, which determined total root biomass (g m^{-2}).

Turfgrass	Clipping Yield Wk 6	Lateral Spread Wk 6	Chlorophyll Wk 6	Root Mass Wk 8	Root Length Density Wk 8
	($g\ m^{-2}$)	(g)	($g\ mg^{-1}$)	(g)	($mm\ cm^{-3}$)
Diamond†	0.33a‡	0.37b	1.71c	0.19c	2.6d
Sea Isle 2000	0.16c	0.58a	2.21b	0.86a	10.7a
Celebration	0.16c	0.59a	2.97a	0.47b	6.5b
Tifway	0.23b	0.29b	2.62ab	0.22c	3.8c

†Diamond: 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass.

‡Values in a column within each week followed by the same letter are not significantly different at P=0.05 by protected LSD.

Table 1. Clipping yield (g), lateral spread (g), shoot chlorophyll concentration ($mg\ g^{-1}$), root mass (g), and root length density ($mm\ cm^{-3}$) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass grown under full-sunlight at the Clemson University Greenhouse Research Complex.

Root total non-structural carbohydrates (TNC, $mg\ g^{-1}$) were collected at week 8, while shoot TNC ($mg\ g^{-1}$) was collected during weeks 4 and 8. TNC analysis was analyzed using Nelson's Assay (19), which determines glucose and fructose in plant tissue (19, 24). For detailed methodology, consult Waltz and Whitwell (29).

Data Analysis

Treatments were arranged in a randomized block design with three replications. All statistical computations were conducted using analysis of variance (ANOVA) within the Statistical Analysis System (SAS Institute, Cary, NC). Means were separated by Fisher's Least Significant Difference (LSD; 0.05). Under full sunlight, significant differences occurred for turfgrass quality, clipping yield, lateral spread, shoot chlorophyll concentration, root biomass, and RLD, therefore, relative values were calculated to determine the impact different types of shade had on each turfgrass.

For root and shoot TNC, no significant treatment by species interactions occurred, therefore, main-effect means are presented. Data are pooled for both repeated studies as no significant study by treatment interaction occurred.

Results

Microenvironment

Canopy temperature under each shade cloth was reduced 15^{o} C (46^{o} C in full sunlight; 31^{o} C in shade), while soil temperature under shade was reduced 2^{o} C (31^{o} C in full sunlight; 29^{o} C in shade) compared to full sunlight. Light intensity under each shade material was reduced by 55% (1,974 mmol m^{-2} s^{-1} full sunlight; 895 mmol m^{-2} s^{-1}) compared to full sunlight. The greenhouse glass provided an additional 10% light reduction. Red to far red ratio was approximately 1.171 for all light treatments.

Full Sunlight

Turfgrasses performance significantly varied under full-sunlight (Table 1). ‘Tifway’ produced 44% greater clipping yield than ‘Celebration’. Meanwhile, ‘Diamond’ had greatest clipping yield compared to other turfgrasses. ‘Celebration’ increased lateral spread 103% compared to ‘Tifway’, while ‘Sea Isle 2000’ had 57% greater lateral spread than ‘Diamond’. ‘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’

Treatment	Turfgrass Quality† Diamond	Sea Isle 2000	Celebration	Tifway
	Week 8			
Sun‡	8.2a§	7.8a	7.5a	7.7a
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
	Relative Clipping Yield (%)			
	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
	Relative Lateral Spread (%)			
	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
Black	73.9 A	52.8c AB	44.3b B	19.4b C

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

‡Sun: full-sunlight, Yellow: filters <520 nm, Red: filters <560 nm, Blue: filters >560 nm, and Black: filters all wavelengths.

§Values within a column within each parameter measured followed by the same letter are not significantly different at P=0.05 by protected LSD.
Values within a row followed by the same letter are not significantly different at P=0.05 by protected LSD.

Table 2. Turfgrass quality, relative clipping yield, and relative lateral spread of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by various types of filtered light (~65% reduction) at the Clemson University Greenhouse Research Complex.

root biomass was approximately 1.1 times greater than 'Diamond' and 'Tifway'. 'Sea Isle 2000' (10.7 mm cm^{-3}) had greatest RLD, followed by 'Celebration' (6.5 mm cm^{-3}), 'Tifway' (3.8 mm cm^{-3}), and 'Diamond' (2.6 mm cm^{-3}).

Shade

Turfgrass Quality

After 8 weeks of 65% shade, 'Diamond' remained above the acceptable turfgrass quality threshold, however, all shade types reduced turfgrass quality approximately 1.5 units compared to full sunlight (Table 2). Blue shade reduced 'Diamond', 'Celebration', and 'Tifway' TQ by 0.8, 1.3, and 1.4 units, respectively, compared to yellow and red shade. The most shade-sensitive turfgrass was 'Tifway' with turfgrass quality scores at or below 4 under all shade treatments. Comparing turfgrasses, 'Sea Isle 2000' TQ was 0.7, 1.2, and 1.4 units greater than 'Celebration' under yellow, blue, and black shade, respectively. Also, 'Celebration''s turfgrass quality was 1.4 units greater than 'Tifway' under all shade types.

Treatment	Diamond	Sea Isle 2000	Celebration	Tifway
		Week 3		
Yellow[†]	64.7c[‡] B[§]	87.8a A	91.2a A	87.2a A
Red	71.2bc	77.0ab	85.9a	78.3a
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
		Week 6		
Yellow	110.1	92.7	90.3	89.4a
Red	99.8	82.6	85.1	83.9a
Blue	100.1	80.2	87.4	79.1a
Black	112.1 A	75.3 B	71.6 B	62.4b B

[†]Yellow: filters <520 nm, Red: filters <560 nm, Blue: filters >560 nm, and Black: filters all wavelengths.

[‡]Values within a column within each week followed by the same letter are not significantly different at P=0.05 by protected LSD.

[§]Values within a row followed by the same letter are not significantly different at P=0.05 by protected LSD.

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

'Diamond''s turfgrass quality was 1.8, 3.2, and 4.5 units greater than 'Sea Isle 2000', 'Celebration', and 'Tifway', respectively, under black shade.

Clipping Yield

Black shade reduced 'Celebration' and 'Tifway' clipping yield by a factor of 0.6 and 1.6, respectively, compared to yellow, red, and blue shade (Table 2). Yellow shade increased 'Diamond' and 'Sea Isle 2000' clipping yield 73% and 39%, respectively, compared to blue shade. Comparing turfgrasses, yellow and black shade reduced 'Tifway' clipping yield by a factor of 0.7 and 1.3, respectively, compared to other turfgrasses. Meanwhile, 'Celebration' produced 30% and 65% greater clipping yield than 'Diamond' under red and blue shade, respectively.

Lateral Spread

Shade did not impact 'Diamond''s lateral spread (Table 2). For all other turfgrasses, lateral spread differences were not detected between yellow and red shade and between red and blue shade. Black shade reduced 'Celebration' and 'Tifway' lateral spread 0.7 and 1.6 times greater, respectively, than yellow, red, and blue shade. Blue shade reduced 'Sea Isle 2000' lateral spread 40% compared to yellow shade. Comparing turfgrasses, 'Celebration''s lateral spread under red and black shade was 0.6 and 1.3 times greater, respectively, than 'Tifway'. Meanwhile, 'Celebration' and 'Sea Isle 2000' lateral spread were similar. 'Diamond''s lateral spread was 47% and 67% greater than 'Celebration' under yellow and black shade, respectively. Similarly, 'Tifway''s lateral spread under yellow and black shade was 0.8 and 2.8 times lower, respectively, than 'Diamond'.

Chlorophyll

By week 3, blue shade increased 'Diamond' chlorophyll concentration 46% and 33% compared to yellow and red shade, respectively (Table 3). Meanwhile, blue and black shade reduced 'Sea Isle 2000' chlorophyll concentration 27% compared to yellow shade. Black shade reduced 'Celebration' and 'Tifway' chlorophyll concentrations 30% and 59%, respectively, com-

Treatment	Root TNC Week 8	Shoot TNC Week 4	Shoot TNC Week 8
	($mg\ g^{-1}$)	----------($mg\ g^{-1}$)------------	
Sun†	37.4a‡	55.6a	59.4a
Yellow	33.2b	50.5b	54.3b
Red	34.8b	48.3bc	54.6b
Blue	33.8b	49.0bc	50.9bc
Black	34.9b	44.1c	49.3c
Turfgrass			
Diamond	34.1b	48.6	54.6ab
Sea Isle 2000	36.5a	47.7	57.5a
Celebration	34.9ab	51.1	51.4b
Tifway	33.8b	50.7	51.3b

†Sun: full-sunlight, Yellow: filters <520 nm, Red: filters <560 nm, Blue: filters >560 nm, and Black: filters all wavelengths.

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

Table 4. Root and shoot total non-structural carbohydrates ($mg\ g^{-1}$) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by full-sunlight and various types of filtered light (~65% reduction) at the Clemson University Greenhouse Research Complex.

pared to yellow, red, or blue shade. Comparing turfgrasses, 'Diamond' had 37% less chlorophyll than 'Sea Isle 2000', 'Celebration', and 'Tifway' under yellow shade. However, 'Diamond' had 27% greater chlorophyll than 'Sea Isle 2000' and 'Tifway' under blue shade. Under black shade, 'Sea Isle 2000' and 'Celebration' had 31% greater chlorophyll than 'Tifway'.

Few chlorophyll differences were noted among turfgrasses by week 6 (Table 3). Black shade reduced 'Tifway' chlorophyll concentration 35% compared to yellow, red, and blue shade. Also, 'Diamond' had 62% greater chlorophyll concentration than 'Sea Isle 2000', 'Celebration', and 'Tifway'.

Root and Shoot TNC

Different shade types did not impact root total non-structural carbohydrates (TNC), however, full sunlight increased root TNC 10% compared to other light treatments (Table 4). 'Sea Isle 2000' had greatest root TNC (36.5 $mg\ g^{-1}$); 'Diamond' (34.1 $mg\ g^{-1}$) and 'Tifway' (33.8 $mg\ g^{-1}$) had lowest root TNC.

Full sunlight increased shoot TNC 16% and 14% at weeks 4 and 8, respectively, compared to all shade types (Table 4). At week 4, yellow shade shoot TNC was 15% higher that 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 2% greater shoot TNC than 'Tifway' and 'Celebration'.

Root Biomass and Root Length Density

Red shade increased 'Diamond''s root biomass by a factor of 3.6 and 1.5 compared to blue and black shade, respectively (Table 5). Comparing turfgrasses, 'Diamond' and 'Sea Isle 2000' performed similarly under yellow and red shade; however, 'Sea Isle 2000' root biomass was 1.9 and 4.7 times greater than 'Diamond' and 'Tifway', respectively, under blue shade.

	Relative Root Biomass (%)			
Treatment	**Diamond**	**Sea Isle 2000**	**Celebration**	**Tifway**
	------------------------------------Week 8------------------------------------			
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
	Relative Root Length Density (%)			
Yellow	65.7ab	46.1ab	37.9	82.9a
Red	82.4a	48.8a	38.2	76.6a
Blue	31.6b	39.3bc	35.8	19.9b
Black	38.7b	36.1c	18.4	36.7ab

[†] Sun: full-sunlight control, yellow: filters <520 nm, red: filters <560 nm, blue: filters >560 nm, and Black: filters all wavelengths.

[‡] Values within a column within each parameter followed by the same letter are not significantly different at P=0.05 by protected LSD.

[§] Values within a row followed by the same letter are not significantly different at P=0.05 by protected LSD.

Table 5. Relative total root biomass (%) and relative root length density (%) of 'Diamond' zoysiagrass, 'Sea Isle 2000' seashore paspalum, 'Celebration' bermudagrass, and 'Tifway' bermudagrass affected by full sunlight and various types of filtered light (~65% reduction) at the Clemson University Greenhouse Research Complex.

Under different shade types, no root length density (RLD) differences were noted between turfgrasses (Table 5). However, different light environments impacted RLD for each turfgrass, except ‘Celebration’. Red shade increased ‘Diamond’ RLD by a factor of 1.4 compared to blue and black shade. Similarly, red shade increased ‘Sea Isle 2000’ RLD 30% compared to blue and black shade. However, blue shade reduced ‘Tifway’ RLD by a factor of 3.0 compared to yellow and red shade.

Discussion

Few previous reports have investigated the morphological and physiological responses of warm-season turfgrasses to different light spectral qualities. Also, ‘Diamond’, ‘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 full sunlight and shade, turfgrasses performance significantly varied. ‘Diamond’ zoysiagrass was the most shade-tolerant turfgrass. Turfgrass quality scores were consistently higher, chlorophyll concentration decreases compared to full-sunlight were minimal, and ‘Diamond’’s lateral spread growth was least impacted by shade compared to other turfgrasses. Bunnell et al. (8) also indicated zoysiagrass was more shade tolerant than two bermudagrass cultivars. Also, ‘Diamond’ zoysiagrass can maintain acceptable turfgrass quality under 75% to 81% shade (21, 22).

Previous studies have also indicated seashore paspalum cultivars are more shade tolerant than bermudagrass cultivars, ‘TifSport’ and ‘TifEagle’ (11, 12). Similar results were noted in this study as ‘Sea Isle 2000’ consistently outperformed 'Tifway' in shade. Data collected indicates 'Celebration' may possess a similar shade-tolerance as 'Sea Isle 2000'. Regardless, both cultivars turfgrass quality scores were below 6 by week 8 of shade stress.

Previous reports indicate 'Celebration' bermudagrass is more shade tolerant than 'Tifway' bermudagrass (2, 8). While plants have evolved adaptive 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'.

In this study, under fullsunlight, 'Celebration' clipping yield was consistently lower than 'Tifway', while 'Celebration' lateral spread was greater than 'Tifway'. Similar trends were for lateral spread were noted under shade. Lateral spread data indicates 'Celebration' minimizes vertical shoot growth and continues energy allocation for continued lateral shoot growth under shade. This morphological adaptation is possibly related to plant hormone manipulation, in particular, gibberellic acid (GA), photoreceptor activity (phytochrome/chromophore), anatomical alterations, or efficient sun-fleck utilization. All of these possibilities would lead to increased carbon dioxide (CO_2) fixation capacity at reduced light intensities.

To the authors' knowledge, this is the first project which examined root length density (RLD) under a shaded microenvironment. Relative to full sunlight, shade, regardless of type, reduced root biomass and RLD for all turfgrasses. A high RLD is correlated with nitrate leaching reductions for turfgrasses (6). Therefore, N rates for turfgrasses under shade should be reduced because these areas are prone to N leaching due to root morphology alterations. Under full sunlight, 'Sea Isle 2000' produced greatest root biomass and RLD. 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.

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 (26). Increased above-ground biomass for shade-sensitive turfgrasses is detrimental due to increased tissue removal from mowing. Overall, 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 reported regarding other plant species (13).

In this study, compared to blue shade, yellow shade increased clipping yield (i.e. plant height). Also, chlorophyll concentrations remained similar between different shade types; however, blue shade increased 'Diamond' chlorophyll concentration 32% and 46% (week 3) compared to red shade. Similar results have been noted in other studies. Briefly, Poudel et al. (20) noted grape genotypes grown under 600-680 nm light had lowest chlorophyll content, but greatest plant height compared to 430-510 nm light. Similarly, Lee et al. (15) 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 summary, this study has demonstrated that both quantity and quality of light impacts growth and development of warm-season 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 most shade tolerant, 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 is warranted, as well as field studies confirming these greenhouse results. Also, this study did not take into account R:FR ratios which could potentially alter results. This study implies different types of shade significantly impact the performance of warm-season turfgrasses.

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