‘L-93’ Creeping Bentgrass Putting Green Responses to Various Winter Light Intensities in the Southern Transition Zone

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Jacklin Seed by Simplot, 5300 West Riverbend Avenue, Post Falls, ID 83854

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Abstract. Seasonal variations in temperature and solar radiation in the warm climatic region of the transition zone increase difficulty of creeping bentgrass [*Agrostis stolonifera* var. *palustris* (Huds.)] management throughout the year. The impact of winter shade on bentgrass quality and subsequent residual effects of winter shade in spring and summer months has not been investigated. Therefore, a 2-year field study investigated trinexapac-ethyl (TE) [4-(cyclopropyl- α -hydroxy-methylene)-3,5-dioxy-cyclohexanecarboxylic acid ethyl ester] as a winter management strategy to alleviate winter shade stress and determined the winter shade tolerance of ‘L-93’ creeping bentgrass under various reduced light environments. Treatments included a full-sunlight control; 58% and 96% morning, afternoon, and full-day shade artificial; and TE (0.02 kg a.i./ha) applied every 2 weeks from December to July. Data collection included daily light measurements (photosynthetic photon flux density), monthly canopy and soil temperatures, visual turfgrass quality (TQ), chlorophyll concentration, clipping yield, total root biomass, and total root nonstructural carbohydrates. Under 96% shade, canopy temperatures were reduced $\approx$ 57% from December to February, whereas soil temperatures were reduced 39% in February compared with full sunlight. Afternoon shade (58%) maintained acceptable TQ throughout winter for both years. Applying TE every 2 weeks in the winter negatively impacted bentgrass quality; however, TE enhanced spring and summer quality. Morning or afternoon shade minimally impacted parameters measured. Overall, moderate winter shade may not limit ‘L-93’ creeping bentgrass performance as a putting green in the transition zone. Results suggest winter shade does not contribute to creeping bentgrass summer decline because all shade-treated plots fully recovered from shade damage in spring months.

Creeping bentgrass [*Agrostis stolonifera* var. *palustris* (Huds.)], a C₃ plant, is widely used as a putting green turfgrass in cooler climate areas and the transition zone (McCarty, 2005). However, as a result of seasonal temperature variation, creeping

bentgrass putting greens face many environmental stresses and agronomic challenges year round, including shade. Cool-season turfgrass decline in severe shade is partially attributed to increased disease pressure (Beard, 1965, 1969; Vargas and Beard, 1981), because tree water transpiration is greatest at night, extending dew duration on turf (Williams et al., 1996, 1998). Management strategies to combat shade stress include raising the height of mowing (Bunnell et al., 2005b; White, 2004), reducing nitrogen (N) input (Baldwin et al., 2009; Bunnell et al., 2005b; Goss et al., 2002), applying plant growth regulators (PGRs) (Baldwin et al., 2009; Bunnell et al., 2005b; Ervin et al., 2004; Qian and Engelke, 1999; Qian et al., 1998; Stier and Rogers, 2001),

and watering deeply and infrequently (Dudeck and Peacock, 1992).

Trinexapac-ethyl (TE, Primo Maxx; Syngenta Chem Co., Greensboro, NC) effectively inhibits gibberellic acid (GA) (GA₂₀ to GA₁) production (Adams et al., 1992) late in the mevalonic acid pathway suppressing shoot vertical growth. In Kentucky bluegrass (*Poa pratensis* L.) cultivars, TE (0.048 kg a.i./ha) reduced GA₁ 49% and increased GA₂₀ 146% under 87% shade (Tan and Qian, 2003). As a result of GA disruption, TE typically enhances warm- and cool-season turfgrass quality when light interception is interrupted.

‘Penn-cross’ creeping bentgrass grown under 80% shade treated with multiple TE applications at 0.042 and 0.070 kg a.i./ha increased fructose concentration $\approx$ 39% with minimal effects on other carbohydrate constituents (Goss et al., 2002). Similarly, Steinke and Stier (2003) noted TE applied monthly and bimonthly enhanced ‘Penn-cross’ creeping bentgrass TQ and chlorophyll concentration under 80% shade. It appears that consistent TE applications is an effective management strategy to reduce shade damage. However, Gardner and Wherley (2005) noted a turfgrass quality (TQ) decline for tall fescue (*Festuca arundinacea* Schreb. ‘Plantation’), rough bluegrass (*Poa trivialis* L.), and sheep fescue (*Festuca ovina* L.) and density decline in tall fescue and rough bluegrass grown under *Acer saccharinum* L. and *Platanus occidentalis* L. trees (91% light reduction) 4 to 6 weeks after TE (0.29 kg a.i./ha) applications.

Although morning shade is perceived as more detrimental than afternoon shade for warm- and cool-season turfgrass growth, few experiments have investigated this observation. Bell and Danneberger (1999) noted shade duration was more detrimental than timing of shade for ‘Penn-cross’ creeping bentgrass. However, a warm-season putting green turfgrass, ‘TifEagle’ bermudagrass [*Cynodon dactylon* (L.) Pers. $\times$ *C. transvaalensis*], declined more readily in the absence of afternoon solar irradiance (Bunnell et al., 2005a).

In the transition zone, creeping bentgrass putting green summer decline is the result of a combination of stresses, which includes high soil and atmosphere temperatures (Xu and Huang, 2000, 2001), elevated soil CO₂ levels (Bunnell et al., 2002; Rodriguez et al., 2005), high summer disease potential (Demoeden, 2002), and increased day and night temperatures (Fu and Huang, 2003; Huang and Gao, 2000). Management practices to combat these stresses are well documented (Bunnell et al., 2004; Feng et al., 2002; Guertal et al., 2005; Liu and Huang, 2003). However, there is a lack of information in the literature and it is currently unknown whether winter shade on a creeping bentgrass putting green is a stressful factor or a contributing factor to creeping bentgrass summer decline because golf courses are in service in winter months in the transition zone. Shade stress is typically considered most problematic during summer months when trees are full of leaves.

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Winter shade may be potentially damaging as a result of shorter photoperiods, reduced light intensities, solar elevation angles, and extended frost accumulation. For example, solar light intensity in the eastern part of the transition zone ranges from less than 300 (winter) to greater than 1800 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (summer) (Baldwin et al., 2008). Also, each year, there is a range of 20 to 30 frost events in which soil/surface temperatures can vary from below ≈ 0 to 20 °C (Baldwin et al., 2008). Lower solar angles and evergreen trees during winter months can cause severe winter month-only shade depending on the orientation and location of a putting green. Creeping bentgrass putting green responses to winter shade impacts in the transition zone and management recommendations to minimize shade stress have yet to be investigated. Also, winter shade effects on spring and summer performance are lacking. Therefore, research objectives were to 1) investigate 'L-93' creeping bentgrass putting green responses to two levels of winter light reduction of 58% and 96% with variation of morning, afternoon, or full-day shade; 2) identify whether TE is effective to reduce winter shade stress; and 3) determine any residual effects of winter month shade on spring and summer turf quality and performance.

Materials and Methods

This research was conducted at the Turfgrass Research Center, Clemson University, Clemson, SC, on a 'L-93' creeping bentgrass field research green established in Aug. 2002 with soil profile constructed to U.S. Golf Association (USGA) recommendations (USGA Green Section Staff, 1993). Artificial light intensity treatments were initiated 1 Dec. 2004 and ended 28 Feb. 2005 and repeated during the subsequent winter. Data collection was continued through July each year to determine any residual effects of treatments on spring and summer bentgrass performance. Light intensity treatments consisted of a control (full sunlight) and 58% and 96% light reduction in morning, afternoon, and full-day intervals using a neutral density, polyfiber black shade cloth (Glenn Harp and Sons, Inc., Tucker, GA) supported by polyvinyl chloride (PVC) 183 cm in length and 152 cm in width with 2.54-cm-diameter PVC pipes. Shade structures were placed 15 cm above the bentgrass surface to reduce early morning and late afternoon sunlight encroachment, yet maintain adequate air movement. By a pre-experiment comparison (data not shown), there was no temperature increase under any shade structures regardless of the structure height from 15 cm to 45 cm. For morning shade, structures were placed over the bentgrass surface at sunrise and removed at solar noon. For afternoon shade, structures were placed over the bentgrass surface at solar noon and removed at sunset. For full-day shade, structures were placed over the bentgrass surface at sunrise and removed at sunset. Regardless of shade treatment, all structures were removed every

evening because a 15-cm-high shade structure would significantly change the dew or frost cover on the research green if not removed nightly.

Trinexapac-ethyl was applied at 0.02 kg a.i./ha every 2 weeks using the emulsifiable concentrate (11.3% a.i.) with a CO₂-pressurized backpack sprayer calibrated at 1010 L·ha⁻¹ beginning 1 Dec. through 31 July each year. The bentgrass green was mowed at a 3.2-mm height two to four times weekly during winter months depending on weather conditions with clippings removed. During spring, summer, and fall, mowing (3.2 mm) occurred six to seven times weekly. A combination of 10N-1.3P-4.2K and 5N-0P-5.8K liquid fertilizers (50:50 in the quantity of N) (Progressive Turf, LLC., Ball Ground, GA) was applied overall plots early Jan. 2005 and 2006 at a rate of 4.9 kg N/ha. In spring, 9.7 kg N/ha every 2 weeks was applied overall plots using Progressive Turf liquid fertilizer, whereas in summer, the same liquid fertilizer (10-1.3P-4.2K and 5-0P-5.8K) was applied at 4.9 kg N/ha every 2 weeks. In fall, 9.7 kg N/ha every 2 weeks was applied overall plots using liquid fertilizers (10N-1.3P-4.2K and 5N-0P-5.8K). Hollow tine aeration (1.3-cm-diameter tines 10 cm in length with 5.0-cm spacing) occurred twice in the spring and once in the fall. After cultivation, 24.4 kg N/ha was applied overall plots using 18N-1.3P-14.9K greens-grade granular fertilizer (Anderson's, Maumee, OH). Disease occurrence in winter was minimal; therefore, no fungicides were applied. In summer, chlorothalonil (Daconil; Syngenta) (11.8 L/ha), azoxystrobin (Heritage; Syngenta) (48 kg a.i./ha), and mefenoxam (Subdue MAXX; Syngenta) (6.4 L·ha⁻¹) were applied as needed for dollar spot (*Sclerotinia homoeocarpa* F.T. Bennet), pythium diseases (*Pythium* spp.), and brown patch (*Rhizoctonia solani* Kuhn.) control, respectively. The bentgrass green did not receive additional topdressing except one after each of the three core aerifications annually.

Data collection. Data collected included microenvironment conditions, visual TQ, clipping yield, chlorophyll concentration, total root biomass, and root total non-structural carbohydrates (TNC).

Microenvironment parameters included surface and soil temperature, air movement, and light quality and quantity. Surface and soil temperature was recorded four times weekly during winter months at solar noon for one full-sunlight plot and under one 58% and 96% shade cloth using a thermometer (Model #1455 and Model #9840; Taylor, Oakbrook, IL). Sensors for canopy temperature were placed on the surface, whereas soil temperatures were recorded at a 7.6-cm depth. Air movement was recorded twice on days with a consistent breeze using an anemometer (Model #CS-800; Clark Solutions, Hudson, MA). Light quality was measured on a clear, cloudless day at solar noon using a spectroradiometer (Model LI-1800; LI-COR, Inc., Lincoln, NE), whereas photon flux density ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was recorded four

times weekly during winter months at solar noon for one full-sunlight plot and under one 58% and 96% shade cloth using a quantum radiometer (Model LI-250; LI-COR, Inc.).

Visual TQ ratings were measured monthly based on color, density, texture, and uniformity of the 'L-93' creeping bentgrass surface. Quality was visually evaluated from 1 to 9 with 1 = brown, dead turfgrass, 6 = minimal acceptable turfgrass, and 9 = ideal green, healthy turfgrass.

Clipping yield (g·m⁻²) was collected mid-January, late-February, and mid-May for both years. Shoot tissue was collected using a walk-behind greens mower (Greenmaster® 800; The Toro Company, Bloomington, MN) after 3 d of growth. Clippings were oven-dried at 80 °C for 48 h and weighed to quantify shoot production.

Chlorophyll concentration (mg·g⁻¹) was determined on the same dates as clipping yield. Fresh clippings were collected (as described previously) from each plot and immediately placed in a plastic bag inside a covered bucket to prevent sunlight degradation. Clippings were weighed (0.1 g) and placed in a glass test tube (1.0 cm in width and 14.8 cm in length) with 10 mL of dimethyl sulfoxide, which eliminates shoot tissue grinding to extract chlorophyll (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. On completion, samples were passed through filter paper (Whatman 41, Whatman, U.K.) and remaining extract (2 mL) transferred into cuvettes. Absorbance values were recorded at 663-nm and 645-nm wavelengths using a spectrophotometer (Genesys™ 20; ThermoSpectronic, Rochester, NY). Blanks were initially run and also after every sixth sample. The following formula was used to calculate total chlorophyll: $\text{mg}\cdot\text{g}^{-1} = (8.02 \cdot D_{663} + 20.2 \cdot D_{645}) \cdot 0.1$ (Arnon, 1949).

Roots were extracted from the soil using a cylinder core sampler (7.5 cm in diameter by 30 cm deep) 15 Jan. and 28 Feb. for both years. One plug was randomly sampled from each plot and refilled with the same root zone sand mix (85:15 sand:peatmoss; v:v). Once all soil was completely removed from each soil plug using tap water over a 1-mm sieve, roots were clipped from the shoot tissue base and placed in an oven (80.0 °C) for 48 h and then weighed.

Root TNC (mg·g⁻¹) was collected at the end of February for both years. Root tissue was harvested using a bulk density sampler, which extracted 206-cm³ (10.2 cm in depth) cores before sunrise to minimize potential diurnal fluctuations (Westhafer et al., 1982). Root 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).

Data analysis. Treatment factors were arranged in a split-block design with four replications. Light treatments (morning, afternoon, full-day shade at two levels of

58% and 96% light reduction) were arranged in a randomized complete block design, whereas TE was the split factor. Treatment effects were evaluated using analysis of variance within SAS (Version 9.1; SAS Institute, Cary, NC). No treatment-by-TE interactions occurred for any parameters; therefore, marginal means for light treatments and TE are explained separately. For TQ scores, year-by-treatment interactions occurred in January, February, or March; therefore, yearly results are presented separately. For chlorophyll and clipping yield, year-by-treatment interactions occurred in January; therefore, yearly results are presented separately. All other parameters showed no significant treatment-by-year interactions; therefore, yearly data were pooled. Means separation was performed using Fisher's protected least significant difference test with $\alpha = 0.05$.

Results

Microenvironment. Light intensity was reduced by 58% and 96% by the shade cloths relative to full sunlight (Table 1). Full-day 58% and 96% shade reduced canopy temperatures $\approx 28\%$ and $\approx 57\%$, respectively, each month compared with full sunlight. In December and February, full-day shade (96%) reduced soil temperatures $\approx 43\%$ compared with full sunlight. Also, coldest surface and soil temperatures occurred in December followed by a gradual warming trend in January and February. Light quality and air movement were unaffected by shade cloths and/or structures (data not shown).

Turfgrass quality. One month after shade treatment initiation, significant differences were noted between shade treatments (Table 2). In December, full-day 96% shade had the highest TQ (7.4) compared with all other treatments; however, this response was transient in Year 1. In Year 2, by January (4.9) and February (4.2), full-day 96% shade had the lowest TQ scores compared with all other treatments. No differences were detected between morning and afternoon shade in December. In January (Year 1), afternoon shade (58%) TQ was 0.6 rating units higher compared with morning shade (58%); however, this difference was not detected in January (Year 2) or in February for either year. Differences were not detected between full-day and diurnal 58% shade in January (Winter 1); however, afternoon 58% shade TQ was 0.6 rating units higher compared with full-day 58% shade. In January (Year 1), morning and afternoon shade (96%) TQ was ≈ 1.9 rating units higher compared with full-day 96% shade. Similarly, in February (Year 1), full-day 96% shade TQ was ≈ 2.1 units lower compared with morning and afternoon 96% shade.

In Year 2, full-day 96% shade remained above the acceptable TQ threshold of 6 through January and February (Table 2). No differences were detected between morning and afternoon shade for either shade intensity. In January and February (Year 2), full-day 58% shade TQ was ≈ 0.8 and ≈ 1.0 rating

units higher than morning or afternoon 58% shade, respectively. Full-day 96% shade TQ was ≈ 0.7 units higher than 96% morning or afternoon shade in January (Year 2).

Applying TE every 2 weeks did not impact TQ scores in December or January (Table 2). However, apply TE decreased TQ ≈ 0.6 rating units in February (Years 1 and 2) compared with TE-treated plots.

In March (Year 1), 96% afternoon shade TQ was 0.8 rating units higher compared with morning 96% shade; however, no morning or afternoon TQ variations were noted under 58% shade (Table 3). Regardless, full-day 96% shade had the lowest TQ (4.3) compared with other treatments in March (after Year 1).

Winter shade minimally impacted spring and summer TQ ratings because all plots had acceptable TQ by April. Trinexapac-ethyl increased TQ by 0.6 and 0.2 rating units in May and June, respectively, compared with non-TE-treated plots.

Chlorophyll. In January (Year 1), 58% afternoon shade had the greatest chlorophyll concentration ($3.0 \text{ mg} \cdot \text{g}^{-1}$); however, in Year 2, 96% full-day shade had the greatest chlorophyll concentration ($2.2 \text{ mg} \cdot \text{g}^{-1}$) (Table 4). No differences were detected between 96% shade treatments in Year 1, whereas morning or afternoon shade did not impact chlorophyll concentration in January (Year 2). In February, full-day 96% shade chlorophyll was

Table 1. Winter surface and soil temperatures ($^{\circ}\text{C}$) recorded at solar noon four times weekly from 1 Dec. to 28 Feb. in Years 1 and 2.

Treatment factor	Surface and soil temp ($^{\circ}\text{C}$)					
	December		January		February	
	Surface	Soil	Surface	Soil	Surface	Soil
Shade						
None	17.3	5.7	20.8	8.4	22.8	8.5
58% full day	13.2	4.3	16.7	7.3	18.0	6.9
96% full day	10.8	3.9	14.0	6.8	14.1	6.1

Table 2. Turfgrass quality of 'L-93' creeping bentgrass in December, January, and February in response to full sunlight and 58% and 96% morning, afternoon, and full-day winter shade (month of December to February from 2004 to 2006) and trinexapac-ethyl (TE; $0.02 \text{ kg} \cdot \text{ha}^{-1}$) applications every 2 weeks from 1 Dec. to 31 July 2004 to 2006.

Treatment factor	Years 1 and 2	Year 1		Year 2	
	December ^z	January	February	January	February
Shade					
Control	5.7 d ^y	6.8 ab	5.5 c	5.2 d	5.1 c
58% morning	6.3 c	6.7 b	6.2 ab	5.5 d	5.3 bc
58% afternoon	6.5 c	7.3 a	6.6 a	5.7 cd	5.4 bc
58% full day	6.7 b	6.8 ab	6.0 bc	6.4 ab	6.3 a
96% morning	6.7 b	6.7 b	6.0 bc	6.1 bc	6.1 a
96% afternoon	6.8 b	6.8 ab	6.6 a	6.1 bc	5.9 ab
96% full day	7.4 a	4.9 c	4.2 d	6.8 a	6.3 a
TE					
0	6.6	6.6	6.2 a	6.1	6.0 a
0.02	6.5	6.5	5.5 b	5.9	5.5 b

^zNo treatment-by-year interaction occurred; therefore, data from each winter are pooled.

^yValues in a column within each treatment factor followed by the same letter are not significantly different at $P \leq 0.05$ by protected least significant difference.

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

Table 3. Turfgrass quality of 'L-93' creeping bentgrass in spring and summer in response to full sunlight and 58% and 96% morning, afternoon, and full-day winter shade (month of December to February in 2004 to 2006) and trinexapac-ethyl (TE; $0.02 \text{ kg} \cdot \text{ha}^{-1}$) applications every 2 weeks from 1 Dec. to 31 July 2004 to 2006.

Treatment factor	Year 1	Year 2	Years 1 and 2			
	March		April ^z	May ^z	June ^z	July ^z
Shade						
None	5.3 b ^y	5.5	6.7	7.1 ab	7.5 c	6.6 a
58% morning	5.7 ab	6.0	6.8	7.1 ab	7.6 ab	6.4 ab
58% afternoon	5.8 ab	6.2	7.1	7.5 a	7.8 a	6.2 b
58% full day	5.5 ab	6.4	6.8	7.4 a	7.5 ab	6.5 a
96% morning	5.3 b	6.0	6.7	7.2 ab	7.4 c	6.2 b
96% afternoon	6.1 a	6.1	7.0	7.2 ab	7.4 c	6.6 a
96% full day	4.3 c	6.3	6.9	6.9 b	7.5 bc	6.6 a
TE						
0	5.5	6.2 a	6.7	6.9 b	7.4 b	6.4
0.02	5.5	5.9 b	6.9	7.5 a	7.6 a	6.4

^zNo treatment-by-year interaction occurred; therefore, data from each year are pooled.

^yValues in a column within each treatment factor followed by the same letter are not significantly different at $P \leq 0.05$ by protected least significant difference.

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

Table 4. Chlorophyll concentration ($\text{mg}\cdot\text{g}^{-1}$) of 'L-93' creeping bentgrass in January, February, and May in response to full sunlight and 58% and 96% morning, afternoon, and full-day winter shade (December to February, 2004 to 2006) and trinexapac-ethyl (TE; $0.02\text{ kg}\cdot\text{ha}^{-1}$) applications every 2 weeks from 1 Dec. to 31 July 2004 to 2006.

Treatment factor	Year 1	Year 2	Years 1 and 2	
	January		February ^z	May ^z
Shade				
None	2.5 b ^y	1.5 d	2.0 d	2.4
58% morning	2.4 b	1.6 cd	2.1 cd	2.4
58% afternoon	3.0 a	1.6 b-d	2.1 cd	2.5
58% full day	2.7 ab	1.7 bc	2.2 bc	2.3
96% morning	2.5 b	1.8 b	2.2 bc	2.4
96% afternoon	2.6 ab	1.8 b	2.3 b	2.4
96% full day	2.5 b	2.2 a	2.5 a	2.5
TE				
0	2.6	1.8	2.2 a	2.5
0.02	2.5	1.7	2.1 b	2.3

^yNo treatment-by-year interaction occurred; therefore, data from each year are pooled.

^zValues in a column within a treatment factor followed by the same letter are not significantly different at $P \leq 0.05$ by protected least significant difference.

Table 5. Clipping yield ($\text{g}\cdot\text{m}^{-2}$) of 'L-93' creeping bentgrass in January, February, and May in response to full sunlight and 58% and 96% morning, afternoon, and full-day winter shade (December to February, 2004 to 2006) and trinexapac-ethyl (TE; $0.02\text{ kg}\cdot\text{ha}^{-1}$) applications every 2 weeks from 1 Dec. to 31 July 2004 to 2006.

Treatment factor	Year 1	Year 2	Years 1 and Year 2	
	January		February ^z	May ^z
Shade				
None	1.56 b ^y	0.70	0.51 b	0.67
58% morning	2.47 ab	0.67	0.63 ab	0.60
58% afternoon	2.83 ab	0.67	0.49 b	0.66
58% full day	2.70 ab	0.61	0.47 b	0.64
96% morning	1.96 b	0.74	0.51 b	0.61
96% afternoon	3.49 a	0.67	0.56 ab	0.66
96% full day	3.89 a	0.54	0.76 a	0.57
TE				
0	3.19 a	0.74 a	0.72 a	0.76 a
0.02	2.23 b	0.55 b	0.40 b	0.50 b

^yNo treatment-by-year interaction occurred; therefore, data from each year are pooled.

^zValues in a column within each treatment factor followed by the same letter are not significantly different at $P \leq 0.05$ by protected least significant difference.

Table 6. Total root biomass ($\text{g}\cdot\text{m}^{-2}$) and root total nonstructural carbohydrates ($\text{mg}\cdot\text{g}^{-1}$) of L93 creeping bentgrass in January and February in response to full sunlight and 58% and 96% morning, afternoon, and full-day winter shade and trinexapac-ethyl (TE; $0.02\text{ kg}\cdot\text{ha}^{-1}$) applications every 2 weeks from 1 Dec. to 31 July 2004 to 2006.

Treatment factor	Root biomass ($\text{g}\cdot\text{m}^{-2}$)		Root TNC ($\text{mg}\cdot\text{g}^{-1}$)
	January	February	February
Shade			
None	0.79	0.89 a ^z	52.6 ab
58% morning	0.64	0.64 b	46.3 b-d
58% afternoon	0.81	0.61 b	55.2 a
58% full day	0.76	0.66 b	41.5 cd
96% morning	0.71	0.58 b	47.9 bc
96% afternoon	0.86	0.60 b	39.9 d
96% full day	0.61	0.51 b	41.9 cd
TE			
0	0.76	0.66	45.5
0.02	0.72	0.62	47.5

^zValues in a column within each treatment factor followed by the same letter are not significantly different at $P \leq 0.05$ by protected least significant difference.

25%, $\approx 17\%$, and $\approx 12\%$ higher compared with full sunlight, 58% shade treatments, and 96% shade treatments, respectively. Meanwhile, morning or afternoon shade did not influence chlorophyll concentrations. Also, chlorophyll differences were not detected in May.

Trinexapac-ethyl minimally impacted winter and spring chlorophyll concentrations (Table 4). In February, non-TE-treated bent-

grass had 5% greater chlorophyll concentration compared with TE-treated plots.

Clipping yield. Full-day 96% shade shoot growth was 2.5 times greater than full sunlight in January (Year 1) (Table 5). Also, morning shade (96%) shoot growth was 78% lower compared with afternoon shade (96%). Clipping yield differences were not detected in January, Year 2. In February, clipping yield was 47% higher under 96% full-day

shade compared with full sunlight. By May, no shoot biomass variations were noted.

Trinexapac-ethyl reduced shoot growth $\approx 38\%$, 79% , and 51% in January (Years 1 and 2), February, and May, respectively, compared with non-TE-treated plots.

Root biomass and total nonstructural carbohydrates. In February, root biomass under shade, regardless of intensity or duration, was $\approx 49\%$ lower than full sunlight (Table 6). Morning shade (58%) root TNC was 19% lower compared with afternoon shade; however, under 96% shade, a 20% root TNC increase was noted for morning shade compared with afternoon shade. Also, full-sunlight root TNC was 27%, 32%, and 26% higher compared with full-day 58% shade, 96% afternoon shade, and 96% full-day shade, respectively. Trinexapac-ethyl did not impact root biomass or root TNC in the winter.

Discussion

Spring is a period of accelerated growth and carbohydrate accumulation of creeping bentgrass before the onset of summer stress in parts of the transition zone. Therefore, winter shade was evaluated to determine if limiting light availability during winter months would inhibit spring and subsequent summer performance. To the authors' knowledge, this was the first research project initiated to specifically investigate the impact of winter shade on creeping bentgrass putting greens in the southern transition zone with year-round golf play.

Results indicate moderate winter shade may not be a detrimental growth factor for creeping bentgrass putting greens in the transition zone without traffic and other stressful impacts. Typically, C_3 plants maintain an appropriate photosynthesis:respiration ratio compared with C_4 plants in low-light environments (Wahid and Rasul, 2005). This is possibly the result of the distance between mesophyll and bundle sheath tissues (i.e., anatomical organization) (Sage and McKown, 2006) or efficient sunfleck use (Horton and Neufeld, 1998).

Previous research indicates creeping bentgrass performs well under moderate shade stress. Goss et al. (2002) stated bentgrass showed minimal deleterious effects under 60% shade, whereas 80% shade inhibited bentgrass growth and development. Bell and Danneberger (1999) also indicated 'Penn-cross' creeping bentgrass maintained acceptable color, density, and tissue mass when grown under 69% shade. Reid (1933) indicated bentgrass grown under heavy shade had a comparable light green color compared with control (full sunlight); however, root growth was restricted. These studies were conducted to coincide with spring season leaf growth and/or fall season leaf drop.

In this study, 3 months of winter shade (except Year 1) consistently showed greater TQ scores and chlorophyll concentrations compared with full-sunlight plots. Studies show that evergreen plants' photosynthetic rates decline when temperatures drop; however,

chlorophyll continues its light-absorbing properties (Verhoeven et al., 2005). Therefore, photoinhibition will occur unless the xanthophyll cycle and/or antioxidant leaf enzymes minimize excessive light accumulation (Deming-Adams and Adams, 1996). In this study, it appears increasing shade intensity served as a photoprotective role under apparent high light stress, thereby minimizing excess light accumulation in the light-harvesting complexes, which ultimately produces reactive oxygen species. Limited research examining the role of xanthophyll pigments in turfgrasses exists. Bell and Danneberger (1999) noted in a field study that bentgrass violaxanthin concentration decreased with increasing shade stress, whereas other pigment concentrations remained constant. McElroy et al. (2006), in a greenhouse study, reported carotenoid (zeaxanthin, antheraxanthin, violaxanthin, neoxanthin, epoxylutein, and β -carotene) concentrations decreased as low-light intensity duration increased. Both of these studies examined carotenoid concentrations during favorable growing temperatures for bentgrass. Future studies investigating xanthophyll activity of cool-season turfgrasses under winter shade is warranted to further clarify the relationship between winter shade impact and creeping bentgrass performance. Differences between 96% full-day shade in Year 1 and 2 may be partially explained by minimum temperature differences in January. The second half of January was greater than 5 °C colder in Year 1 compared with the second half of January in Year 2. Also, no minimum temperature variations in January were noted in Year 2; however, minimum temperature fluctuated by greater than 10 °C in Year 1. It appears temperature fluctuation in January (Year 1) negatively affected 'L-93' creeping bentgrass performance under 96% shade. No differences in precipitation occurred over this 2-year field study (data not shown); therefore, it appears this yearly fluctuation is independent of moisture availability.

Although TE typically enhances cool-season turfgrass in shade (Goss et al., 2002; Steinke and Stier, 2003; Tegg and Lane, 2004), this study indicates TE applied every 2 weeks during winter negatively impacted creeping bentgrass growth and color. Creeping bentgrass growth slowed as a result of cool winter temperatures; therefore, applying TE, a GA-inhibiting PGR that slows growth, further reduced growth and discolored creeping bentgrass. Other studies on warm-season turfgrasses have noted surface discoloration and density decrease if TE is applied during periods below an optimal growth temperature range (Fagerness and Yelverton, 2000; McCullough et al., 2006, 2007). Also, Gardner and Wherley (2005) reported TE applied every 6 weeks decreased visual TQ and density of cool-season turfgrasses under shade stress. Greater intervals between winter TE applications or reduced rates may have been more beneficial. Beasley et al. (2007) noted TE uptake was greatest when temperatures were warm, whereas dissipation rate

was reduced with cooler temperatures. Therefore, during cool winter months, applying TE in 2-week intervals is unnecessary and caused bentgrass discoloration. Once shade treatments were removed and temperatures were consistently warm, TE enhanced spring and summer bentgrass performance.

Moderate winter shade was beneficial for parameters measured in this study; however, long-term effects of 96% shade through spring and into summer may decrease bentgrass visual quality. Although TQ and shoot chlorophyll concentrations increased under 96% shade in February (Year 2), root mass and root TNC declined compared with full-sunlight. This indicates bentgrass reallocated energy constituents and carbohydrate reserves to shoot tissue to maintain winter green color and continued winter growth instead of carbohydrate conservation. This strategy would presumably be detrimental (i.e., carbohydrate depletion) for sustaining a high-quality putting green during summer stress if 96% shade continued through the spring. However, Beard and Daniel (1966) noted temperature reductions enhanced 'Old Orchard' creeping bentgrass root activity. Thus, partial spring and summer shade, which reduces canopy and soil temperatures, may improve creeping bentgrass survival in the hot, humid transition zone by initiating new summer root growth as long as a prudent disease control program is initiated.

Trinexapac-ethyl did not impact root biomass. This is in general agreement with results by Fagerness and Yelverton (2000) and McCullough et al. (2007). Although TE did not increase root TNC in this study, Ervin and Zhang (2007) reported increases in bentgrass leaf carbohydrate content after sequential TE applications in a greenhouse study. Goss et al. (2002) reported TE-treated creeping bentgrass increased carbohydrate content under 80% shade stress compared with non-TE-treated creeping bentgrass. Also, Goss et al. (2002) observed significant increases in shoot carbohydrate content compared with root carbohydrate content of creeping bentgrass when grown under 80% shade. In our study, sampling shoot TNC may have been more appropriate than root TNC as a shade stress indicator.

Overall, morning or afternoon shade minimally impacted parameters measured. Results agree with Bell and Danneberger (1999), which stated shade duration rather than diurnal shade was more detrimental to 'Penncross' creeping bentgrass growth under 80% or 100% shade. However, 58% and 96% diurnal shade impact on parameters measured was inconsistent. For example, 58% morning shade reduced root TNC, whereas 96% morning shade increased root TNC compared with afternoon shade. Bunnell et al. (2005a) noted afternoon shade decreased root carbohydrate content of 'TifEagle' bermudagrass compared with morning shade. However, Bell and Danneberger (1999) did not detect any bentgrass carbohydrate content variation in response to diurnal shade. It appears time of shade may be more critical

for bermudagrass putting greens rather than cool-season putting greens. Future research of other turfgrass species' and cultivars' response to morning or afternoon shade would prove beneficial.

In summary, moderate winter shade did not cause stresses rather enhanced bentgrass growth, whereas few differences were noted between morning or afternoon winter shade in the transition zone. Trinexapac-ethyl applications on creeping bentgrass putting greens should not be applied during winter months under shade conditions. Regardless of winter stress, all plots fully recovered by early spring because TQ scores were above the acceptable threshold of 6. Therefore, this study suggests that winter shade is not a contributing factor for creeping bentgrass summer decline. Future studies should investigate creeping bentgrass performance and responses under winter shade, including traffic factors and lighter rates of TE plus other influential environmental factors. Also, other creeping bentgrass cultivars as well as other turfgrass species, including winter overseeding species winter shade performance, should be evaluated to determine if a reduced light environment inhibits growth during winter months.

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