

TURFGRASS SCIENCE

Influence of Trinexapac-Ethyl on Diamond Zoysiagrass in a Shade Environment

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ABSTRACT

'Diamond' zoysiagrass [*Zoysia matrella* (L.) Merr.] has excellent shade tolerance when compared with other zoysiagrass cultivars. However, because of excessive shoot growth and carbohydrate depletion, turf stand declines with time when shade levels exceed 80%. Two separate studies were conducted to determine if the plant growth regulator trinexapac-ethyl (TE), which suppresses shoot growth, could improve turf performance of Diamond zoysiagrass under shade conditions. Well-established turf was subjected to a constant 86 and 88% shade in the greenhouse and polyhouse, respectively. Trinexapac-ethyl treatments included monthly applications at 0.048 kg a.i. ha⁻¹ (MTE), bimonthly applications at 0.096 kg a.i. ha⁻¹ (BTE), trimonthly applications at 0.192 kg a.i. ha⁻¹ (TTE), and the untreated control. Treatments in 1997 were made from January through August for the greenhouse study and from April to September for the polyhouse study. Diamond receiving MTE and BTE maintained acceptable turf quality throughout the study, while turf quality of the control deteriorated to unacceptable levels <3 mo after shading. Diamond treated with TTE maintained better turf quality than that of the control, but was inferior to MTE and BTE treatments. Compared with control plots, turf receiving MTE and BTE had (i) 76 to 73% less shoot vertical growth and 77 to 75% less clippings, (ii) 40 to 38% higher total nonstructural carbohydrate content, (iii) 60 to 50% higher root mass and 51 to 46% higher root viability, and (iv) 48 to 42% higher photosynthesis. Results suggested that monthly or bimonthly repeated application of TE at 0.048 or 0.096 kg a.i. ha⁻¹ greatly enhanced the shade tolerance of Diamond zoysiagrass.

SHADE, whether from trees or buildings, presents a problem in the management of turfgrasses. Few turfgrasses can survive long term when shading exceeds 75% (Warren, 1962). Diamond zoysiagrass has been noted for its good shade tolerance when compared with other zoysiagrass cultivars (Riffell et al., 1995). A preliminary study demonstrated that acceptable turf quality of Diamond was maintained for more than 5 mo under 73% shade, but not under 86% shade (Qian and Engelke, 1997).

Compared with full sun conditions, a shade level of 86% resulted in a four-fold increase in shoot vertical growth and two-fold increase in clipping yields of Diamond zoysiagrass (Qian and Engelke, 1997). Increased shoot growth is also promoted by gibberellic acid (GA) in most plants (Endo et al., 1989). Although no research has been done on turfgrasses, Gawronska et al. (1995) found that increased biosynthesis of GA partially con-

tributed to excessive shoot growth of field pea (*Pisum sativum* L.) in response to low light intensity. It is possible that a similar physiological process occurs in zoysiagrass under heavy shade. Increasing shoot growth is a shade avoidance mechanism of plants, but it is ineffective and undesirable in turfgrass because of regular mowing. Rapid vertical shoot growth leading to more clippings accelerates the energy depletion of turfgrass tissue. We have observed an 85% decrease in total nonstructural carbohydrate content (TNC) of Diamond zoysiagrass under 86% shade, which led to decreased turf density and stand persistence (Qian and Engelke, 1997).

Therefore, we hypothesize that shade tolerance may be increased by using an antigibberellic acid type of plant growth regulator (PGR), such as TE. Trinexapac-ethyl exerts its effect by blocking the formation of 3 β -OH late in the GA biosynthesis pathway, thus inhibiting plant elongation (Adams et al., 1992). Trinexapac-ethyl has been widely used to suppress turfgrass shoot growth and reduce mowing frequency to lower maintenance costs. While much research has been done under natural sunlight conditions (Marcum and Jiang, 1997; Johnson, 1992, 1993a,b, 1994), no studies have been done under heavily shaded environments. Information is needed about the effects of TE on the rooting, carbohydrate status, and photosynthesis characteristics of turfgrass subjected to heavy shade conditions. The objective of this study was to evaluate the influence of TE at various rates on turfgrass shade tolerance by (i) determining the growth habit and turf performance, (ii) measuring root production and root viability; and (iii) determining the effects of TE on photosynthesis rate and nonstructural carbohydrate status of Diamond zoysiagrass grown in a heavy shade condition.

METHODS AND MATERIALS

Greenhouse Study

This study was conducted at the Texas A&M University Dallas Research Center. Sod of mature Diamond zoysiagrass was harvested on 22 Nov. 1996 from a field of Houston black clay soil (very-fine, montmorillonitic, thermic Typic Chromudert). Washed sod was transplanted to a heat bench measuring 2.8 m long, 1.6 m wide, and 0.6 m deep. The bench was filled with sterilized sand premixed with 17-2.6-8.3 N-P-K resin-coated fertilizer to provide 24 kg N ha⁻¹. A 20-8.8-16.6 N-P-K soluble fertilizer was applied monthly to provide 24 kg

Abbreviations: BTE, bimonthly trinexapac-ethyl treatment; GA, gibberellic acid; MTE, monthly trinexapac-ethyl treatment; PAR, photosynthetically active radiation; PGR, plant growth regulator; Pn, canopy photosynthesis; TNC, total nonstructural carbohydrate; TE, trinexapac-ethyl; TTC, 2,3,5-triphenyltetrazolium chloride; TTE, trimonthly trinexapac-ethyl treatment.

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N ha^{-1} . To stimulate an active growth of Diamond, root zone temperature was maintained between 23 and 26°C from December 1996 to March 1997. The heat bench was designed to circulate controlled-temperature water through a copper pipe grid system, which was embedded 15 cm under the soil surface. Greenhouse air temperature ranged from 24 to 34°C. Turf was watered daily to prevent drought stress.

Shading was imposed on 4 January when turf was well established. A shade cloth with 75% light-filtering property was mounted on a polyvinyl chloride frame and supported 50 cm above the turf canopy. The shade cloth was draped on all sides to prevent the effect of incline light. Photon flux densities in $\mu\text{mol m}^{-2} \text{s}^{-1}$ were taken under shade and outside of the greenhouse with a quantum radiometer (model LI-170, Li-Cor, Lincoln, NE). Shade level was expressed as $[(\text{PAR}_{\text{outside of the greenhouse}} - \text{PAR}_{\text{under the shade cloth}}) / \text{PAR}_{\text{outside of the greenhouse}}] \times 100\%$, where PAR is photosynthetically active radiation.

Trinexapac-ethyl treatments were first applied on 12 Jan. 1997. Treatments included: (i) MTE, monthly TE application at 0.048 kg a.i. ha^{-1} — made on 12 January, 14 February, 24 March, 9 April, 9 May, 9 June, 9 July, and 4 August; (ii) BTE, bimonthly application at 0.096 kg a.i. ha^{-1} — made on 12 January, 24 March, 9 May, 9 July; (iii) TTE, trimonthly TE application at 0.192 kg a.i. ha^{-1} — made on 12 January, 9 April, and 9 July; and (iv) the untreated control. Trinexapac-ethyl was applied with a CO_2 -pressurized sprayer that delivered 518 L ha^{-1} at a pressure of 1.5 kg cm^{-2} . Treatments were arranged in a randomized complete block design and replicated three times with each experimental unit measuring 80 by 46 cm. Turf was clipped weekly at a 2.0-cm height.

Turf quality was visually assessed weekly on a 1 (poorest) to 9 (best) scale; ratings of ≤ 6 were considered unacceptable. The estimation of turf quality was based on primary components of color, density, and uniformity. Turf canopy height was measured before the clipping event. Shoot growth rate was calculated as the difference between the canopy height and mowing height.

Tiller number, root mass, and percentage of living roots were determined after using a core sampler (3.2 cm in diam. by 60 cm deep) to remove two cores per plot at 10, 15, and 20 wk after the initial TE treatment. Immediately after harvesting, cores were cut along the soil–thatch interface and the tiller number was counted. The underground sections were transferred to the laboratory, where roots were gently washed free of soil over two layers of fine screen, blotted dry, and the root fresh weight was determined. Then, 10 to 15 root tip segments of ≈ 2 cm were randomly selected and cut. The segments were transferred to test tubes and immediately covered with 5 mL 2,3,5-triphenyltetrazolium chloride (TTC) solution (6 mg mL^{-1}) in 0.05 M phosphate buffer (pH 7.4) (Joslin and Henderson, 1984). Samples were vacuum infiltrated and incubated at 30°C for 20 hr. Viable roots were able to reduce TTC (colorless) to Formazan (red). The number of root segments that turned red were counted under a microscope, and the percentage of living roots was calculated as the indicator of root viability.

To determine total nonstructural carbohydrate content (TNC) for underground tissues (rhizome + root), two cores were taken from each plot 5, 10, 15, and 20 wk after the initial treatment. Soil and foreign matter were removed from rhizomes and roots. Aboveground plant material was excised at the thatch–soil interface. The cleaned tissues were placed in an oven at 100°C for 1 h and then dried at 70°C to constant weight. Samples were ground in a Wiley mill to pass through a screen with 425- μm openings. Approximately 30 mg of the ground sample was placed in a test tube with 10 mL of deionized water. The test tubes were autoclaved for 1 h to extract the

hot-water soluble carbohydrates and gelatinize starch. After cooling, sample was added with acetate buffer (pH 5.0), and 50 units of amyloglucosidase (A7420, Sigma Chemical Co., St. Louis, MO), and incubated for 1 h at 55°C. The reaction was terminated by placing samples in a boiling water bath for 10 min. After centrifugation, 250 μL of supernatant was used for TNC analysis. The analysis of TNC was performed using procedures after Nelson (1944) and Somogyi (1952). Carbohydrates in this analysis included free monosaccharides, short-chain glucose polymers, and starch.

Photosynthetic measurements were determined using a portable infrared gas analyzer system (Model LCA-3, ADC Ltd., Hoddesdon, Herts, UK) equipped with a clear plexiglass canopy chamber (PSC500, Photosynthesis Chamber, Dynamax Inc., Houston, TX). The chamber had a 10-cm i.d. and an 8-cm height. The Tygon tubes (connecting the chamber to infrared gas analyzer) and pumps allowed the entrance of reference air and exit of sample air. The bottom of the chamber was open and the opening edge was beveled so that it could be positioned over a 78-cm² area of turf and pressed 2 mm down to the soil, forming an effective seal around the edge of the canopy chamber. The chamber allowed measurement of canopy photosynthesis (P_n) with minimum disturbance of the natural turf surface. Measurements were generally made 1 d wk^{-1} (1–2 d after clipping event) between 13 to 21 wk after the initial TE application. The majority of these measurements were performed from 1100 to 1300 h with relatively stable irradiance conditions. Part of the data were taken when the shade cloth was uncovered and part were taken with the shade covering on so that P_n data were collected at a range of PAR (from below light compensation to solar noon levels). No attempt was made to measure turf respiration because of the difficulty of excluding soil respiration in this experiment setting. Therefore, the measured photosynthesis is the rate of apparent photosynthesis per unit land area after deducting the turfgrass shoot respiration and potential soil microbial respirations. Measurements of incident PAR were made within 10 s of the P_n measurements. This was done by placing a light quantum sensor (model LI-170, LI-COR) next to the canopy chamber.

Data on turf quality, tiller number, root mass and viability, and TNC from each measurement date were analyzed using GLM procedures of the Statistical Analysis System (SAS Institute, 1987). Treatment means were separated using Fisher's protected LSD. Nonlinear regression analysis, where PAR was the independent variable and P_n the dependent variable, was performed for each treatment to describe the relationship between P_n and PAR. Through a preliminary screen, a segmented (quadratic with plateau) model was found to best describe the data. When PAR was less than the saturation point, the relation between P_n and PAR was quadratic; when PAR was greater than saturation point, the P_n was constant. The model fitting procedure required partial derivatives of the unknown parameters. A separate regression equation was generated from data for each experimental unit. Light compensation point, light saturation point, and maximum P_n for each experimental unit were calculated or derived from the fitted equation. These parameters were then treated as response variables and subjected to an analysis of variance to test for differences among treatments.

Polyhouse Study

This study was conducted between April and September, 1997 in a polyurethane-roofed house (polyhouse) at the Texas A&M University Dallas Research Center. Diamond zoysiagrass (6 by 6 m) was originally sodded in 1991 on a 10-cm sand-based root zone mixture above a plastic barrier. The

plastic was placed atop a 10-cm gravel layer above the natural soil. Shading was imposed on 1 Apr. 1997 using a shade cloth with 75% light-filtering property mounted on a metal frame and supported 2 m above the turf canopy. The shade cloth was draped on all sides to prevent the effect of incline light. The MTE applications were made on 9 April, 9 May, 9 June, 9 July, 1 August, and 9 September. The BTE applications were made on 9 April, 9 June, and 1 August. The TTE applications were made on 9 April and 9 July. The maintenance of turf and procedures of data collection were identical to those of the greenhouse study with the following exceptions.

1. There was a relatively wide range of air temperature fluctuation (18–45°C) due to the inefficient temperature control system.
2. Turf was mowed weekly at the height of 1.2 cm and clipping yield was collected.
3. Because of root restriction from the plastic barrier, no data were collected on rooting characteristics.
4. Canopy photosynthesis was only measured on three dates, 14, 84, and 154 d after the initial PGR treatments. All measurements were done with the shade covering on.

Data collected were analyzed using GLM procedures. Treatment means were separated using Fisher's protected LSD (SAS Institute, 1987).

RESULTS AND DISCUSSION

Great seasonal and diurnal fluctuations of light intensity were observed under the shade cloths both in the greenhouse and the polyhouse. For example, midday light intensity under shade cloth in the greenhouse ranged from 55 $\mu\text{mol m}^{-2} \text{s}^{-1}$ on an overcast day in January to 560 $\mu\text{mol m}^{-2} \text{s}^{-1}$ on a clear day in July. On July 8, the range of light intensity in the greenhouse was 144 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at 0800 h and 560 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at 1300 h. Despite the great seasonal and diurnal fluctuations of light intensity, the light level under the shade cloth in the greenhouse was consistently at $14 \pm 2\%$ natural sunlight, i.e., $86 \pm 2\%$ shade. The light level under shade cloth in the polyhouse was at $12 \pm 2\%$ natural sunlight, i.e., $88 \pm 2\%$ shade. However, 108 d after initiating the study, a storm removed the plastic roof of the polyhouse. This resulted in a shade level of only 75% during the rest of the study period.

Shoot Growth

Greenhouse Study

In agreement with a previous study, shade at 86% highly stimulated the vertical shoot growth of Diamond

compared with full sun condition (Qian and Engelke, 1997). The excessive vertical shoot growth induced by shade was markedly inhibited by TE at all described rates 7 to 10 d after application, with the duration of suppression appearing to depend on treatments and environments (data not shown). The MTE treatment (0.048 kg a.i. ha^{-1}) provided the most consistent growth suppression; the mean shoot growth rate over the study period was only 25% of the control (Table 1). The BTE treatment (0.096 kg a.i. ha^{-1}) exhibited a similar level of shoot growth suppression (27% of the control) as MTE. However, 57, 73, and 80 d after the initial treatment BTE had higher shoot growth than that of MTE, whereas 31 and 38 d after the initial treatment the inverse was true (data not shown). Trimonthly application suppressed shoot growth for ≈ 2 mo after each application. Thereafter it became evident that the effectiveness of growth suppression was reduced. Shoot growth rates of TTE-treated turf and the control were not different 73 to 105 and 165 to 193 d after the initial application (data not shown).

Polyhouse Study

Compared with the control, MTE, BTE, and TTE resulted in a mean reduction of shoot vertical growth by 78, 74, and 66%, respectively (Table 2). The MTE and BTE treatments exhibited relatively consistent shoot growth suppression. The TTE produced $<20\%$ vertical shoot growth of the control for 2 mo, but vertical shoot growth was not different with the control 70 to 90 d after TE application (data not shown). The mean fresh clipping yields were 9.0, 2.5, 2.5, and 2.9 $\text{g m}^{-2} \text{wk}^{-1}$ for the control, MTE, BTE, and TTE, respectively (Table 2).

Both greenhouse and polyhouse results indicated that the most consistent suppression of shoot growth under shade was obtained by frequent application with low rates of TE.

Turf Quality

Weekly turf quality for the greenhouse study is presented in Fig. 1A. For the control, turf exhibited acceptable quality only in the first 6 wk; thereafter, quality declined to a commercially unacceptable level (<6). The slight recovery in turf quality of the control between June and August may have been due to the seasonal improvement of light conditions. All TE treatments re-

Table 1. Influence of trinexapac-ethyl (TE) treatments on shoot growth rate, root mass, percentage of living root, and tiller number of Diamond zoysiagrass grown under 86% shade in the greenhouse.

Treatment‡	Shoot growth mm d^{-1}	Root mass, WAT†				Living root, WAT				Tiller, WAT			
		10	15	20	Avg.	10	15	20	Avg.	5	10	15	20
		mg				%				(no. cm^{-2})			
Control	2.30a§	60c	120b	110b	100b	35b	61NS	52NS	49	5.5NS	4.7b	4.3b	4.7b
MTE	0.59b	120ab	200a	200a	160a	72a	77	74	74	5.8	6.7a	6.0a	6.0a
BTE	0.63b	100b	130b	190a	150a	75a	71	75	73	5.6	6.6a	5.4a	5.8a
TTE	1.14ab	130a	140b	160ab	140ab	71a	67	62	67	5.7	6.2a	4.7b	5.4ab

† WAT, weeks after the initial treatment.

‡ MTE, BTE, and TTE represent monthly TE application at 0.048 kg a.i. ha^{-1} , bimonthly TE application at 0.096 kg a.i. ha^{-1} , and trimonthly TE application at 0.19 kg a.i. ha^{-1} , respectively.

§ Means followed by same letter within the same column are not significantly different at the 0.05 probability level using Fisher's LSD test.

Table 2. Influence of trinexapac-ethyl (TE) treatments on shoot growth rate, clipping yield, tiller number, and canopy photosynthesis rate (Pn) of Diamond zoysiagrass grown under 88% shade in the polyhouse.

Treatment‡	Shoot growth mm d ⁻¹	Clipping yield g m ⁻² wk ⁻¹	Tiller, WAT†			Pn‖, WAT		
			2	7	12	2	12	22
			no. cm ⁻²			μmol m ⁻² s ⁻¹		
Control	2.07a§	9.0a	10.4 _{NS}	8.1b	6.3b	2.8 _{NS}	0.9b	3.1b
MTE	0.45b	2.5b	11.1	10.9a	9.8a	2.6	2.7a	4.6a
BTE	0.53b	2.5b	11.4	9.3ab	8.4ab	2.3	2.8a	4.4a
TTE	0.71b	2.9b	10.8	10.0ab	9.0ab	2.2	3.0a	4.0ab

† WAT, weeks after the initial treatment.

‡ MTE, BTE, and TTE represent monthly TE application at 0.048 kg a.i. ha⁻¹, bimonthly TE application at 0.096 kg a.i. ha⁻¹, and trimonthly TE application at 0.19 kg a.i. ha⁻¹, respectively.

§ Means followed by same letter within the same column are not significantly different at the 0.05 probability level using Fisher's LSD test.

‖ The levels of PAR were 305, 318, and 837 μmol m⁻² s⁻¹ during Pn measurements 2, 12, and 22 WAT, respectively.

markably improved the quality of shaded Diamond. Mean turf qualities during the 8-mo period were 8.0, 7.9, and 7.3 for Diamond receiving MTE, BTE, and TTE treatments, respectively. Enhanced vigor, color, and density were consistently observed for turf receiving MTE and BTE. The TTE treatment caused slight foliar injury 1 to 2 wk after application, but subsequent turf quality was significantly enhanced compared with the control. Ten to 12 wk after treatment, when the response of shoot growth suppression was diminished for TTE, turf quality declined by 0.5 to 1.0 units. Twelve of 26 ratings indicated that MTE or BTE treatments were more effective for increasing shade tolerance of Diamond than that of TTE in terms of turf quality.

In the polyhouse, the control plots exhibited acceptable quality only in the first 10 wk after shading. Thereafter, quality declined to unacceptable levels (Fig. 1B). In contrast to the greenhouse, turf of the control declined greatly between June and July in the polyhouse. The higher temperature in the polyhouse may have accelerated depletion of carbohydrate reserves despite the improved light conditions in midsummer. Quality of

the control recovered slightly when the shade level was reduced from 88 to 75%. Treatments of MTE and BTE remarkably improved the quality of shaded Diamond 2 mo after the initial TE treatments. Mean turf qualities during the study were 8.0 and 7.9 for Diamond receiving MTE and BTE, respectively. Trinexapac-ethyl at 0.192 kg a.i. ha⁻¹ caused foliar injury 2 to 6 wk after application, reducing turf quality by ≈1.0 unit, but subsequent turf quality was significantly enhanced compared with the control. Mean turf quality was 7.4 for TTE treated turf.

Turf quality was negatively correlated with shoot vertical growth ($P < 0.0001$ and $r = -0.55$). This suggested that the ability of TE to limit the excessive growth under heavy shade contributed partially to the increase of turf quality.

Tiller Number

Diamond in the control treatment exhibited a gradual decline in tiller number 5 to 15 wk after shading in the greenhouse (Table 1). Twenty weeks after the initial treatment, increased tiller number was observed, proba-

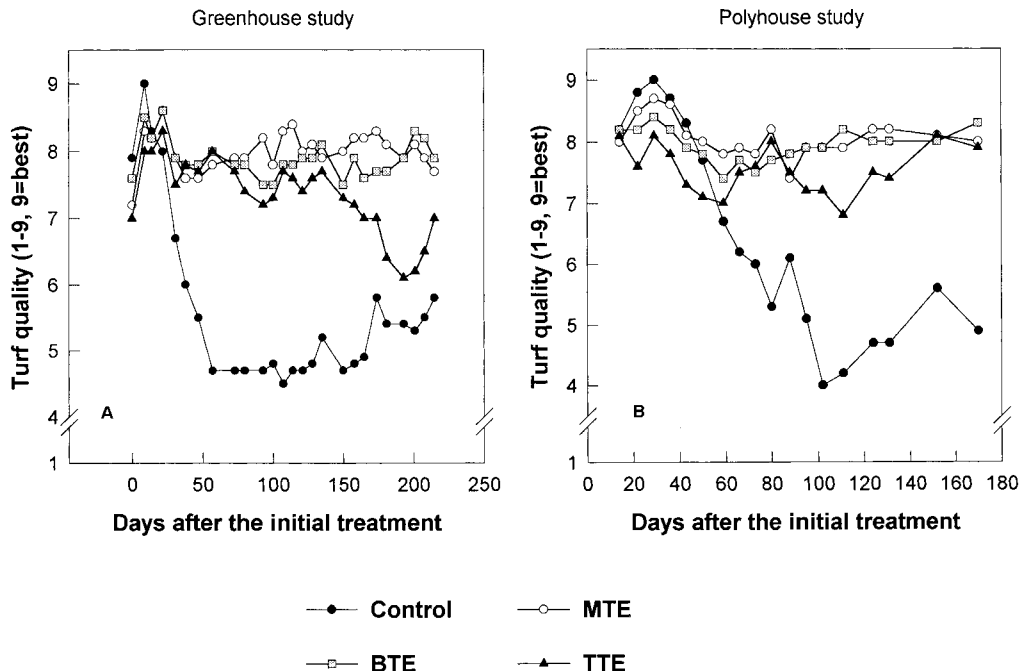


Fig. 1. Influence of trinexapac-ethyl (TE) monthly (MTE), bimonthly (BTE), and trimonthly (TTE) treatments on visual turf quality of Diamond zoysiagrass under (A) 86% shade in the greenhouse and (B) 88% shade in the polyhouse.

bly due in part to the seasonal improvement of solar irradiance. Turf treated with MTE, BTE, and TTE exhibited higher tiller numbers than that of the control 10 wk after treatments. Fifteen weeks after the initial treatment, turf receiving MTE and BTE had a higher tiller number than both the control and TTE treatment. Turf receiving MTE and BTE had 27% more tillers than that of the control 20 wk after the initial treatment.

In the polyhouse, tiller number declined with time for each treatment after shading (Table 2). Trinexapac-ethyl did not increase tiller number 2 wk after the initial treatments; however, 7 and 12 wk after the initial treatment, turf receiving MTE produced 34 and 56% higher tiller number than that of the control.

Increasing tiller number has been reported for other turfgrass when treated with antigibberellin PGRs (Dernoeden, 1984; Watschke et al., 1992). However, this response was magnified under our heavy shade conditions. Another study with three light regimes and two PGR treatments indicated that the greatest suppression of vertical shoot growth and the most significant increase in tiller number and turf quality occurred at the highest shade level when environmental conditions favored rapid growth (Qian et al., 1998). Trinexapac-ethyl caused little reduction in vertical shoot growth and little or no increase in turf quality and tiller number when conditions favored slow growth.

Root Production and Root Viability

In the greenhouse, turf receiving MTE, BTE, and TTE exhibited 100, 67, and 116% higher root mass than that of the untreated control 10 wk after the TE treatments (Table 1). The root mass production of MTE treated turf was superior to BTE, TTE, and the control 15 wk after treatments. Twenty weeks after the initial treatment, MTE and BTE had >70% root mass than that of the control. Though TE has been reported to decrease total root length of 'Kentucky-31' tall fescue (*Festuca arundinacea* Schreb.) under natural greenhouse light conditions (Marcum and Jiang, 1997), our results indicated that TE increased root mass of Diamond zoysiagrass under heavy shade.

Considerably increased root viability was also detected for all TE treatments 10 wk after the initial treatment in the greenhouse study, but not at later sampling dates (Table 1). Decreased shoot growth and increased root mass and root viability suggested that TE decreased the sink strength of the shoot and shifted limited assimilates to the root system. The altered partitioning of assimilates resulted in more root mass as well as higher root viability under heavy shade. Increased TNC in root tissue was observed for 'Tifway' bermudagrass (*Cynodon dactylon* × *tranvaalensis*) 2 and 6 wk after application of TE at 0.015 kg a.i. ha⁻¹ (Waltz et al., 1996). Steffens and Wang (1984) and Steffens et al. (1985) observed shifted growth patterns and the reallocation of more nonstructural carbohydrates to fibrous roots when apple (*Malus domestica* Borkh.) seedlings were treated with plant growth regulator paclobutrazol. However, 'Majestic' Kentucky bluegrass (*Poa pratensis* L.) exhibited a reduced photosynthate partitioning to roots

4 wk after the application of paclobutrazol and Flurprimidol (Hanson and Branham, 1987).

Carbohydrate Reserve Status

Total nonstructural carbohydrate content of Diamond zoysiagrass grown under 86% shade in the greenhouse was extremely low, especially between January and March when the natural light intensity was low (Table 3). Increased TNC between 16 and 20 wk after the initial treatment may have been due to the improvement of light conditions during summer. Trinexapac-ethyl treatments significantly increased the TNC in rhizome + root tissue. Compared with the control, MTE increased TNC by 142 and 74%, 10 and 16 wk, respectively, after the initiation of treatment. Bimonthly TE treatment resulted in 100% higher TNC 10 wk after treatment.

Despite the improved light conditions in midsummer, TNC across all treatments in the polyhouse study declined with time (Table 3). Trinexapac-ethyl treatments significantly improved TNC status. Combining all sampling dates, MTE, BTE, and TTE had 24, 33, and 28% higher TNC than that of the control.

The TNC increase in TE-treated turf was probably due to a higher rate of photosynthesis per unit of turf area, as we will discuss below. Decreased shoot growth may also partially account for the carbohydrate buildup in TE treated turf (Brown and Blaser, 1965).

Canopy Photosynthesis and its Light Response Pattern

Greenhouse Study

The general light response pattern of apparent photosynthetic rate was similar to that reported for many other plant species; increased Pn at a diminishing rate as irradiance was increased until light saturation was achieved (Fig. 2). Three specific parameters (light compensation point, light saturation point, and maximum Pn) for each treatment are presented in Table 4. Light saturation point and maximum Pn were derived from regression analysis using a quadratic with plateau segment model. Light compensation point was determined by substituting a zero apparent Pn to the fitted equation of each treatment.

Light saturation points (the amount of light required

Table 3. Influence of trinexapac-ethyl (TE) treatments on total nonstructural carbohydrate content (TNC) of Diamond zoysiagrass grown on sand soil under 86% shade in the greenhouse and 88% shade in the polyhouse.

Treatment‡	Greenhouse WAT†					Polyhouse WAT†			
	5	10	16	20	Avg.	3	8	13	Avg.
	TNC (mg g ⁻¹)								
Control	17 ^{NS}	12b§	27b	37 ^{NS}	23b	53b‡	50 ^{NS}	33 ^{NS}	45b
MTE	26	29a	47a	57	39a	70a	60	38	56a
BTE	21	24a	38ab	49	34ab	79a	56	45	60a
TTE	18	30a	36ab	35	30ab	73a	64	39	58a

† WAT, weeks after the initial treatment.

‡ MTE, BTE, and TTE represent monthly TE application at 0.048 kg a.i. ha⁻¹, bimonthly TE application at 0.096 kg a.i. ha⁻¹, and trimonthly TE application at 0.19 kg a.i. ha⁻¹, respectively.

§ Means followed by same letter within the same column are not significantly different at the 0.05 probability level using Fisher's LSD test.

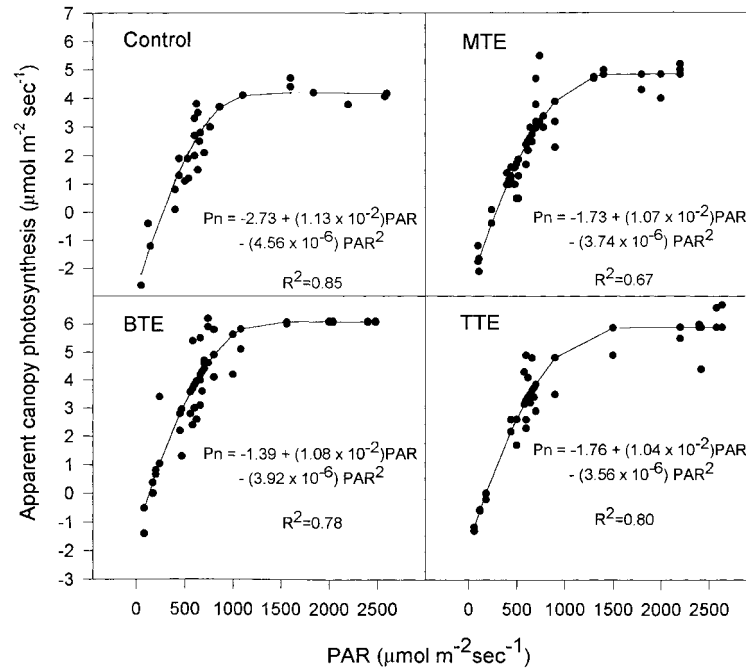


Fig. 2. Canopy apparent photosynthesis response to irradiance as affected by three monthly (MTE), bimonthly (BTE), and trimonthly (TTE) trinexapac-ethyl (TE) treatments and the control of Diamond zoysiagrass grown under 86% shade in the greenhouse. Each listed equation indicates the response of apparent photosynthesis rate to irradiance up to the light saturation point.

to maximize the photosynthetic rate of turf community) were not significantly different among treatments. The mean light saturation point for all treatments was 1333 µmol m⁻² s⁻¹.

Maximum photosynthetic rates among treatments were different. Diamond treated with TE had a significantly higher maximum P_n than that of the control. Maximum photosynthetic rates of MTE, BTE, and TTE treated turf were 5.8, 6.0, and 5.8 µmol m⁻² s⁻¹, which are 38, 42, and 38% higher than that of the control, respectively. Though estimates of maximum photosynthesis rates under heavy shade were not as meaningful as compensation point (since the former is rarely achieved under heavy shade conditions), this result suggests that TE increased the photosynthesis capacity of Diamond grown under heavy shade.

Light compensation point (the amount of light where photosynthesis balances respiration) of the control was ≈270 µmol m⁻² s⁻¹. Light levels below this value were frequently measured under shade during rainy or overcast days. Hence, turf deterioration occurred, especially

when turfgrass exhibited excessive growth. Trinexapac-ethyl treatments significantly reduced light compensation points, calculated as 175, 135, and 180 µmol m⁻² s⁻¹ for MTE, BTE, and TTE, respectively. The advantage of the reduced light compensation point led to a more positive energy balance.

Polyhouse Study

Apparent canopy photosynthesis rates among the treatments were not different 2 wk after the initial treatments (Table 2). Twelve weeks after the initial treatment, P_n of the control was at least 66% lower than that of TE treated turf. Twenty-two weeks after the initial treatment, Diamond receiving MTE and BTE provided 42 and 48% higher P_n than that of the control.

The increased P_n and reduced light compensation point compared with the control suggested that TE increased the light utilization efficiency of Diamond grown under heavy shade. The higher tiller number, which resulted in greater amount of leaf tissue, may partially contribute to the higher photosynthesis rate and increased CO₂ consumption for TE-treated Diamond. Morgan and Brown (1982) reported that P_n of bermudagrass increased with the leaf area index, which was calculated as [(leaf weight/soil area) × specific leaf weight].

CONCLUSIONS

Shade caused an excessive vertical shoot growth and resulted in a shoot canopy with fewer living tillers of Diamond zoysiagrass. We have documented with these experiments that monthly TE application at 0.048 kg a.i. ha⁻¹ or bimonthly TE at 0.096 kg a.i. ha⁻¹ could effectively suppress shoot elongation and increase the tiller density. Resulting benefits included (i) improved

Table 4. Influence of trinexapac-ethyl (TE) treatments on light compensation point, light saturation point, and maximum net photosynthesis rate (P_n) of Diamond zoysiagrass grown on sand under 86% shade in the greenhouse.

Treatment†	Light compensation point	Light saturation point	Maximum P _n
	µmol m ⁻² s ⁻¹		
Control	270a†	1231 ^{ns}	4.2b
MTE‡	175b	1427	5.8a
BTE	135b	1384	6.1a
TTE	180b	1458	5.8a

† MTE, BTE, and TTE represent monthly TE application at 0.048 kg a.i. ha⁻¹, bimonthly TE application at 0.096 kg a.i. ha⁻¹, and trimonthly TE application at 0.19 kg a.i. ha⁻¹, respectively.

‡ Means followed by same letter within the same column are not significantly different at the 0.05 probability level using Fisher's LSD test.

plant carbohydrate reserve status, (ii) improved root system, (iii) increased canopy photosynthesis, and ultimately enhanced turf quality compared with the control under heavy shaded conditions. However, it should be noted that these experiments were conducted in the greenhouse and under artificial shade. Further research is needed to evaluate the effects of TE on turf performance under natural shade settings before TE can be confidently recommended as a management tool to enhance the shade tolerance of Diamond zoysiagrass.

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