RESEARCH

A Growing Degree Day Model to Schedule Trinexapac-ethyl Applications on *Agrostis stolonifera* Golf Putting Greens

William C. Kreuser* and Douglas J. Soldat

ABSTRACT

Trinexapac-ethyl (TE) is a widely used growth regulator in the turfgrass industry. Poor summer efficacy has been related to more rapid metabolism in the plant. The purpose of this study was to determine if a growing degree day (GDD) model could be used to identify the optimum TE reapplication interval for putting greens. This objective was accomplished through model development and validation. Model development was conducted on a creeping bentgrass (*Agrostis stolonifera* L.) golf putting green in Madison, WI, during 2008. The treatments consisted of five TE reapplication intervals (100, 200, 400, 800 GDD, and 4 wk) and a control. Growing degree days were calculated in degrees C with a base temperature of 0°C. Trinexapac-ethyl was applied at the rate of 0.05 kg a.i. ha^{-1}. Clippings were collected daily. The 100- and 200-GDD reapplication intervals provided consistent 20 and 12% yield suppression, respectively. Other reapplication intervals had alternating periods of yield reduction followed by yield enhancement. Model validation occurred on a different creeping bentgrass green in 2009 and 2010. The experiment was a 3 × 2 factorial CRD with three TE rates (0.00, 0.05, and 0.10 kg a.i. ha^{-1}) and two reapplication frequencies (200 GDD and 4 wk). The 200-GDD interval consistently suppressed clipping yield. Application rate had no effect on the duration of suppression. Reapplying TE every 200 GDD provides more consistent growth regulation than a calendar-based application schedule.

W.C. Kreuser, Dep. of Horticulture, Cornell Univ., Ithaca, NY 14853; D.J. Soldat, Dep. of Soil Science, Univ. of Wisconsin-Madison, Madison, WI 53706. Received 19 Jan. 2011. *Corresponding author (wck38@cornell.edu).

Abbreviations: AUGC, area under growth curve; GA, gibberellic acid; GDD, growing degree day; TE, trinexapac-ethyl; TNC, total nonstructural carbohydrates.

The plant growth regulator trinexapac-ethyl (TE) is widely used to suppress clipping yield on all commonly managed turfgrass species (Table 1). Trinexapac-ethyl suppresses clipping yield by inhibiting gibberellic acid (GA) synthesis through inhibition of GA_{20} conversion to GA_1, the bio-active gibberellin in cool-season turfgrasses (Reid and Ross, 1991; Rademacher, 2000). As a result, cell elongation decreases while GA_{20} and total nonstructural carbohydrates (TNC) increase in concentration (Han et al., 1998, 2004; Tan and Qian, 2003). These alterations reduce leaf length while mesophyll cell density, chlorophyll concentration, tiller density, and leaf area are enhanced (Ervin and Koski, 1998; Ervin and Koski, 2001; Stier and Rogers, 2001; Bunnell et al., 2005; Beasley et al., 2007). These physiologic alterations are typically noted to cause turfgrass color and visual quality enhancement. Once TE is metabolized within the plant, increased GA_{20} and TNC concentrations are thought to cause a period of enhanced growth rate relative to nontreated turfgrass (Ervin and Zhang, 2008). Fagerness and Yelverton (2000) first described this period of yield enhancement following yield suppression as "post-inhibition growth enhancement." This effect will hereafter be called the *rebound phase* of growth regulation. The rebound phase has since been observed in other grass species including Kentucky

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Table 1. Influence of trinexapac-ethyl application rate and reapplication frequency on magnitude and duration of growth suppression in various turfgrass species.

Turfgrass species and mowing height	Application rate	Reapplication frequency	Growth suppression	Approximate duration of growth suppression	Reference
mm	kg a.i. ha^{-1}	wk	% control	wk	
Agrostis stolonifera L.; 3.2	0.05	4	20	2	McCullough et al., 2006a
Agrostis stolonifera L.; 3.2	0.02, 0.03, 0.05	1, 2, 3	20–40	3	McCullough et al., 2007
Poa pratensis L.; 30	0.05	4–6	20	4–6	Stier and Rogers, 2001
Poa pratensis L.; 35	0.05	4	50	4	Tan and Qian, 2003
Poa pratensis L.; 32	0.14, 0.29, 0.58	None	44–73	4–5†	Beasley and Branham, 2007
Poa trivialis L.; 80	0.29	6	55–80	6	Gardner and Wherley, 2005
Festuca ovina L.; 80	0.29	6	35–50	6	Gardner and Wherley, 2005
Stenotaphrum secundatum (Walter) Kuntze; 75	0.14, 0.29	2, 4	50	4	McCarty et al., 2004
Poa supina Schrad.; 30	0.05	4–6	60	4–6	Stier and Rogers, 2001
Festuca arundinacea Schreb.; 38	0.29	None	44–77	4	Richie et al., 2001
Festuca arundinacea Schreb.; 80	0.29	6	58–76	6	Gardner and Wherley, 2005
Cynodon dactylon (L.) Pers. × *C. transvaalensis* Burtt Davy; 3.2	0.05	4	60	3	McCullough et al., 2007
Cynodon dactylon (L.) Pers. × *C. transvaalensis* Burtt Davy; 16	0.07, 0.11	4	60	4	Fagerness and Yelverton, 2000
Cynodon dactylon (L.) Pers. × *C. transvaalensis* Burtt Davy; 25	0.11	4	50	4	Fagerness et al., 2004
Zoysia japonica Steud.; 12	0.05, 0.10	4, 8	25, 27	4–6	Qian and Engelke, 1999

† Duration dependent on summer or fall season.

bluegrass (*Poa pratensis* L.) and creeping bentgrass (*Agrostis stolonifera* L.) (Beasley and Branham, 2005).

A majority of the turfgrass species summarized in Table 1 had 50% relative yield suppression for a period of 4 to 6 wk following TE application. One notable exception, however, is creeping bentgrass maintained at golf putting green mowing heights. McCullough et al. (2006a) showed that TE-treated creeping bentgrass, managed as a putting green during summer in South Carolina, had a 20% decrease in relative clipping yield that lasted for 2 wk at the labeled application rate of 0.05 kg a.i. ha^{-1}.

McCullough et al. (2007) investigated the effect of TE application interval on creeping bentgrass putting green yield during the spring in South Carolina. In that study, total TE application rate was constant for all treatments. They found that TE reduced relative clipping yield by 20 to 40% and more frequent applications provided more uniform yield suppression. However, the magnitude and duration of yield suppression on creeping bentgrass putting greens was still low relative to other turfgrass species and is likely a result of the low application rate specified by the product label for golf course putting greens.

Lickfeldt et al. (2001) and Beasley et al. (2007) found TE efficacy decreased as air temperatures increased during summer. A similar effect was observed in hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt Davy] during fall (Fagerness et al., 2002). As the daily mean air temperature decreased, the duration and magnitude of the suppression period increased. Beasley and Branham (2005) showed the half-life of the plant-active form of TE, trinexapac acid, was directly related to air temperature and turfgrass species. The half-lives for creeping bentgrass and Kentucky bluegrass were 6.4 and 5.3 d at 18°C and 3.1 and 3.4 d at 30°C, respectively; doubling air temperature roughly doubled rate of TE metabolism. Additionally, Fagerness and Penner (1998) reported that TE is not subject to rapid ultraviolet degradation, and it further supports plant metabolism as the primary pathway of TE degradation within the plant.

Since TE metabolism is directly affected by air temperature, a logical step forward was to develop a model that uses air temperature to predict when TE should be reapplied. Growing degree day (GDD) systems are useful models that use air temperature as a method to estimate plant growth and development (McMaster and Wilhelm, 1997; Ritchie and NeSmith, 1991). In a typical GDD model, daily mean air temperature is recorded, subtracted from a base temperature where metabolism is minimal, and is added with previous day's temperature to calculate cumulative GDD (Ritchie and NeSmith, 1991). Cumulative GDD is then correlated with plant observations and used to predict plant development. It is likely that such a model could be developed to predict relative clipping yield following TE application and aid in reapplication scheduling.

The objective of this study was to develop and validate a GDD model as a means to estimate TE metabolism in creeping bentgrass putting greens. The hypothesis of this study was that a GDD model would predict TE metabolism, thus resulting in more accurate timing of TE applications and season-long yield suppression. Development of a functional GDD model would result in accurate prediction of the magnitude and duration of growth regulation and indicate when TE reapplications are required to maintain the growth suppression phase. These objectives were accomplished with two experiments over three growing seasons. The GDD model was first developed through a calibration study (Experiment 1) and then validated during the following two seasons on a different creeping bentgrass putting green (Experiment 2).

MATERIALS AND METHODS

Experiment 1: Model Calibration

Site Description

A field experiment was conducted on a creeping bentgrass (cv. L-93) putting green at the O.J. Noer Turfgrass Research and Education Facility in Madison, WI, during 2008. The green was constructed in 2002 to United States Golf Association specifications (USGA Green Section Staff, 1993) with sand amended with 20% peat (by volume). Daily overhead irrigation supplemented precipitation to 80% of estimated potential evapotranspiration. The green was mowed 6 d wk^{-1} at 3.2 mm with a Toro Greensmaster 1000 walking greens mower (Toro Co., Bloomington, MN) following data collection. The study area was fertilized weekly with 5 kg N ha^{-1} as liquid urea. Approximately 10 mm of irrigation was applied to the plot immediately after fertilizer application. Mehlich-3 soil testing indicated supplemental phosphorus and potassium were not required (Mehlich, 1984). Chlorothalonil was applied weekly to control disease; products with known plant growth regulatory properties, that is, demethylation-inhibiting fungicides, were avoided. The plots were topdressed monthly with approximately 1000 kg ha^{-1} sand.

Experimental Design

Plots measured 1.8 by 0.9 m. Treatments consisted of six TE reapplication intervals arranged in a randomized complete block design with four replicates. Reapplication intervals were every 100, 200, 400, or 800 GDD, every 4 wk, and a nontreated control. Cumulative GDD model was calculated as the summation of the daily mean air temperature (°C) with a base of 0°C following the most recent TE application. Daily mean air temperature was calculated from hourly temperature data. After the GDD treatment thresholds had been surpassed, TE was reapplied, and GDD for that particular treatment was reset to zero. Trinexapac-ethyl (Primo MAXX, Syngenta Co., Greensboro, NC) was applied at 0.05 kg a.i. ha^{-1} with a CO_2-powered backpack sprayer equipped with TeeJet XR 11004 nozzles (TeeJet Technologies, Wheaton, IL) calibrated to deliver 370 L ha^{-1} at 276 kPa. The spray boom was held approximately 0.5 m above the turfgrass surface with four nozzles spaced 0.5 m apart. Applications began on 22 June and continued to 19 Aug. 2008.

Data Collection

Weather permitting, clippings were collected five times per week from 25 June until 21 Aug. 2008 by mowing one 1.8-m-long pass down the center of each plot 24 h (1200 ± 2 h) after the previous mowing with a 0.54-m-wide Toro Greensmaster 1000 greens mower (Toro Co., Bloomington, MN). Before clipping collection, 0.27-m-wide buffer alleys were mowed at the top and bottom of each plot, perpendicular to the direction of clipping collection, to reduce variation caused by starting and stopping the mower. The effective clipping collection area for each plot was 0.68 m^2 after compensating for the alleys. Clippings were then brushed from the mower collection bucket into paper bags. Sand debris was removed from clipping samples with the water method described in Kreuser et al. (2011). The sample mass from treatments receiving TE were divided by the mass of the nontreated plot within the appropriate block to obtain relative clipping yield (kg kg^{-1}). Turfgrass visual quality was rated on a 1-to-9 scale weekly, with 1 representing completely dead, 6 minimally acceptable, and 9 perfect putting green visual quality as described by Skogley and Sawyer (1992).

Statistical Analysis

The mean daily relative clipping yields from all five TE treatments were plotted as a function of date and cumulative GDD after the most recent TE application to identify growth phase (suppression or rebound) and determine the GDD threshold that maintained season-long yield suppression. Treatments with suppression and rebound growth phases were pooled together and subjected to three-parameter sine regression to create the model with the nonlinear procedure in SAS 9 (SAS Institute, Cary, NC). Base temperature was determined by recalculating GDD with base temperatures ranging from 0 to 12°C. The most appropriate base temperature, as determined by pseudo-R^2 value (1 − sum of squares error/total sum of squares), was selected for final model development. Area under the growth curve (AUGC) was calculated from the actual clipping yields for each treatment as described by Shaner and Finney (1977) to determine the effect of TE reapplication treatment on net clipping yield. Treatment AUGCs were separated with Fisher's protected LSD at $\alpha = 0.05$ in SAS 9. Visual turfgrass quality differences were quantified using repeated-measures analysis and Fisher's protected LSD means separation at $\alpha = 0.05$ with JMP 8 statistical software (version 8.0.2, SAS Institute, Cary, NC).

Experiment 2: Model Validation

Site Description

A field experiment was conducted on a creeping bentgrass (cv. Penncross) putting green at the O.J. Noer Turfgrass Research and Education Facility in Madison, WI, during 2009 and 2010. The green was constructed to United States Golf Association specifications in 2005 with sand amended with 20% peat by volume (USGA Green Section Staff, 1993). All cultural practices, including mowing, irrigation, fertilization, and pest control, were identical to those described in Experiment 1.

Experimental Design

Plot sizes were lengthened to 3.6 by 0.9 m to increase the effective clipping collection area to 1.65 m^2. Plots were arranged in a completely randomized design with four replicates. Treatments consisted of a 3 × 2 factorial of TE application rate and TE reapplication intervals. Trinexapac-ethyl was applied at the rates of 0, 0.05, and 0.10 kg a.i. ha^{-1} every 200 GDD or every 4 wk. The addition of the 0.10 kg a.i. ha^{-1} TE application rate was included to evaluate the model at the maximum rate permitted by the product label for a golf course putting green. Growing degree days were calculated as stated in Experiment 1 where TE was reapplied every 200 GDD for those treatments.

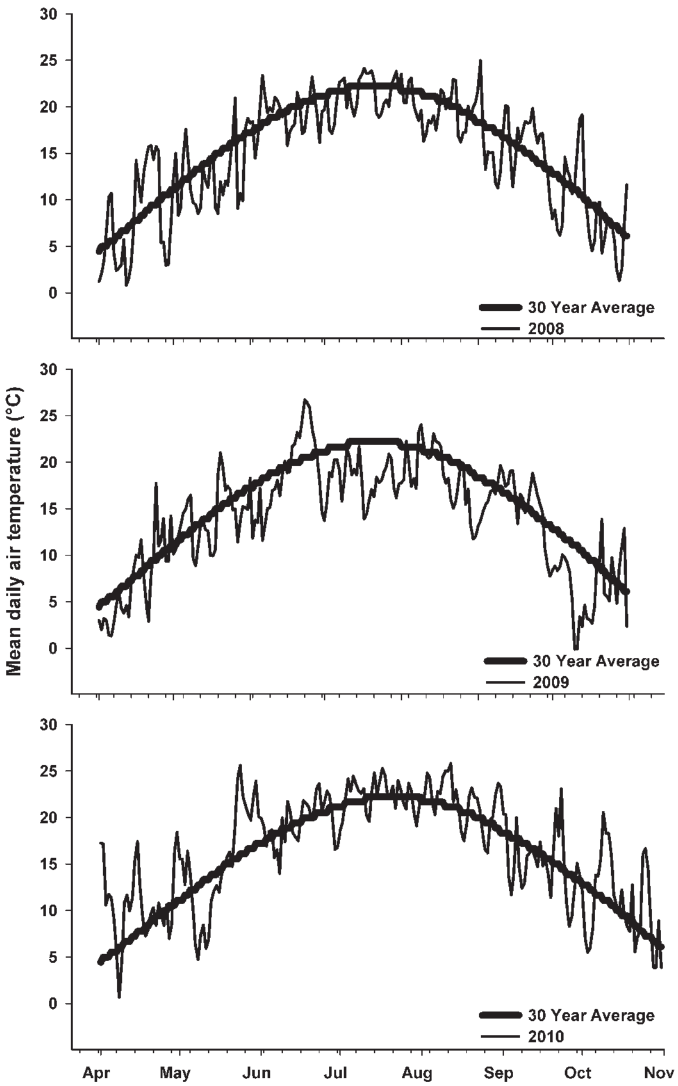

Figure 1. Daily mean air temperature at the O.J. Noer Turfgrass Research and Education Facility during 2008, 2009, and 2010. The bold black line represents the 30-yr average temperature from Dane County Regional Airport.

Trinexapac-ethyl (Primo MAXX, Syngenta Co., Greensboro, NC) was applied with a CO_2-powered backpack sprayer equipped with two TeeJet AI 11004 nozzles (TeeJet Technologies, Wheaton, IL) calibrated to deliver 370 L ha^{-1} at 276 kPa. Applications began on 29 Apr. 2009, continued until 14 Oct. 2009, and resumed on 1 Apr. 2010 until 19 Sept. 2010.

Data Collection

Clippings were collected approximately three times per week from 7 May until 19 Oct. 2009 and 22 Apr. until 8 Oct. 2010; weather permitting, following the same methods described in Experiment 1 within 1 h of 1200 h. Visual quality was measured biweekly by the methods described in Experiment 1.

Statistical Analysis

Repeated-measures analysis was used to calculate the mean clipping yield for all treatments on all days. Relative yield was calculated by dividing the mean daily clipping yield from each treatment by the average of the two nontreated controls. Relative clipping yields from the 4-wk reapplication interval treatments were fitted to the model generated in Experiment 1 using the nonlinear procedure to compare models. Relative clipping yields from treatments applied every 200 GDD were compared to 100- and 200-GDD treatments of Experiment 1 using ANCOVA with Fisher's protected LSD. Visual quality differences were quantified using repeated-measures analysis and Fisher's protected LSD for means separation at $\alpha = 0.05$. Statistical procedures were performed using the JMP software package (version 8.0, SAS Institute Inc., Cary, NC), except the nonlinear procedure, which was analyzed with SAS (version 9.0, SAS Institute, Inc., Cary, NC).

RESULTS

Weather Data

Daily mean air temperatures ranged from −0.1 to 26.7°C during experimentation in 2008, 2009, and 2010 (Fig. 1). The 2008 and 2009 growing seasons had below-average daily air temperatures, 0.9 and 1.9°C below normal during data collection, respectively. The summer of 2009, with exception of late June, was exceptionally cool. During 2010 data collection, the mean daily air temperature averaged 0.3°C above normal. The above-average temperatures in early spring 2010 allowed for earlier TE application than in 2008 and 2009 because of earlier turfgrass green-up. The below- and above-normal air temperatures in 2009 and 2010 allowed differing temperature ranges to test the model generated in 2008.

Experiment 1: Model Calibration

The treatments resulted in a wide range of relative clipping yield responses (0.61 to 1.26 kg kg^{-1} of the control). Clipping yield suppression and rebound phases of growth occurred when TE reapplications occurred every 400 GDD, 800 GDD, and 4 wk (Fig. 2). Therefore, the relative clipping yields from those treatments were pooled together and subjected to regression analysis with relative yield as function of cumulative GDD following the most recent TE application (Fig. 3). This analysis produced a model to predict the effect of TE on the relative clipping yield of creeping bentgrass putting green turfgrass following TE application. Three-parameter sine regression proved to be the most appropriate model with a domain of 0 to 800 GDD, $R^2 = 0.520$, and $p < 0.001$ (Fig. 3):

$$\text{Relative yield (kg kg}^{-1}) = 1.000 + 0.183 \times \sin(2\pi \times \text{GDD}^{0.738}/138.828 - \pi)$$

This model is appropriate because it describes how TE application causes relative yield suppression followed by rebound before the turfgrass returns to a clipping yield similar to the nontreated turfgrass. The intercept was set to 1.000 while the amplitude, period, and skew terms were determined with the nonlinear procedure in SAS 9. The domain is limited to 800 GDD because the function continues to decrease after 800 GDD and has no experimental or theoretical basis. Base temperature analysis

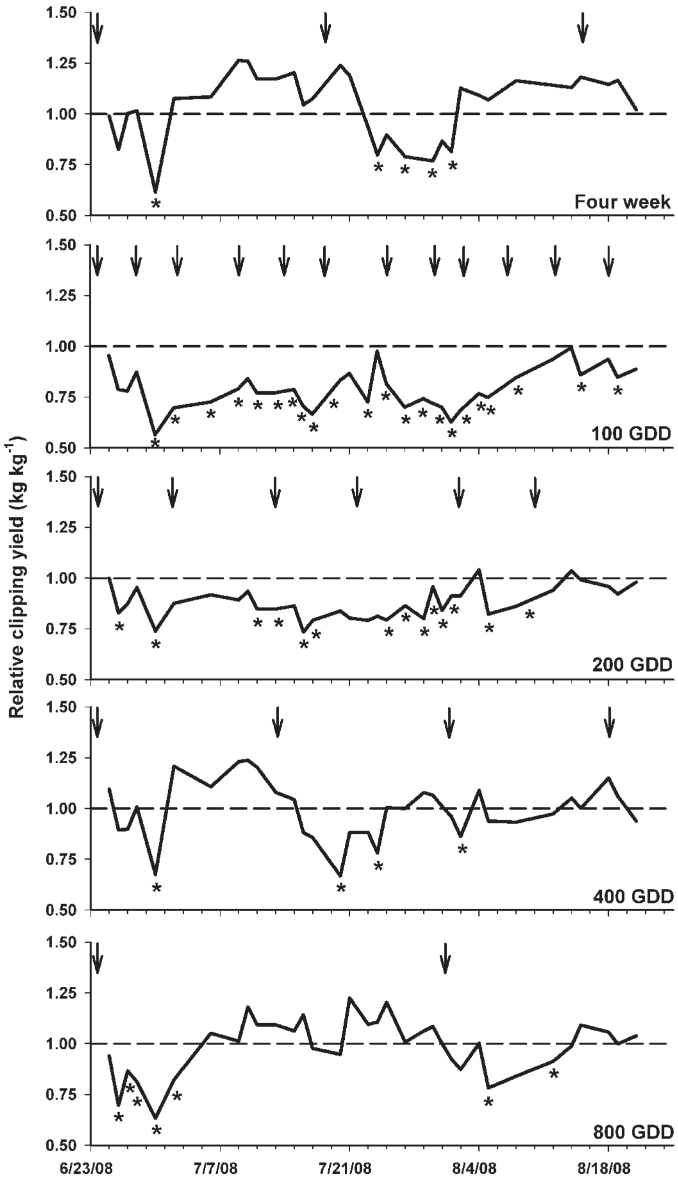

Figure 2. Daily average relative clipping yield (kg kg^{-1} of nontreated control) for the five trinexapac-ethyl (TE) application intervals in Experiment 1. Black arrows indicate TE application, and stars indicate days that clipping yield was statistically less than the control plot after Student's *t* tests at $\alpha = 0.05$. The growing degree day reapplication threshold (GDD) is the summation of daily mean air temperature (°C) following the previous TE application with base temperature of 0°C.

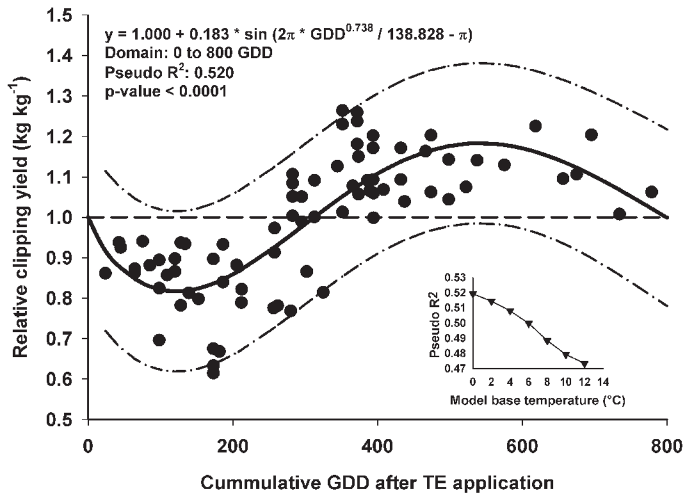

Figure 3. Development of the growing degree day (GDD) three-parameter sine regression model relating relative clipping yield (kg kg^{-1}) from the 400-GDD, 800-GDD, and 4-wk treatments to cumulative GDD after the previous trinexapac-ethyl (TE) application. Cumulative GDD was the summation of the daily mean air temperature (°C) following the previous TE application with base temperature of 0°C. The solid line represents the predicted value while the dot/dashed line represents the 95% CI for any observation within the model. To determine base temperature, cumulative GDD after TE application was recalculated with different base temperatures (0 to 12°C) and subject to sine regression. The model with the largest pseudo-R^2 value was used in the final model (inset).

indicated that the 0°C had the greatest pseudo-R^2 value compared to models where GDD was recalculated with base temperatures ranging from 2 to 12°C (Fig. 3).

Mean maximum growth suppression occurred 122 GDD units after TE application and reduced clipping yield by 18.3% on average. Transition from the suppression to rebound phase occurred at 312 GDD before the maximum rebound occurred at 541 GDD with a 18.3% increase in relative yield. The effect of TE on clipping yield appeared to dissipate 700 to 800 GDD following TE applications (Fig. 3).

The 100- and 200-GDD reapplication treatments resulted in consistent yield suppression and were not used to create the GDD model. Analysis of covariance indicated that the relative clipping yields of the 100- and 200-GDD reapplication treatments were not affected by GDD after application, indicating constant growth suppression (Table 2), although the level of yield suppression, represented by the intercept, was highly significant. The relative yield for the 100- and 200-GDD treatments was statistically less than the control: 20 and 12%, respectively.

Calculation of AUGC was used to determine the effect of TE reapplication interval on net clipping yield. The AUGC for the 100- and 200-GDD TE reapplication treatments were statistically lower yield compared to the nontreated control over the study period (Table 3). All other TE application intervals, including the labeled 4-wk interval, had similar net clipping yields as the control; the rebound phase cancelled out yield suppression for those reapplication intervals. More frequent TE applications in the 100- and 200-GDD treatments prevented the development of the rebound phase, which resulted in a net yield reduction.

Application of TE statistically enhanced turfgrass visual quality compared to the nontreated control for all reapplication intervals except for the 800-GDD interval (data not shown). At no point was turfgrass quality unacceptable for any treatment. Visual quality of the TE treatments was not statistically different from the control until 6 to 7 wk after the initial TE applications. Delayed visual quality enhancement results are consistent with findings reported by McCullough et al. (2006a).

Table 2. Relative clipping yield, indicated by the intercept, as affected by trinexapac-ethyl application rate and reapplication interval on from treatments in Experiments 1 and 2 not exhibiting a rebound phase. Data from 2009 and 2010 were pooled together at each respective application rate.

Experiment no.	Application rate	Reapplication frequency	df	Intercept
	kg a.i. ha^{-1}			g g^{-1}
1	0.05	100 GDD†		0.802a‡
1	0.05	200 GDD		0.876ab
1	0.00	N/A§		1.000c
2	0.05	200 GDD		0.793a
2	0.10	200 GDD		0.895b
2	0.00	N/A		1.000c
		ANCOVA		
Source of variation				
Treatment			4	***
GDD			1	NS
Treatment × GDD			4	NS

*** Significant at the 0.001 probability level.

† Growing degree day (GDD) was the summation of mean daily air temperature (base °C) after trinexapac-ethyl (TE) application. After the GDD threshold was surpassed, TE was reapplied and the model was reset to zero.

‡ Column means followed by different letters are statistically different according to Fisher's LSD (α = 0.05).

§ Not applicable.

Experiment 2: Model Validation

In 2009 and 2010, the 4-wk reapplication treatments performed similarly to the 400-GDD, 800-GDD, and 4-wk reapplication intervals from Experiment 1 with p-values ranging from 0.991 to 1.000 (Fig. 4). Relative yield suppression was not held constant at any application rate when TE was applied every 4 wk. In both years, relative yield suppression was followed by yield rebound; approximately 20% less or greater than the nontreated control, respectively (Fig. 4). There was not a year effect despite the below-normal temperatures in 2009, which allowed for years to be pooled together. Additionally, application rate did not influence the magnitude or duration of growth suppression (Fig. 4)

The 200-GDD reapplication frequency sustained growth suppression by 21 and 11% for the 0.05 and 0.10 kg a.i. ha^{-1} application rates, respectively (Table 2). The slope of the GDD by relative yield regression was not significant (p = 0.8081) regardless of application rate or year, which is consistent with Experiment 1. This indicates that the 200-GDD reapplication maintained consistent growth suppression across a wide range of Wisconsin summer temperatures. Additionally, the 200-GDD application rate at the 0.10 kg a.i. TE ha^{-1} application rate consistently provided the highest visual quality. Visual quality enhancement due to TE applications occurred 4 to 6 wk after the initial TE applications and caused the rate × date interactions in both years (data not shown).

Table 3. Area under the growth curve calculation (Shaner and Finney, 1977) of net annual clipping yield across all trinexapac-ethyl reapplication treatments at the 0.05 kg a.i. ha^{-1}application rate in Experiment 1.

Reapplication interval	Area under growth curve
100 GDD†	53.54A‡
200 GDD	59.41AB
400 GDD	65.23BC
800 GDD	65.16BC
4 wk	68.84C
Nontreated control	67.06C

† Growing degree day (GDD) was the summation of mean daily air temperature (base °C) after trinexapac-ethyl (TE) application. After the GDD threshold was surpassed, TE was reapplied and the model was reset to zero.

‡ Column means followed by different letters are statistically different according to Fisher's LSD (α = 0.05).

DISCUSSION

Basing reapplication of plant growth regulators on metabolism and not arbitrary calendar intervals can vastly increase the precision by which these products are used. For example, the number of days in the suppression phase for the 0.10 a.i. ha^{-1} TE treatment varied within the growing season (Fig. 5). During early spring (15 Apr. to 21 May 2010) yield suppression lasted approximately 23 d. The second TE application (19 May until 17 June 2010) resulted in approximately 17 d of growth suppression. Finally, the third TE application (28 June to 25 July 2010) resulted in approximately 14 d of yield suppression. The average daily mean air temperatures during those periods were 11.3, 19.8, and 22.6°C, respectively. During these specific time periods, and based on the recommended 200-GDD interval, TE would need to be reapplied every 17, 10, and 8 d to maintain yield suppression, respectively. This is in direct agreement with the finding of Beasley and Branham (2005), which indicated that the rate of trinexapac acid metabolism is related to air temperature. Other field studies have also demonstrated reduced TE efficacy during warmer air temperatures in direct support of our findings (Lickfeldt et al., 2001; Beasley et al., 2007). The GDD model presented here accounts for those differences in TE metabolism and accurately indicates when TE needs to be reapplied to sustain yield suppression. The magnitude of the suppression phase increased as the growing season progressed in the previous example. However, increased yield suppression did not sustain the duration of suppression during periods of increased air temperature.

Reapplication of TE every 200 GDD is likely the furthest reapplication interval to sustain yield suppression. Although the model predicts relative yield to intersect the nontreated yield 312 GDD after TE application (Fig. 3), maximum relative yield suppression occurs near 122 GDD, likely as TE is converted to the plant-active form trinexapac acid. Reapplication of TE at 200 GDD allows time for this reaction and smoothes out the transition between TE applications.

Doubling application rate from 0.05 to 0.10 kg a.i. ha^{-1} did not lengthen the duration of the suppression phase or enhance the magnitude of relative yield suppression. Based on the results of Beasley and Branham (2005), the projected half-life of trinexapac acid is approximately 100 GDD within the plant. As a consequence, increasing TE application rate is not a successful strategy to lengthen the yield suppression phase during periods of high temperature. For example, doubling application rate when daily mean air temperatures averaged 25°C would theoretically lengthen the yield suppression phase by only 4 d and was not evident in the data. The only effective management strategy to maintain season-long yield suppression during midsummer is to increase application frequency, and is supported by the literature (Lickfeldt et al., 2001; Beasley et al., 2007).

Unlike many of the turfgrass species presented in Table 1, TE suppressed creeping bentgrass putting green yield by an average of 11 to 21% for all TE reapplication intervals at the labeled application rate. Growth suppression was further suppressed in the 100-GDD treatment of Experiment 1 compared to the other treatments in that experiment. This is evidence that TE was being reapplied faster than it was being metabolized and resulted in a gradual accumulation of TE in the plant, increased growth suppression, and greater visual quality enhancement.

The GDD model developed in this study is specific to creeping bentgrass golf putting greens. Other grass species including *Poa annua* L., *P. trivialis* L., and *Cynodon* species likely have different growth response characteristics following TE application. *Cynodon dactylon* × *transvaalensis* experienced >50% yield suppression for a period of 4 wk (Table 1). Application of TE every 200 GDD to *Poa pratensis* maintained at 30 mm was too frequent and resulted in 95% yield suppression (Kreuser, unpublished data, 2011). As a result, 200-GDD reapplication interval would be inappropriate for those species. Additionally, this model has not been thoroughly evaluated in locations with challenging growing conditions such as prolonged temperature extremes, year-round growing seasons, or situations with excessive shade. These environments should be evaluated in the future to further validate the GDD model.

Other factors besides trinexapac acid concentrations within the plant may also affect relative clipping yield; specifically, feedback regulation of the GA pathway. A review of GA metabolism by Hedden and Phillips (2000) found that GA 20-oxidase and GA 3-oxidase, two rate-limiting enzymes late in the GA pathway, are up-regulated when GA_1 concentrations are low. Calvo et al. (2004) found that application of another GA inhibitor, paclobutrazol, dramatically increased expression of GA 20-oxidases. It is likely that TE application also up-regulates the GA pathway similarly to paclobutrazol. Additionally, other factors such as auxin concentration, photoperiod, and light quality are known to regulate the GA pathway, and in conjunction with GA feedback mechanisms, likely contribute to the small daily fluctuations in relative yield observed during the growing season (Hedden and Phillips, 2000). Amid these complications, however, the 200-GDD reapplication interval proved to be successful at maintaining yield suppression during the entire 6-mo growing season in Wisconsin.

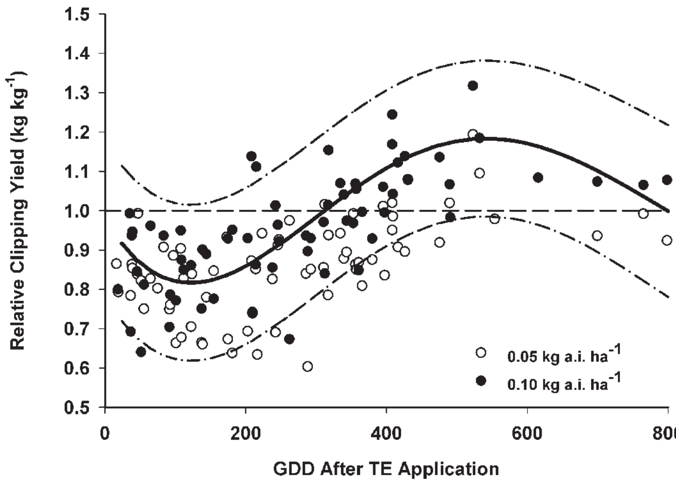

Figure 4. Relative clipping yield (kg kg^{-1}) for the 0.05 and 0.10 kg a.i. ha^{-1} application rates were plotted as a function of growing degree day (GDD) after the previous trinexapac-ethyl (TE) application from the 4-wk reapplication interval in Experiment 2. The bold line is the predicted value from the model generated in Experiment 1 with associated 95% CI for any observation within the model. The GDD was the summation of the daily mean air temperature (°C) following the previous TE application with base temperature of 0°C.

There are several important consequences to maintenance of season-long yield suppression with TE. Han et al. (1998, 2004) found that TNC concentrations increased in the leaves of creeping bentgrass 2 wk after initial TE application. Elevated TNC levels then declined 4 to 16 wk after TE application. A similar phenomenon occurred in hybrid bermudagrass after sequential TE applications (Waltz and Whitwell, 2005). Richie et al. (2001) found TE had no effect on *Festuca arundinacea* Schreb. TNC concentrations 6 to 7 wk after application; this result is not surprising based on the findings of Han et al. (1998, 2004).

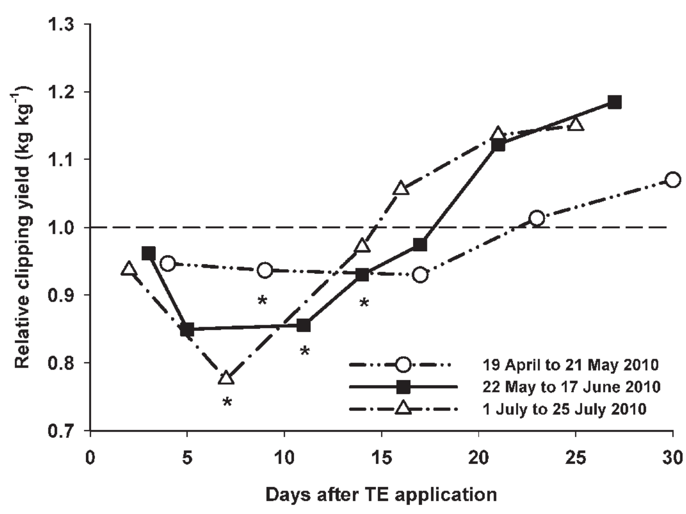

Figure 5. Relative clipping yield as a function of days after previous trinexapac-ethyl (TE) application from the 0.10 kg a.i. ha^{-1} TE application rate when TE was reapplied every 4 wk in 2010. Trinexapac-ethyl was applied on 15 April, 19 May, and 28 June. Daily mean air temperatures between TE applications averaged 11.3, 19.8, and 22.6°C, respectively.

Temporal variability of TNC concentrations is likely result of the sinusoidal effect of TE on clipping yield. Increased TNC concentration in the plant 2 wk after TE application coincides with yield suppression and is supported by Table 1. As turfgrass growth rate increases during the rebound phase, TNC concentrations diminish as a likely result of increased growth rate. Therefore, maintenance of yield suppressing would likely sustain enhanced TNC concentrations. As an additional point, the effect of TE on various turfgrass attributes, that is, ball roll distance, TNC concentration, and stress tolerance, need to be accompanied with relative yield data especially when TE is reapplied on a calendar-based schedule. Ervin and Zhang (2008) review a great deal of contradictory data regarding the effect of TE on numerous turfgrass attributes. A further review of those articles found that relative clipping yield was not quantified; thus, the authors could not be certain the turfgrass was in the suppression or rebound phase. Due to the sinusoidal nature of relative clipping yield response following TE application, and depending on the frequency of sampling, researchers could observe vastly different results. Quantification of relative clipping yield may help to avoid contradictory results in the future.

Preservation of season-long yield suppression with 200-GDD TE applications likely sustains several secondary benefits associated with use of TE, such as ball roll distances, turfgrass quality, and reduced turfgrass nutrient requirements. Nutrient removal during mowing is a major source of removal loss from a turfgrass system. Nutrient removal is a function of clipping yield and clipping tissue nutrient status. In addition to reducing clipping yield, TE partitions N from the clippings to the plant roots (Fagerness et al., 2004; McCullough et al., 2006b), likely due to diminished leaf N demand, and further reduces N loss during mowing. Fagerness et al. (2004) speculated the TE applications would likely reduce turfgrass N requirements. Kreuser (2010) found that creeping bentgrass putting green N requirements could be reduced 25 to 50% when yield suppression was maintained with 200-GDD TE applications. These reductions did not occur when yield suppression was not maintained because of too-infrequent TE reapplications.

CONCLUSIONS

A GDD model, with base temperature of 0°C, successfully predicted the duration of the suppression and rebound growth phases. Reapplication of TE every 4 wk did not sustain yield suppression on creeping bentgrass putting greens in contradiction to the product label. Application of TE every 200 GDD sustained season-long yield suppression by an average of 11 to 21%. The only successful method to increase the magnitude of yield suppression was to reapply TE more frequently than 200 GDD, while application rate did not affect the magnitude or duration of the suppression phase. Use of a GDD model to reschedule TE applications to creeping bentgrass golf putting greens is an extremely useful tool to maintain yield suppression and sustain the ancillary benefits associated with TE application.

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References

Beasley, J.S., and B.E. Branham. 2005. Analysis of paclobutrazol and trinexapac acid in turfgrass clippings. Int. Turfgrass Soc. Res. J. 10:1170–1175.

Beasley, J.S., B.E. Branham, and L.A. Spomer. 2007. Plant growth regulators alter Kentucky bluegrass canopy leaf area and carbon exchange. Crop Sci. 47:757–766. doi:10.2135/cropsci2005.11.0432

Bunnell, B.T., L.B. McCarty, and W.C. Bridges. 2005. 'TifEagle' bermudagrass response to growth factors and mowing height when grown at various hours of sunlight. Crop Sci. 45:575–581. doi:10.2135/cropsci2005.0575

Calvo, A.P., C. Nicolás, G. Nicolás, and D. Rodriguez. 2004. Evidence of cross-talk regulation of the GA 20-oxidase (*FsGA20ox1*) by gibberellins and ethylene during the breaking of dormancy in *Fagus sylvatica* seeds. Physiol. Plant. 120:623–630. doi:10.1111/j.0031-9317.2004.0270.x

Ervin, E.H., and A.J. Koski. 1998. Growth responses of *Lolium perenne* to trinexapac-ethyl. HortScience 33:1200–1202.

Ervin, E.H., and A.J. Koski. 2001. Trinexapac-ethyl increases Kentucky bluegrass leaf cell density and chlorophyll concentration. HortScience 36:787–789.

Ervin, E.H., and X. Zhang. 2008. Applied physiology of natural and synthetic plant growth regulators on turfgrasses. p. 171–200. *In* M. Pessaraki (ed.) Handbook of turfgrass management and physiology. CRC Press, Boca Raton, FL.

Fagerness, M.J., D.C. Bowman, F.H. Yelverton, and T.W. Rufty, Jr. 2004. Nitrogen use in Tifway bermudagrass, as affected by trinexapac-ethyl. Crop Sci. 44:595–599.

Fagerness, M.J., and D. Penner. 1998. Spray application parameters that influence the growth inhibiting effects of trinexapac-ethyl. Crop Sci. 38:1028–1035. doi:10.2135/cropsci1998.0011183X003800040024x

Fagerness, M.J., and F.H. Yelverton. 2000. Tissue production and quality of 'Tifway' bermudagrass as affected by seasonal application patterns of trinexapac-ethyl. Crop Sci. 40:493–497. doi:10.2135/cropsci2000.402493x

Fagerness, M.J., F.H. Yelverton, D.P. Livingston III, and T.W. Rufty, Jr. 2002. Temperature and trinexapac-ethyl effects on bermudagrass growth, dormancy, and freezing tolerance. Crop Sci. 42:853–858. doi:10.2135/cropsci2002.0853

Gardner, D.S., and B.G. Wherley. 2005. Growth response of three turfgrass species to nitrogen and trinexapac-ethyl in the shade. HortScience 40:1911–1915.

Han, S.W., T.W. Fermanian, J.A. Juvik, and L.A. Spomer. 1998. Growth retardant effects on visual quality and nonstructural carbohydrates of creeping bentgrass. HortScience 33:1197–1199.

Han, S., T.W. Fermanian, J.A. Juvik, and L.A. Spomer. 2004. Total nonstructural carbohydrate storage in creeping bentgrass treated with trinexapac-ethyl. HortScience 39:1461–1464.

Hedden, P., and A.L. Phillips. 2000. Gibberellin metabolism: New insights revealed by the genes. Trends Plant Sci. 5:523–530. doi:10.1016/S1360-1385(00)01790-8

Kreuser, W.C. 2010. The effect of growing degree day scheduled trinexapac-ethyl applications on the growth rate and fertility requirements of creeping bentgrass golf putting greens. M.S. thesis. Univ. of Wisconsin-Madison, Madison.

Kreuser, W.C., M.P. Fish, D.J. Soldat, and S. Bauer. 2011. Removing sand from putting green clipping samples substantially reduces clipping weight measurement error. Crop Sci. 51:1268–1273.

Lickfeldt, D.W., D.S. Gardner, B.E. Branham, and T.B. Voigt. 2001. Turfgrass management: Implications of repeated trinexapac-ethyl applications on Kentucky bluegrass. Agron. J. 93:1164–1168. doi:10.2134/agronj2001.9351164x

McCarty, L.B., J.S. Weinbrecht, J.E. Toler, and G.L. Miller. 2004. St. Augustinegrass response to plant growth retardants. Crop Sci. 44:1323–1329. doi:10.2135/cropsci2004.1323

McCullough, P.E., H. Liu, L.B. McCarty, and J.E. Toler. 2006a. Ethephon and trinexapac-ethyl influence creeping bentgrass growth, quality, and putting green performance. Appl. Turfgrass Sci. doi:10.1094/ATS-2006-0324-01-RS

McCullough, P.E., H. Liu, L.B. McCarty, and J.E. Toler. 2007. Trinexapac-ethyl application regimens influence growth, quality, and performance of bermudagrass and creeping bentgrass putting greens. Crop Sci. 47:2138–2144. doi:10.2135/cropsci2006.04.0256

McCullough, P.E., H. Liu, L.B. McCarty, T. Whitwell, and J.E. Toler. 2006b. Growth and nutrient partitioning of 'TifEagle' bermudagrass as influenced by nitrogen and trinexapac-ethyl. HortScience 41:453–458.

McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. Agric. For. Meteorol. 87:291–300. doi:10.1016/S0168-1923(97)00027-0

Mehlich, A. 1984. Mehlich 3 soil extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416. doi:10.1080/00103628409367568

Qian, Y.L., and M.C. Engelke. 1999. Influence of trinexapac-ethyl on diamond zoysiagrass in a shade environment. Crop Sci. 39:202–208. doi:10.2135/cropsci1999.0011183X003900010031x

Rademacher, W. 2000. Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. Annu. Rev. Plant Physiol. Plant Mol. Biol. 51:501–531. doi:10.1146/annurev.arplant.51.1.501

Reid, J.B., and J.J. Ross. 1991. Gibberellin mutants in *Pisum* and *Lathyrus*. p. 40–50. *In* Takahashi et al. (ed.). Gibberellins. Springer Verlag, New York.

Richie, W.E., R.L. Green, and F. Merino. 2001. Trinexapac-ethyl does not increase total nonstructural carbohydrate content in leaves, crowns, and roots of tall fescue. HortScience 36:772–775.

Ritchie, J.T., and D.S. NeSmith. 1991. Temperature and crop development. p. 5–29. *In* J. Hanks and J.T. Ritchie (ed.) Modeling plant and soil systems. Agron. Monogr. 31. ASA, CSSA, SSSA, Madison, WI.

Shaner, G., and R.E. Finney. 1977. The effect of nitrogen fertilization on the expression of slow-mildewing resistance in Knox wheat. Phytopathology 67:1051–1056. doi:10.1094/Phyto-67-1051

Skogley, C.R., and C.D. Sawyer. 1992. Field research. p. 589–614. *In* D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, SSSA, Madison, WI.

Stier, J.C., and J.N. Rogers III. 2001. Trinexapac-ethyl and iron effects on supina and Kentucky bluegrasses under low irradiance. Crop Sci. 41:457–465. doi:10.2135/cropsci2001.412457x

Tan, Z.G., and Y.L. Qian. 2003. Light intensity affects gibberellic acid content in Kentucky bluegrass. HortScience 38:113–116.

USGA Green Section Staff. 1993. USGA recommendations for a method of putting green construction: The 1993 revision. USGA Green Sect. Rec. 31:1–3.

Waltz, F.C., Jr., and T. Whitwell. 2005. Trinexapac-ethyl effects on total nonstructural carbohydrates of field-grown hybrid bermudagrass. Int. Turfgrass Soc. Res. J. 10:899–903.