

Growing Degree Day Models for Plant Growth Regulator Applications on Ultradwarf Hybrid Bermudagrass Putting Greens

E. H. Reasor, J. T. Brosnan, J. P. Kerns, W. J. Hutchens, D. R. Taylor, J. D. McCurdy, D. J. Soldat, and W. C. Kreuser*

ABSTRACT

Plant growth regulators (PGRs) are commonly applied to ultradwarf hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy] putting greens during the growing season. Trinexapac-ethyl (TE) and prohexadione-Ca (PH) are PGRs that inhibit gibberellic acid biosynthesis and are used to reduce clipping yield and improve turfgrass visual quality. Growing degree day (GDD) models have optimized the timing of PGR reapplications to creeping bentgrass (*Agrostis stolonifera* L.) putting greens, but no information is available regarding proper PGR reapplication timing on bermudagrass putting greens. The objective of this research was to develop a GDD model to determine optimal TE and PH application frequencies on bermudagrass putting greens. Field research was conducted on three ultradwarf cultivars at separate locations in the southeastern United States: 'MiniVerde' in Knoxville, TN, 'Champion' in Durham, NC, and 'TifEagle' in Starkville, MS. Peak yield suppression was 49 to 65% after TE application at 0.034 kg a.i. ha⁻¹ and 50 to 54% after 0.154 kg PH ha⁻¹. Peak suppression occurred later for TE (166–177 GDD calculated using 10°C as the base temperature [GDD_{10C}]) than for PH (92–97 GDD_{10C}), which resulted in an estimated PGR reapplication interval of 216 to 230 for TE and 120 to 126 GDD_{10C} for PH. Enhanced clipping yield and rebound did not follow clipping yield suppression. The use of a GDD model to schedule PGR applications on bermudagrass putting greens has the potential to maximize PGR benefits; however, season-long implementation of this GDD model needs comparison with current PGR programs used on ultradwarf putting surfaces.

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Abbreviations: GA, gibberellic acid; GDD, growing degree days; GDD_{10C}, growing degree days calculated using 10°C as the base temperature; PGR, plant growth regulator; PH, prohexadione-calcium; TE, trinexapac-ethyl.

ULTRADWARF HYBRID BERMUDAGRASS cultivars [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy] are frequently used on golf course putting greens (Reasor et al., 2016). Plant growth regulators (PGRs) are commonly applied to bermudagrass putting greens to reduce vertical shoot growth and maintain consistent playing surfaces (Fagerness et al., 2000; McCullough et al., 2007). Two commonly used PGRs in turfgrass are trinexapac-ethyl (TE) and prohexadione-Ca (PH). These active ingredients are absorbed by turf foliage and inhibit the production of active gibberellic acid (GA) by blocking the late 3β-hydroxylation reaction of GA₂₀ to GA₁ (Watschke and DiPaola, 1995; Fagerness et al., 2000; Rademacher, 2000; Beam and Askew, 2007).

Strategies for using TE on bermudagrass putting greens have been explored for many years; however, research on PH use in turfgrass is limited (Beam and Askew, 2007; Beam, 2004; Marchi

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et al., 2015). The impact of TE on bermudagrass putting greens varies by application regime and cultivar differences (McCullough et al., 2005, 2006, 2007; Baldwin et al., 2009; McCarty et al., 2011). McCullough et al. (2007) evaluated three different TE application rates and frequencies (0.017 kg a.i. ha⁻¹ wk⁻¹, 0.033 kg a.i. ha⁻¹ 2 wk⁻¹, and 0.05 kg a.i. ha⁻¹ 3 wk⁻¹) on 'TifEagle'. Clipping yield reduction among the TE regimes was not significantly different, although there was a 49 to 59% reduction in clipping yield compared with nontreated TifEagle (McCullough et al., 2007). McCarty et al. (2011) and McCullough et al. (2006) reported a 32 to 46 and 67% clipping yield reduction compared with nontreated plots of TifEagle with 0.0175 kg a.i. ha⁻¹ 2 wk⁻¹ and 0.05 kg a.i. ha⁻¹ 3 wk⁻¹ of TE, respectively. Similarly, applications of TE at 0.02 kg a.i. ha⁻¹ 2 wk⁻¹ on 'Champion' bermudagrass reduced clipping yield by 48% compared with non-TE-treated Champion 2 wk after the final application (Baldwin et al., 2009). The aforementioned studies were conducted on a single cultivar established in field conditions; however, McCullough et al. (2005) examined the response of six bermudagrass cultivars to applications of TE at 0.0125 kg a.i. ha⁻¹ 10 d⁻¹. Applications of TE significantly reduced clipping yield on Champion, MiniVerde, and TifEagle bermudagrasses compared with nontreated plots, with MiniVerde having the most reduction (69%) and TifEagle having the least (46%) (McCullough et al., 2005). Ultradwarf cultivars have varied responses to TE likely due to the different rates, application frequencies, and environmental conditions when applied.

Temperature has been reported to affect TE efficacy on hybrid bermudagrass and Kentucky bluegrass (*Poa pratensis* L.) (Lickfeldt et al., 2001; Fagerness et al., 2002; Beasley and Branham, 2007; Beasley et al., 2007). Fagerness et al. (2002) showed that TE provided greater growth suppression duration and magnitude of 'Tifway' bermudagrass at 20/10°C day/night air temperatures as opposed to 35/25°C. Beasley and Branham (2007) found similar trends after TE application on Kentucky bluegrass (*Poa pratensis* L.) at 23/18°C day/night air temperatures or 30/25°C. The previous two studies explored TE efficacy at different air temperatures controlled within growth chamber experiments. Beasley et al. (2007) and Lickfeldt et al. (2001) showed TE applications were more effective on Kentucky bluegrass (i.e., greater magnitude and duration of growth suppression) during cooler air temperatures of the spring and fall compared with applications during summer months.

The effect of temperature on TE efficacy can be explained by the half-life of trinexapac acid, the plant-active form of TE, in plant residues (Beasley and Branham, 2005; Beasley et al., 2007). Beasley and Branham (2005) reported that the half-life of trinexapac acid at 18°C was 5.3 d in Kentucky bluegrass and 6.4 d in creeping bentgrass (*Agrostis*

stolonifera L.), whereas the half-life at 30°C was 3.4 and 3.1 d for Kentucky bluegrass and creeping bentgrass, respectively. Beasley et al. (2007) found a similar temperature effect on TE metabolism in a Kentucky bluegrass sward where the half-life of trinexapac acid was 5.8 d after a spring TE application and 4.2 d after a summer application. However, the initial concentrations of trinexapac acid in Kentucky bluegrass were greater in summer than spring.

Air temperatures have been reliable for determining optimal TE application intervals on creeping bentgrass putting greens using a cumulative growing degree day (GDD) model (Kreuser and Soldat, 2011; Kreuser et al., 2017). The GDD model subtracted a base temperature from the daily mean air temperature and then added the remainder to the previous day's temperature. The cumulative GDD was then correlated to creeping bentgrass clipping yield after a TE application. Kreuser and Soldat (2011) stated that TE applications every 200 GDD (base 0°C) sustained season-long yield suppression and consistently provided the greatest turfgrass quality on creeping bentgrass greens (*Agrostis stolonifera* L.). Development of a GDD model to determine PGR application frequencies on ultradwarf hybrid bermudagrass putting greens would be beneficial to achieve season-long yield suppression in an array of environmental conditions. The objective of this research was to develop a GDD model to determine optimal TE and PH application frequencies on Champion, MiniVerde, and TifEagle ultradwarf hybrid bermudagrass putting greens.

MATERIALS AND METHODS

The methods for development of a GDD model for TE applications on bermudagrass putting greens were similar to those outlined by Kreuser and Soldat (2011) and Kreuser et al. (2017). Experiments were conducted June to October 2017 on three ultradwarf hybrid bermudagrass cultivars at three separate locations in the southeastern United States: MiniVerde at the East Tennessee Research and Education Center in Knoxville, TN; Champion at the Hope Valley Country Club in Durham, NC; and TifEagle at the R.R. Foil Plant Science Research Center in Starkville, MS. Putting greens were constructed following US Golf Association root zone specifications (USGA, 2004), and N was applied at 10 kg ha⁻¹ 14 d⁻¹. Experimental areas were irrigated to ~70% of the evapotranspiration rate, and pesticides were applied on a preventative basis. Onsite weather stations at each location measured daily air temperatures that were used to calculate cumulative GDD (McMaster and Wilhelm, 1997). First, the daily mean air temperature was calculated from the maximum and minimum daily air temperature. Next, the base temperature (10°C) was subtracted from the daily mean air temperature, and the difference was the daily GDD value. Consecutive daily GDD values were then added to calculate cumulative GDD. The base temperature of 10°C was selected as that is the temperature where photosynthesis becomes minimal for C₄ plants (Berry and Björkman, 1980; McMaster and Wilhelm, 1997) and has been used as the base temperature in

previous GDD studies with C_4 plants (Cross and Zuber, 1972; Elmore et al., 2013). Research predicting the base temperatures of warm-season turfgrasses has been limited to that of Unruh et al. (1996), who reported that base temperatures ranged from -0.1 to 12.3°C across warm-season turfgrass species.

Plots measured 3 by 1.5 m (Tennessee and Mississippi) or 3 by 1 m (North Carolina), and the experiment was a randomized complete block design with three replications. Treatments included a single application of TE (Primo MAXX, Syngenta) at $0.034 \text{ kg a.i. ha}^{-1}$, PH (Anuew, NuFarm) at $0.154 \text{ kg a.i. ha}^{-1}$, and two sets of nontreated controls. The two sets of nontreated controls were included to increase the accuracy of calculating relative clipping yield (Kreuser et al., 2017). Repeated PGR applications were made monthly in June, July, and August on areas with no previous PGR applications. Applications on MiniVerde in Tennessee were made on 12 June, 17 July, and 14 Aug. 2017; Champion in North Carolina on 1 June, 30 June, and 1 Aug. 2017; and TifEagle in Mississippi on 19 June, 10 July, and 14 Aug. 2017. Applications were made with CO_2 -pressurized broadcast sprayers calibrated to deliver a spray volume of 374 L ha^{-1} . Application dates at each location are summarized in Table 1.

Clipping Collection

In Tennessee and Mississippi, clippings were harvested three times per week beginning 2 d after each PGR application and continued until ~ 600 GDD. At that point, clippings were harvested once per week until effects of PGR application subsided (>900 GDD). However, in North Carolina, clippings were harvested twice per week until effects of PGR application subsided. Plots were mowed at 3.2 mm with a 0.54-m-wide greens mower (Toro Greensmaster 2100, Toro Company). Plot areas between clipping collection events were mowed with either the Toro Greensmaster 2100 or a Toro riding greens mower with the same effective height of cut. Clippings were harvested using the following procedure: 0.27-m-wide perpendicular buffer alleys were mowed at the top and bottom of each plot to define the clipping collection area, and then a 2.73-m-long strip was mowed down the middle of the plot for a clipping collection area of 1.47 m^2 . Harvested clippings were

Table 1. Location, location coordinates, ultradwarf hybrid bermudagrass cultivar, and application dates of trinexapac-ethyl (Primo MAXX) or prohexadione-Ca (Anuew).

Location†	Coordinates	Cultivar	Application date‡
Knoxville, TN	35.9606° N 83.9207° W	MiniVerde	12 June
			17 July
			14 Aug.
Durham, NC	35.9940° N 78.8986° W	Champion	1 June
			30 June
			8 Aug.
Starkville, MS	33.4505° N 88.8184° W	TifEagle	19 June
			10 July
			14 Aug.

† Research was conducted in Knoxville, TN, at the East Tennessee Research and Education Center, in Durham, NC, at Hope Valley Country Club, and in Starkville, MS, at the R.R. Foil Plant Science Research Center.

‡ Each plant growth regulator application was made on areas of the putting greens with no previous plant growth regulator use in 2017.

dried in a forced-air oven at a minimum temperature of 60°C for 36 h and then weighed. Prior to weighing, sand and debris were separated from turfgrass clippings via the vibrating pan method of Kreuser et al. (2011).

Statistical Analysis

Data from all locations were statistically analyzed with sinewave regression models. Daily mean clipping yields were plotted relative to GDD after PGR application. Data from June, July, and August applications for each PGR treatment at each location were pooled to elucidate potential differences among experimental locations. Four parameter, amplitude-dampened, sinewave models were fit to the data with nonlinear regression in SigmaPlot 14 (Systat Software, 2018) (Kreuser et al., 2017). The following equation from Kreuser et al. (2017) was used to calculate relative growth suppression:

$$\text{Relative growth suppression (g g}^{-1}\text{)} = Y_{\text{int}} + \text{Amplitude} \times e^{\left(\frac{-\text{GDD}}{\text{Decay}}\right)} \times \sin\left(2\pi \frac{\text{GDD}}{\text{Period}} + \pi\right)$$

where Y_{int} is the y intercept, Amplitude is the magnitude of the suppression and rebound growth stages, Decay is the amplitude decay coefficient, and GDD is the cumulative GDD since the last PGR application. The resulting model graphs were normalized with the resulting Y_{int} coefficient equal to 1.0 g g^{-1} for easier visual interpretation.

RESULTS AND DISCUSSION

Normalized relative clipping yield (g g^{-1}) data at each location are presented in Fig. 1 and 2 for TE and PH, respectively. Table 2 lists the sinewave equation for each PGR treatment at each location. These models accurately predicted relative growth suppression with SEs $\leq 0.172 \text{ g g}^{-1}$ and R^2 values ranging from 0.53 to 0.83 (Fig. 1 and 2).

Peak suppression values after a TE application at $0.034 \text{ kg a.i. ha}^{-1}$ in this study ranged from 49 to 62% and are similar to those previously reported by Baldwin et al. (2009), McCullough et al. (2005), McCullough et al. (2006), and McCullough et al. (2007). Herein we report greater peak suppression with TE than McCarty et al. (2011), likely because of the lower TE rate used in that study ($0.0175 \text{ kg a.i. ha}^{-1}$). Peak suppression values after a PH application at $0.154 \text{ kg a.i. ha}^{-1}$ in this study ranged 50 to 54%, similar to previous reports (Beam, 2004; Marchi et al., 2015). Beam (2004) measured 10 to 70% reductions in common bermudagrass (*C. dactylon* cultivar Vamont) clipping yield after two PH applications at 0.14 to $0.67 \text{ kg a.i. ha}^{-1}$ on a 3-wk interval. Additionally, Marchi et al. (2015) reported 57 and 65% reductions in clipping yield of St. Augustinegrass [*Stenotaphrum secundatum* (Walter) Kuntze] after applications of PH at 0.1 and $0.2 \text{ kg a.i. ha}^{-1}$, respectively.

Peak suppression of ultradwarf hybrid bermudagrass clipping yield after TE application was similar to that of PH on TifEagle in Mississippi and Champion in North

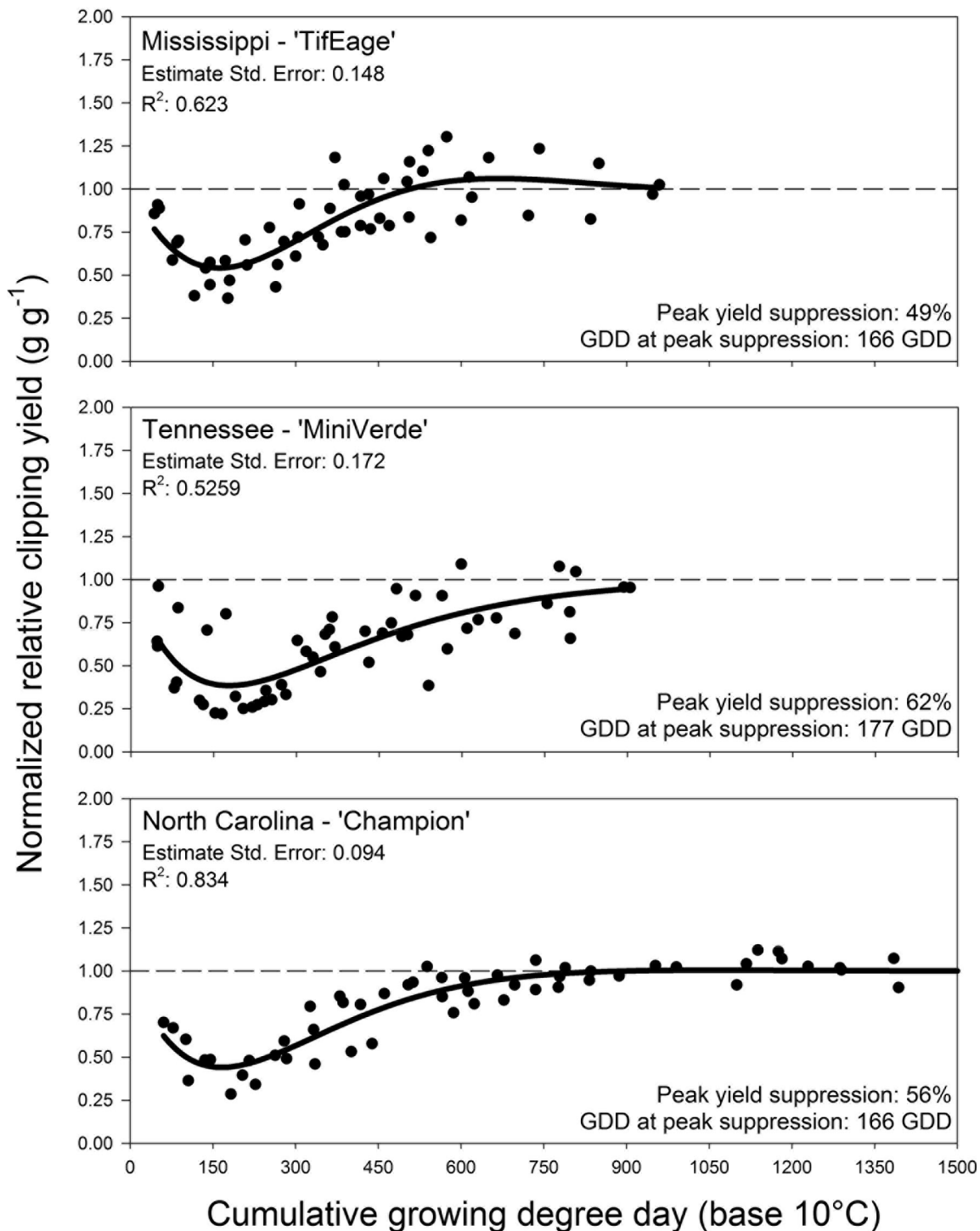


Fig. 1. Normalized relative clipping yield (g g^{-1}) of 'TifEage', 'MiniVerde', and 'Champion' ultradwarf hybrid bermudagrass putting greens in Mississippi, Tennessee, and North Carolina, respectively, after trinexapac-ethyl application. The estimated standard error and R^2 values of the sinewave model equations used to calculate relative growth suppression are included along with percent peak yield suppression and the growing degree days (GDD) at peak suppression.

Carolina (Fig. 1 and 2). However, peak suppression after TE application exceeded PH by 0.12 g g^{-1} on MiniVerde in Tennessee. Previous research by Marchi et al. (2015) on St. Augustinegrass showed that applications of PH at 0.1 and $0.2 \text{ kg a.i. ha}^{-1}$ reduced clipping yield 57 and 65%, respectively, whereas $0.113 \text{ kg TE ha}^{-1}$ reduced clipping yield 59%. In rice (*Oryza sativa* L.), Na et al. (2011) found

that PH significantly reduced plant height and internode length compared with applications of TE at the same concentrations. The observed difference in peak suppression between the two PGRs in Tennessee is not well understood; however, our GDD model is more accurate for predicting PGR application frequencies rather than the magnitude of growth suppression.

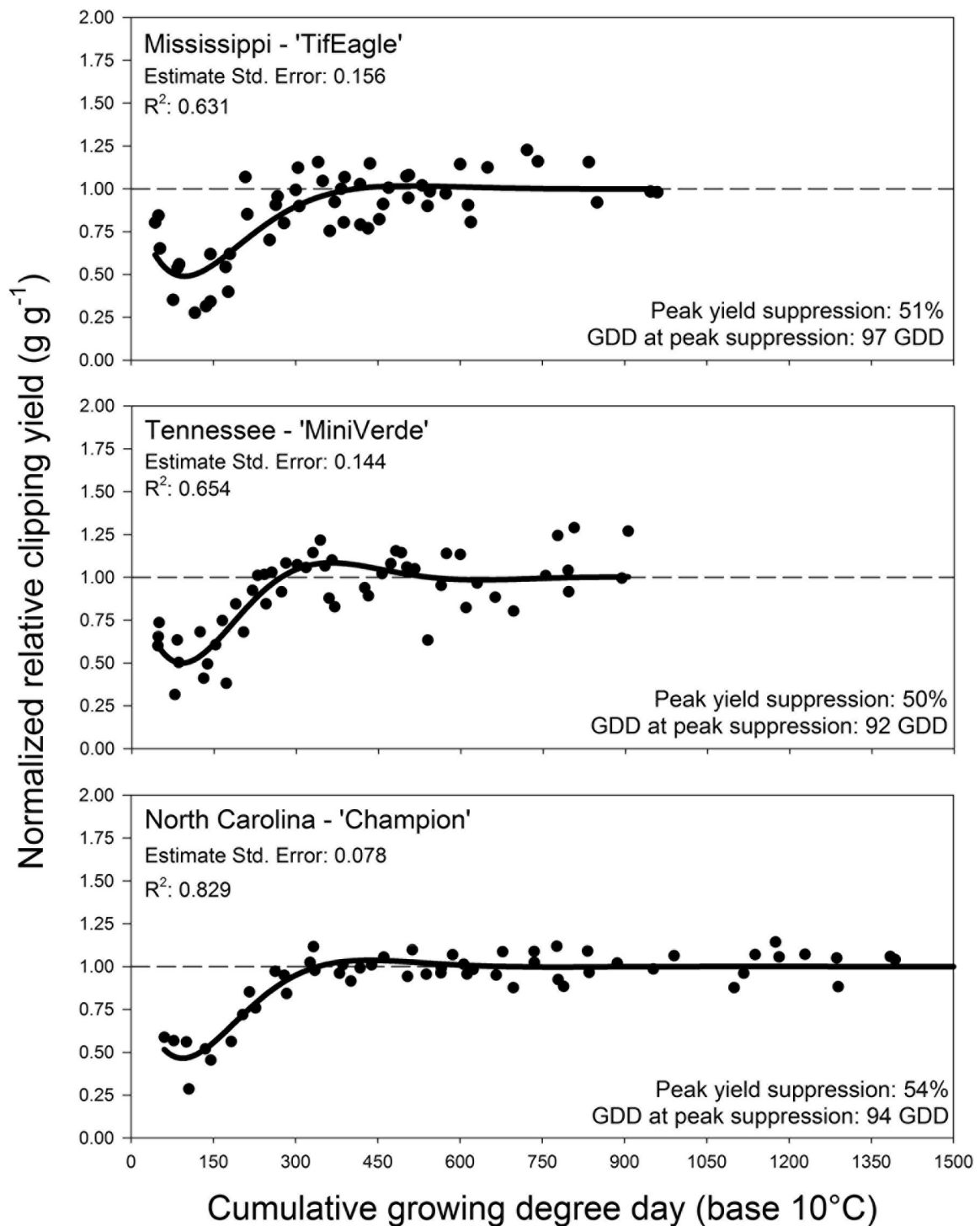


Fig. 2. Normalized relative clipping yield (g g⁻¹) of 'TifEagle', 'MiniVerde', and 'Champion' ultradwarf hybrid bermudagrass putting greens in Mississippi, Tennessee, and North Carolina, respectively, after prohexadione-Ca application. The estimated standard error and R² values of the sinewave model equations used to calculate relative growth suppression are included along with percent peak yield suppression and growing degree days (GDD) at peak suppression.

Peak suppression occurred between 166 and 177 GDD calculated using 10°C as the base temperature (GDD_{10C}) and was similar across all locations after TE application, compared with 92 to 97 GDD_{10C} for PH (Table 3). The mean GDD_{10C} to TE peak suppression (170 GDD_{10C}) would occur 34 and 9 d after application at a mean air temperatures of 15 and 30°C, respectively. The mean

GDD_{10C} to PH peak suppression (95 GDD_{10C}) would occur 19 d after application at 15°C and 5 d at 30°C. Weekly PGR applications to ultradwarf putting greens are typical throughout the southern United States, but these indicate that it takes longer to reach peak growth suppression after a single application.

Table 2. Sinewave model equations used to calculate relative growth suppression (y , $g\ g^{-1}$) of ultradwarf hybrid bermudagrass putting green clipping yield in response to plant growth regulators (PGR) trinexapac-ethyl (TE) or prohexadione-Ca (PH) at three separate locations.

PGR	Location	Sinewave equation
TE	TN	$y = 1.01 + 2789e^{\left(\frac{-GDD}{177.8}\right)} \sin\left(2\pi \frac{GDD}{186,976} + \pi\right)$
	NC	$y = 1.07 + 2.46e^{\left(\frac{-GDD}{187.84}\right)} \sin\left(2\pi \frac{GDD}{1792.44} + \pi\right)$
	MS	$y = 0.98 + 1.03e^{\left(\frac{-GDD}{251.7}\right)} \sin\left(2\pi \frac{GDD}{1012} + \pi\right)$
PH	TN	$y = 0.27 + 1.05e^{\left(\frac{-GDD}{153.18}\right)} \sin\left(2\pi \frac{GDD}{555.13} + \pi\right)$
	NC	$y = 0.91 + 1.47e^{\left(\frac{-GDD}{126.99}\right)} \sin\left(2\pi \frac{GDD}{681.68} + \pi\right)$
	MS	$y = 1.19 + 1.69e^{\left(\frac{-GDD}{120.36}\right)} \sin\left(2\pi \frac{GDD}{816.94} + \pi\right)$

The difference in time to peak suppression between TE and PH is likely due to their biological activity (Rademacher, 2014). Similar to TE, PH is biologically active in its acid form, but unlike TE, the acid prohexadione is present once the Ca salt is dissolved in water and is primarily acropetally translocated. Conversely, the ester TE is translocated systemically with significant quantities reaching the root and then transported acropetally once metabolized into its acid form. This process for TE is time consuming, but PH can act almost immediately after application (Rademacher, 2014). The biological activity of TE and PH within plants was supported by an immediate reduction in shoot elongation of wheat (*Triticum aestivum* L.) after an application of PH, whereas TE activity on shoot elongation was observed 10 d after application (Rademacher, 2014). Peak suppression after TE application required more GDD_{10C} than PH due to the biological activity once the PGR is absorbed into the plant.

Knowledge of the cumulative GDD to reach peak suppression was important to determine application

intervals of PGRs that maximize growth suppression and minimize rebound growth (Kreuser and Soldat, 2011). Kreuser and Soldat (2011) suggested that PGRs are to be reapplied at 1.3× the GDD value at peak suppression to minimize rebound growth and maximize PGR benefits.

Ervin and Zhang (2008) described rebound growth after complete metabolism of TE as enhanced growth rate relative to nontreated turfgrass. Rebound growth has been documented in creeping bentgrass (Kreuser and Soldat, 2011), but minimal rebound growth was observed after peak suppression, regardless of PGR, in this study (Fig. 1 and 2). Turfgrass quality assessed 7 d after PGR treatment was significantly lower than nontreated controls at all locations (data not presented). Conversely, creeping bentgrass quality either improved or remained consistent after TE application (Fagerness et al., 2000). Ultradwarf cultivar phototoxicity after PGR application likely caused the absence of rebound growth because it did not exceed that of nontreated controls. Our models indicate that TE should be reapplied to ultradwarf hybrid bermudagrass putting greens between 216 and 230 GDD_{10C}, compared with 120 to 126 GDD_{10C} for PH (Table 3). The 1.3× multiplier used to calculate these reapplication intervals may be increased for ultradwarf cultivars due to the lack of rebound growth, but field confirmation of this is warranted.

CONCLUSIONS

A sinewave equation successfully calculated and predicted ultradwarf hybrid bermudagrass clipping yield in response to TE and PH treatment and GDD_{10C} accumulation. In Mississippi and North Carolina, peak growth suppression was similar after TE and PH applications. However, peak growth suppression after TE application was greater than PH in Tennessee. The GDD_{10C} to peak growth suppression differed between PGRs with TE requiring 72 to 85 more GDD_{10C} than PH to achieve peak growth suppression. The GDD_{10C} to peak suppression is important for the calculation of optimal PGR reapplication intervals; however, the multiplier used for reapplication on creeping bentgrass may require adjustment to accurately fit ultradwarf hybrid bermudagrass due to the observed lack of rebound growth. Future research should focus on

Table 3. Percentage peak suppression and the cumulative growing degree days calculated using 10°C as the base temperature (GDD_{10C}) at peak suppression obtained from sinewave models of ultradwarf hybrid bermudagrass putting green clipping yield in response to plant growth regulators (PGR) trinexapac-ethyl (TE) or prohexadione-calcium (PH) at three separate locations.

PGR	Location	Cultivar	Peak suppression	Reapplication interval†	
				%	cumulative GDD _{10C}
TE	TN	MiniVerde	62	177	230
	NC	Champion	56	166	216
	MS	TifEagle	49	166	216
PH	TN	MiniVerde	50	92	120
	NC	Champion	54	94	122
	MS	TifEagle	51	97	126

† Reapplication interval of TE and PH calculated by multiplying the cumulative GDD_{10C} at peak suppression by 1.3.

season-long implementation of this GDD model compared with current PGR programs used on ultradwarf putting surfaces. The use of a GDD model to determine PGR applications on creeping bentgrass putting greens has been successful and will likely be equally useful on ultradwarf hybrid bermudagrass.

Conflict of Interest

The authors declare that there is no conflict of interest.

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