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# Effect of core cultivation, fertility, and plant growth regulators on recovery of voided creeping bentgrass greens canopies following annual bluegrass control via methiozolin

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## Abstract

Methiozolin is commonly used for the safe and selective removal of annual bluegrass from creeping bentgrass golf greens. Studies were conducted in 2013 and 2014 with the objective of assessing fertility programs consisting of synthetic fertilizers and biostimulants, with and without the plant growth regulator trinexapac-ethyl, to aid putting green canopy recovery following annual bluegrass removal via methiozolin. Additional studies were conducted to compare recovery of creeping bentgrass following an aggressive core aerification event with fertility programs with and without methiozolin. In all cases, the addition of 7 kg ha$^{-1}$ of N-P-K from fertilizer or biostimulant biweekly to greens increased turfgrass recovery time by 1 to 3 wk compared to a standard green's fertility program alone. Creeping bentgrass treated with biostimulants recovered equivalent to or quicker than creeping bentgrass treated with synthetic fertilizer (SF) in all cases. In the presence of methiozolin treatments, trinexapac-ethyl reduced time to 90% recovery ($T_{90}$) by 0.25 to 0.5 wk at two locations, and increased $T_{90}$ recovery time by 0.1 wk at one location. Otherwise, plots treated with SF plus trinexapac-ethyl were equivalent to plots treated with SF only. Methiozolin slowed turfgrass recovery time at one location where severe drought stress occurred but not at the other location that did not experience drought stress. These results suggest that turf managers should increase fertilizer treatments but will not need to discontinue trinexapac-ethyl use to maximize creeping bentgrass recovery following annual bluegrass control with methiozolin. These data also suggest that methiozolin has the potential to negatively affect creeping bentgrass recovery when drought stress is experienced.

## Introduction

Annual bluegrass regularly infests creeping bentgrass putting greens and ultimately can outcompete the desirable creeping bentgrass in climates that are conducive to annual bluegrass growth. This is problematic due to the propensity of annual bluegrass to disrupt the uniformity of the playing surfaces of creeping bentgrass putting greens, thus reducing the trueness of ball roll on these surfaces (Rana and Askew 2018). The plant growth regulators paclobutrazol and flurprimidol are commonly used on creeping bentgrass putting greens due to the ability of the herbicides to selectively reduce annual bluegrass populations over time (Johnson and Murphy 1995, 1996). However, methiozolin is the only herbicide labeled for postemergence control of annual bluegrass in creeping bentgrass putting greens. Although methiozolin typically controls annual bluegrass over several weeks, it may interact with environmental factors and cause annual bluegrass to decline rapidly, leaving voids in the putting surface (Petrovsky 2019; Venner et al. 2012).

When voids occur on putting greens, golf course superintendents strive to quickly repair the area through various fertility programs, seeding, and sodding (Jones and Christians 2012; Rossi and Grant 2009; Walker et al. 2003). Most commonly, superintendents use soluble nitrogen fertilizers that are ammonia- or nitrate-based. Another common practice of superintendents is to add micronutrient supplements to fertility programs to improve color and overall quality. Biostimulants are a group of products that are derived from natural sources such as seaweed, humic acids, and other organic sources (Kahn et al. 2009; Schmidt et al. 2003). These products contain not just nitrogen, phosphorus, and potassium, but also a vast array of compounds such as auxins, cytokinins, and gibberellins—hormones that are important for mediating plant growth (Xu and Huang 2010; Zhang et al. 2003, 2013; Zhang and Ervin 2004).

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**Table 1.** Products used in annual bluegrass removal and core-cultivation studies.[a,b]

| Common name | Trade name | Rate | Manufacturer | Location and website |
|---|---|---|---|---|
| Synthetic fertilizer (20-20-20) | Bulldog, 20-20-20 with micros | 7.03 kg ha$^{-1}$ | SQM North America | Atlanta, GA; www.sqm.com |
| Urea (46-0-0) | Southern States Urea, 46-0-0 | 2.34 kg ha$^{-1}$ | Southern States Cooperative, Inc. | Richmond, VA; www.southernstates.com |
| Trinexapac-ethyl | Primo® MAXX | 0.048 kg ha$^{-1}$ | Syngenta Crop Protection, LLC. | Greensboro, NC; www.syngentacropprotection.com |
| Biostimulant (0-0-0) | Astron | 19.1 L ha$^{-1}$ | Floratine Products Group | Collierville, NC; www.floratine.com |
| Biostimulant (13-0-0) | Per-4-Max | 19.1 L ha$^{-1}$ | Floratine Products Group | Collierville, NC; www.floratine.com |
| Biostimulant (12-0-0) | Knife Plus | 19.1 L ha$^{-1}$ | Floratine Products Group | Collierville, NC; www.floratine.com |
| Biostimulant (6-2-3) | Protesyn | 9.5 L ha$^{-1}$ | Floratine Products Group | Collierville, NC; www.floratine.com |
| Biostimulant (0-22-28) | Power 23-0-0 + Mo | 9.5 L ha$^{-1}$ | Floratine Products Group | Collierville, NC; www.floratine.com |
| Biostimulant (23-0-0) | Power 0-22-28 | 9.5 L ha$^{-1}$ | Floratine Products Group | Collierville, NC; www.floratine.com |

[a]Abbreviations: ABR1 and ABR2, annual bluegrass removal study sites 1 and 2 in 2013, respectively; ABR3, annual bluegrass removal study site in 2014; CC1 and CC2, core-cultivation study sites 1 and 2, respectively.
[b]Applications in 2013 occurred on the following days: April 14, May 2, May 14, May 26, and June 5 at ABR1, ABR2, and CC1 and June 19 also at CC1. Applications in 2014 occurred on the following days: May 2, May 17, June 6, and June 20 at ABR3 and CC2; and July 1, July 11, and July 26 also at CC2.

Biostimulants have been shown to increase the percentage of creeping bentgrass cover that is nearly equivalent to commercial fertility programs following aeration (Bigelow et al. 2010). When applied to creeping bentgrass plants under summer stress, Xu and Huang (2010) found that plots treated with biostimulant products had between 22% and 100% greater turfgrass quality than nontreated checks, and plots sprayed with the plant growth regulator trinexapac-ethyl (TE). Biostimulants and TE maintained up to 76% and 56% more chlorophyll content, respectively, in leaves compared to leaves in nontreated turf (Xu and Huang 2010). Additionally, many biostimulants can improve overall turfgrass vigor, rooting, and shoot growth (Acuña et al. 2022; Xu and Huang 2010; Zhang and Ervin 2008).

It is well established that root-inhibiting herbicides can reduce the speed at which turfgrasses can spread or recover from injury or disease. Beck et al. (2013) found that recovery time of bermudagrass (*Cynodon dactylon* L. Pers.) from spring dead spot (*Ophiosphaerella* spp.) was lengthened when treated with root-inhibiting herbicides compared to a nontreated check. The use of root-inhibiting preemergence herbicides at sprigging increased the time required for bermudagrass establishment in sod production (Brosnan et al. 2014). To date, no peer-reviewed literature exists investigating the options for putting green recovery following rapid annual bluegrass removal with methiozolin. The objectives of this research were to 1) determine the influence of increased fertility programs from SFs alone or with TE or from biostimulants on speed of putting green recovery following rapid annual bluegrass removal with methiozolin or on creeping bentgrass removed via core cultivation, and 2) to determine whether methiozolin interacts with various fertility programs to influence the speed of creeping bentgrass recovery on golf greens following core cultivation.

## Materials and Methods

Two separate studies were conducted at various locations in Virginia to assess fertility programs in conjunction with methiozolin use on golf greens. In one study, voids were created in the putting surface via rapid removal of annual bluegrass using methiozolin. This study will be referred to as the annual bluegrass removal (ABR) study. In the second study, voids in the putting green canopy were created using a core-cultivator (Greens Aerator; The Toro Company, Bloomington, MN) to remove approximately 30% of a pure creeping bentgrass canopy. This study will be referred to as the core-cultivation (CC) study.

### Annual Bluegrass Removal Study

The ABR study was conducted at the Virginia Tech Golf Course in Blacksburg, VA (37.23°N, 80.44°W), at three sites between 2013 and 2014 on two separate greens, both constructed in the 1950s and originally seeded with 'Pennlu' and 'C-19 Congressional' creeping bentgrass. Studies were initiated at two sites (ABR1 and ABR2) on March 22, 2013, and one site (ABR3) on March 27, 2014. All greens were maintained at 4 mm mowing height. The purpose of the ABR study was to create voids in the putting green canopy via rapid control of annual bluegrass to allow assessment of creeping bentgrass recovery rate as influenced by fertility, biostimulant, and plant growth regulator (PGR) programs. Initial annual bluegrass cover averaged 48%, 47%, and 65% at ABR1, ABR2, and ABR3, respectively, with standard deviations of 5% to 7% depending on location. Rapid removal of annual bluegrass was achieved by treating the entire study area with methiozolin applied at 3,000, 500, and 500 g ai ha$^{-1}$ on a biweekly interval at initiation. This methiozolin program completely controlled annual bluegrass at all sites within 45 d, with no apparent injury to creeping bentgrass.

In order to assess creeping bentgrass recovery as influenced by fertility programs, a randomized complete block design study was initiated at each of the three sites. Four treatments were replicated three times at each site. A more detailed description of fertility programs is provided in Table 1, but generally, treatments can be described as 1) increased fertility using SF, 2) increased fertility via SF plus TE applied every 200 growing degree days with a base of 0 C ($GDD_0$), 3) increased fertility via biostimulants, and 4) no increased fertility treatment.

"Increased fertility" treatments are additional treatments added to a superintendent's standard fertility program on each green (Table 1). Six Virginia golf course superintendents, representing a range of golf course designs and budgets and one company sales representative, were consulted to determine an appropriate amount of macronutrient increase assuming a 40% loss of putting green turf cover. Based on these discussions, the macronutrients increase in each treatment, regardless of source, was biweekly treatments of 7 kg N ha$^{-1}$, 7 kg P ha$^{-1}$, and 7 kg K ha$^{-1}$. These treatments were repeated until complete turf recovery and included five treatments at ABR1 and ABR2 and four treatments at ABR3.

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Increased fertility treatments were initiated at the first sign of canopy voiding, which occurred on April 14, 2013, at ABR1 and ABR2; and May 2, 2014, at ABR3. Digital images were collected with an 8.0-megapixel Canon Digital Rebel XT camera (Canon U.S.A., Inc., Melville, NY) at the following settings: F16, ISO100, white balance set to fluorescent, and 2-s shutter speed. The camera was mounted to a wooden 68-cm × 51-cm × 68-cm box that functioned to completely exclude natural light. The interior of the box was equipped with four 13-watt compact fluorescent light bulbs to ensure image uniformity. Images were analyzed for percent green pixels using SigmaScan Pro 5.2 software (Systat Software, Inc., San Jose, CA), which optimizes green color detection (Karcher and Richardson 2003). Normalized difference vegetation index (NDVI) was assessed using a multispectral analyzer (GeoScout GLS-400; Holland Scientific, Inc., Lincoln, NE) on each rating date for the duration of the study.

To standardize the influence of varying annual bluegrass population levels, percentage cover of green pixels was converted to a percentage recovery of green turf using Equation 1:

$$Y = (Pi - Ci)/(100 - Ci) \qquad [1]$$

where $Y$ is the percentage recovery of voided turf on a given date, $P_i$ is the observed percentage green pixels in plot $i$ on a given date, and $C_i$ is the observed percentage of green pixels in plot $i$ on the initial observation date. To control for variance structure in measurements taken over time, percentage recovery data from each plot were subjected to the hyperbolic function using the NLIN procedures with SAS software (version 9.2; SAS, Cary, NC) with Equation 2:

$$Y = (iX)/\left(1 + \left(\frac{iX}{a}\right)\right) \qquad [2]$$

where $Y$ is the percentage recovery of voided turf, $X$ is time in weeks, $i$ is an estimated parameter that approximates the rate of recovery as time approaches zero, and $a$ is an estimated parameter that approximates the upper asymptote of percentage turf recovery. Using the estimated parameters, the hyperbolic function was used to determine the time required in weeks to reach 75% ($T_{75}$) and 90% ($T_{90}$) recovery. These $T_{75}$ and $T_{90}$ values and NDVI data were determined to be normal using the NORMAL option in the UNIVARIATE procedure (with SAS software) and Shapiro-Wilk statistic, and homogeneity was assessed by visually inspecting plotted residuals. Data were subjected to ANOVA using the GLM procedure with sums of squares partitioned to reflect the effect of cultural treatments and trial sites, which were considered random. Mean squares associated with trial interactions were used to test for significance of treatment effects (McIntosh 1983). If significant trial interactions occurred, data were presented separately by trial, otherwise, data were pooled over trial. Mean responses of $T_{75,}$ $T_{90}$, and NDVI were separated with Fisher's Protected least significant difference test at $P \leq 0.05$.

### *Core-Cultivation Study*

The CC study was conducted at the Turfgrass Research Center in Blacksburg, VA, on a U.S. Golf Association specification 'L-93' green that is maintained at 3.2 mm. The studies were initiated on March 22, 2013, and March 27, 2014. The purpose of the CC study was to assess creeping bentgrass recovery rate following approximately 30% canopy reduction via aggressive core-cultivation as influenced by methiozolin application and fertility, biostimulant, and PGR programs. Annual bluegrass cover averaged 3% in 2013 and 7% in 2014.

In order to assess creeping bentgrass recovery as influenced by methiozolin and cultural treatment programs, a split-plot study was initiated at each site, designated CC1 and CC2. Treatments were replicated three times at each site. Main plots consisted of fertility treatments, and subplots consisted of two rates of methiozolin. Subplots contained either no methiozolin or methiozolin applied at 500 g ai ha$^{-1}$ six times at 2-wk intervals beginning on March 23, 2013, and March 27, 2014. Fertility programs were the same as outlined in the ABR Study, and can be found in Table 1. Superintendent-administered fertility programs applied to the entire green can be found in Table 2.

Fertility treatments were repeated at 2-wk intervals beginning immediately prior to core-cultivation on April 14, 2013, and May 2, 2014, and lasted until turfgrass was completely recovered and included six treatments at CC1 and seven treatments at CC2. Digital images, NDVI, and cover ratings were taken as outlined in the ABR Study. However, the spectrum analyzer used at the CC1 and CC2 locations had a calibration error that compromised data integrity. Thus, NDVI from CC1 and CC2 will not be presented. Statistical analyses were also performed as outlined previously, with the exception that sums of squares were further partitioned to evaluate effects of main plots, subplots, and interactions of these with each other and with trial.

## Results and Discussion

### *Annual Bluegrass Removal Study*

The interaction of location by treatment was significant for $T_{75}$ ($P < 0.0001$) and $T_{90}$ ($P < 0.0001$); therefore, data are presented separately by location (Table 3). Differences between locations were likely due to inconsistencies in the performance of both biostimulant and SF plus TE. For example, the biostimulant treatment had the fastest $T_{75}$ in ABR2 and ABR3 but was equivalent to that of SF in ABR1 (Table 3). The $T_{90}$ of SF plus TE was equivalent to that of SF alone at ABR1 and ABR2 but required more time at ABR3 (Table 3). Additionally, plots that received biostimulants were damaged due to mower scalping at ABR3 and had lower NDVI than plots receiving no additional fertility. This damage likely created the location interaction at one of the rating dates (Table 4). Despite these differences, some consistencies in responses between locations were noted. For example, biostimulant and SF treatments reduced 75% and 90% recovery times compared to the no-additional-fertility check at all locations (Table 3).

The $T_{75}$ times ranged from 2.5 to 7.3 wk depending on treatment and location (Table 3). In general, $T_{75}$ required more time in 2013 than in 2014. Biostimulant treatments required significantly less time than all other treatments at two of three locations. Synthetic fertilizer alone was equivalent to that of SF plus TE at all locations except ABR3 where the two differed in $T_{75}$ recovery time by about 3 d (Table 3). In 2013, all additional fertility treatments reduced $T_{75}$ recovery time by at least 2.4 wk at ABR1 and 1.8 wk at ABR2 (Table 3). The biostimulant program reduced $T_{75}$ recovery time by 2.5 to 2.8 wk at these two locations compared to the no-additional-fertility program (Table 3). Although macronutrient concentrations were equivalent between biostimulant and SF programs, the biostimulants likely provided plants with various hormones and micronutrients that elicited immediate growth responses as opposed to the SF program, which provided necessary nutrients but required time to produce such hormones. The

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**Table 2.** Superintendent-administered fertility programs for both annual bluegrass removal and core-cultivation studies during the duration of each study.[a]

| Year | Date | Location | Common name | Nitrogen rate | Manufacturer, location, and website |
|---|---|---|---|---|---|
| 2013 | April 22 | ABR1, ABR2 | Nutralene Slow Release (40-0-0) | 24.4 kg ha$^{-1}$ | Koch Agronomic Services, LLC., Wichita, KS; www.kochagronomicservices.com |
| | May 23 | ABR1, ABR2 | Proforma 18-3-6 SRN | 4.4 kg ha$^{-1}$ | Agriliance, LLC., St. Paul, MN; no website |
| | May 6 | CC1 | Southern States 46-0-0 SGN 80 | 24.4 kg ha$^{-1}$ | Southern States Cooperative, LLC., Richmond, VA; www.southernstates.com |
| | May 21 | CC1 | Southern States 46-0-0 SGN 80 | 9.76 kg ha$^{-1}$ | Southern States Cooperative, LLC., Richmond, VA; www.southernstates.com |
| | June 3 | CC1 | Southern States 46-0-0 SGN 80 | 7.3 kg ha$^{-1}$ | Southern States Cooperative, LLC., Richmond, VA; www.southernstates.com |
| | June 17 | CC1 | Southern States 46-0-0 SGN 80 | 7.3 kg ha$^{-1}$ | Southern States Cooperative, LLC., Richmond, VA; www.southernstates.com |
| 2014 | April 21 | ABR3 | Nutrite (21-0-16) | 48.8 kg ha$^{-1}$ | Nutrite, Pheonix, AZ; www.nutrite.com |
| | May 20 | ABR3 | Proforma 18-3-6 SRN | 4.4 kg ha$^{-1}$ | Agriliance, LLC., St. Paul, MN; https://agriliance.com |
| | June 10 | ABR3 | Proforma 18-3-6 SRN | 4.4 kg ha$^{-1}$ | Agriliance, LLC., St. Paul, MN; https://agriliance.com |
| | May 5 | CC2 | Southern States 46-0-0 SGN 80 | 24.4 kg ha$^{-1}$ | Southern States Cooperative, LLC., Richmond, VA; www.southernstates.com |
| | May 19 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |
| | June 3 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |
| | June 16 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |
| | July 1 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |
| | July 15 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |
| | July 28 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |
| | August 5 | CC2 | Bulldog 20-20-20 plus Micros | 7.3 kg ha$^{-1}$ | SQM North America, Atlanta, GA; www.sqm.com |

[a]Abbreviations: ABR1, annual bluegrass removal study location 1; ABR2, annual bluegrass removal study location 2; ABR3, annual bluegrass removal study location 3; CC1, core-cultivation study location 1; CC2, core-cultivation study location 2.

**Table 3.** Time required in weeks to reach 75% and 90% recovery of voided putting green turf following rapid removal of annual bluegrass with methiozolin and as influenced by various fertility and plant growth regulator programs at locations ABR1, ABR2, and ABR3.[a,c]

| | $T_{75}$ | | | $T_{90}$ | | |
|---|---|---|---|---|---|---|
| Fertility program[b] | ABR1 | ABR2 | ABR3 | ABR1 | ABR2 | ABR3 |
| | wk | | | | | |
| No additional fertility | 7.3 a | 6.8 a | 3.0 a | 8.8 a | 8.2 a | 5.3 a |
| Synthetic fertilizer | 4.7 bc | 5.0 b | 2.6 b | 6.5 b | 6.5 bc | 4.4 c |
| SF plus trinexapac-ethyl | 4.9 b | 5.1 b | 3.0 a | 6.6 b | 6.6 b | 5.1 b |
| Biostimulant | 4.5 c | 4.3 c | 2.5 c | 5.9 b | 5.9 c | 4.5 c |

[a]Abbreviations: ABR1, annual bluegrass removal study location 1; ABR2, annual bluegrass removal study location 2; ABR3, annual bluegrass removal study location 3; SF, synthetic fertilizer; $T_{75}$, time required in weeks to recover 75% of putting green turf voided by annual bluegrass removal by methiozolin; $T_{90}$, time in weeks to recover 90% of voided turf.
[b]Fertility programs were added to standard greens management programs and consisted of additional nitrogen, phosphorus, and potassium applied at 7, 7, and 7 kg ha$^{-1}$ every 2 wk starting when canopy voids first appeared on the putting green. Trinexapac-ethyl was applied at 0.048 kg ai ha$^{-1}$ and repeated at 200 growing degree days at base 0 C. More information about products applied appears in Table 1.
[c]Means within a column followed by the same letter are not significantly different ($P \leq 0.05$).

addition of biostimulants increases the amount of immediately-available amino acids, cytokinins, auxins, and other antioxidant-type compounds within the plant (Gao and Li 2012; Zhang et al. 2009). Increased cytokinin concentrations have been shown to negatively influence the effects of ethylene production, thereby reducing overall plant senescence. Increased fertility imparted by biostimulant products could speed turfgrass recovery by increasing turfgrass rooting, thereby allowing more shoots to be produced and increasing cover more rapidly (Bigelow et al. 2010; Tucker et al. 2006).

When plots reached $T_{90}$, actual putting green canopy coverage was approximately 96% and was commercially acceptable (>95% coverage; data not shown). Some differences were noted between trends in $T_{90}$ response times and those of $T_{75}$. For example, biostimulant and SF programs were equivalent for $T_{90}$ times and generally averaged about 6 to 6.5 wk in 2013 and 4.5 wk in 2014 (Table 4). These two treatments reduced the time required for 90% recovery by more than 2 wk compared to the no-additional-fertility check at two sites in 2013 and about 1 wk at one site in 2014 (Table 4). The addition of TE to SF did not increase recovery time at two of three locations. Trinexapac-ethyl reduces cellular elongation and may increase the time required to sufficiently mask voids in turfgrass canopies due to reduced vertical plant growth (Ervin and Zhang 2007; Rademacher 2000). In low heights of cut like those on a putting green, vertical growth rate is of minimal benefit in masking canopy voids, and TE has been shown to have minimal impact on lateral recovery in some studies due to increased levels of cytokinin production leading to increased tiller production after several sequential applications (Ervin et al. 2002; Ervin and Zhang 2007). Variability in recovery time between sites could be partially attributed to turfgrass cultivar as has been demonstrated in previous studies (Jones and Christians 2009; Karcher et al. 2005).

At ABR1 and ABR2, plots that received no additional fertility had lower NDVI than all plots that received additional fertility at 6 wk after initial treatment (WAIT) and 8 WAIT, respectively (Table 4).

## Core-Cultivation Study

The interaction of location by methiozolin by treatment was significant for $T_{75}$ ($P < 0.0001$) and $T_{90}$ ($P < 0.0001$). Therefore, data are presented separately by methiozolin treatment and location. The interaction between CC1 and CC2 could be attributed to a mid-season irrigation malfunction on the CC2 putting green, which lasted for approximately 4 wk. Two out of four irrigation

**Table 4.** Influence of fertility and plant growth regulator program following rapid annual bluegrass removal on putting green normalized difference vegetative index averaged over three locations at 1 and 6 WAIT and separated by location at 8 WAIT.[a,c]

| | | | 8 WAIT | | |
|---|---|---|---|---|---|
| Fertility program[b] | 1 WAIT | 6 WAIT | ABR1 | ABR2 | ABR3 |
| | 0-1.0 | | | | |
| No additional fertility | 0.592 a | 0.734 b | 0.712 b | 0.753 b | 0.751 a |
| Synthetic fertilizer | 0.610 a | 0.763 a | 0.746 a | 0.787 a | 0.744 ab |
| SF plus trinexapac-ethyl | 0.607 a | 0.761 a | 0.766 a | 0.791 a | 0.747 ab |
| Biostimulant | 0.617 a | 0.763 a | 0.747 a | 0.787 a | 0.734 b |

[a]Abbreviations: ABR1, annual bluegrass removal study location 1; ABR2, annual bluegrass removal study location 2; ABR3, annual bluegrass removal study location 3; SF, synthetic fertilizer; WAIT, weeks after initial fertility treatment.
[b]Fertility programs were added to standard greens management programs and consisted of additional nitrogen, phosphorus, and potassium applied at 7, 7, and 7 kg ha$^{-1}$ every 2 wk starting when canopy voids first appeared on the putting green. Trinexapac-ethyl was applied at 0.048 kg ai ha$^{-1}$ and repeated at 200 growing degree days at base 0 C. More information about products applied appears in Table 1.
[c]Means within a column followed by the same letter are not significantly different ($P \leq 0.05$).

**Table 5.** Time required to reach 75% recovery of voided putting green turf following core-cultivation as influenced by methiozolin and various fertility and plant growth regulator programs at CC1 and CC2 sites.[a,c,d]

| | With methiozolin | | Without methiozolin | |
|---|---|---|---|---|
| Fertility program[b] | CC1 | CC2 | CC1 | CC2 |
| | wk | | | |
| No additional fertility | 3.3 a | 4.7 a* | 3.4 a | 2.9 a* |
| Synthetic fertilizer | 2.4 b | 3.7 c* | 2.5 b | 2.4 b* |
| SF plus trinexapac-ethyl | 2.2 c | 4.0 b* | 2.3 c | 2.5 b* |
| Biostimulant | 2.4 bc | 3.8 c* | 2.3 c | 2.5 b* |

[a]Abbreviations: CC1, core-cultivation site 1; CC2, core-cultivation site 2; SF, synthetic fertilizer; $T_{75}$, time required in weeks to recover 75% of putting green turf that was subject to 30% canopy removal via core-cultivation.
[b]Fertility programs were added to standard greens management programs and consisted of additional nitrogen, phosphorus, and potassium applied at 7, 7, and 7 kg ha$^{-1}$ every 2 wk starting when canopy voids first appeared on the putting green. Trinexapac-ethyl was applied at 0.048 kg ai ha$^{-1}$ and repeated at 200 growing degree days at base 0 C. More information about products applied appears in Table 1.
[c]Means within a column followed by the same letter are not significantly different ($P \leq 0.05$).
[d]An asterisk (*) following any mean indicates that methiozolin significantly impacted recovery time ($P \leq 0.05$) within a given fertility program and location.

heads surrounding the putting green failed, and were not immediately noticed, as the green was aggressively core cultivated and topdressed to meet study objectives. It was not until heat stress became evident that the issue was discovered and corrected. As a result of this severe stress, turf quality in most plots fell to below 3 on a 1-to-9 scale where 6 is considered minimally acceptable (data not shown). Methiozolin-treated plots recovered more slowly than those not treated with methiozolin at CC2, a phenomenon that did not occur at CC1 (Table 5). Despite issues with irrigation, trends in 75% and 90% recovery as influenced by fertility treatments were generally consistent across locations (Table 5).

Recovery times for $T_{75}$ ranged from 2.2 to 4.7 wk depending on treatment, location, and methiozolin rate (Table 5). All fertility and PGR treatments recovered more quickly than treatments that received no additional fertility at all sites. When methiozolin was applied, 75% creeping bentgrass recovery required an additional 1.5 wk on average at CC2 but no additional time at CC1 (Table 5). Due to the general immobility of methiozolin in soil, substantial root loss is likely required to elicit creeping bentgrass injury from methiozolin in most cases (Brosnan et al. 2013; Flessner et al. 2015). Murphy et al. (1993) observed a 16% decrease in root weight density following cultivation, most likely due to root severing and trauma to the soil. Furthermore, when soil has reduced moisture, roots are more susceptible to injury than when soil is wet (Murphy et al. 1993). At CC1 where drought stress did not occur, methiozolin had no impact on creeping bentgrass recovery rate (Tables 5 and 6). The combined effects of core cultivation and drought at CC2 may have caused temporary root loss, and methiozolin may have prevented new root development.

Creeping bentgrass treated with SF reached $T_{75}$ at the same time as creeping bentgrass treated with biostimulants at both locations regardless of methiozolin use (Table 5). Trinexapac-ethyl influence on creeping bentgrass $T_{75}$ recovery time was independent of methiozolin use but dependent on location. At CC1, TE plus SF improved creeping bentgrass $T_{75}$ recovery time equivalent to the best performing treatments (Table 5). At CC2, where the drought injury occurred, TE programs were inferior to SF in the absence of methiozolin and both SF and biostimulant in the presence of methiozolin (Table 5). The location dependency of TE programs could be attributed to the increased levels of plant hormones contained in biostimulant products and growth regulation imparted

**Table 6.** Time required to reach 90% recovery of voided putting green turf following core-cultivation as influenced by methiozolin and various fertility and plant growth regulator programs at CC1 and CC2 sites.[a,c,d]

| | With methiozolin | | Without methiozolin | |
|---|---|---|---|---|
| Fertility program[b] | CC1 | CC2 | CC1 | CC2 |
| | wk | | | |
| No additional fertility | 5.9 a* | 8.6 a* | 7.9 a* | 5.8 a* |
| Synthetic fertilizer | 4.5 b | 7.3 b* | 4.6 b | 4.5 c* |
| SF plus trinexapac-ethyl | 4.0 c | 7.0 c* | 4.1 b | 4.8 b* |
| Biostimulant | 4.6 b | 6.6 d* | 4.6 b | 4.6 bc* |

[a]Abbreviations: CC1, core-cultivation site 1; CC2, core-cultivation site 2; SF, synthetic fertilizer; $T_{90}$, time required in weeks to recover 90% of putting green turf that was subject to 30% canopy removal via core-cultivation.
[b]Fertility programs were added to standard greens management programs and consisted of additional nitrogen, phosphorus, and potassium applied at 7, 7, and 7 kg ha$^{-1}$ every 2 wk starting when canopy voids first appeared on the putting green. Trinexapac-ethyl was applied at 0.048 kg ai ha$^{-1}$ and repeated at 200 growing degree days at base 0 C. More information about products applied appears in Table 1.
[c]Means within a column, followed by the same letter are not significantly different ($P \leq 0.05$).
[d]An asterisk (*) following any mean indicates that methiozolin significantly impacted recovery time ($P \leq 0.05$) within a given fertility program and location.

by the TE application. Although commonly reported in warm-season turfgrass species like bermudagrass, increases in root growth as a direct result of TE application are inconsistent (Beasely et al. 2005; McCann and Huang 2007; Wherley and Sinclair 2009). Wherley and Sinclair (2009) and Beasley et al. (2005) did not observe changes in creeping bentgrass or Kentucky bluegrass root growth following applications of TE but postulated that rooting increases are more likely directly related to nitrogen application.

Although recovery trends were evident at $T_{90}$ and canopy coverage had reached approximately 95%, differences between sites became more evident, particularly at CC2 with methiozolin (Table 6). All fertility treatments recovered between 1.3 and 3.3 wk more rapidly than the no-additional-fertilizer treatment. When biweekly treatments of methiozolin were applied, biostimulant and SF treatments improved $T_{90}$ recovery time by approximately 0.5 wk compared to SF plus TE (Table 6). At CC2 where the drought stress occurred, biostimulant treated plots achieved 90% recovery 0.7 wk faster than SF and 0.4 wk faster than SF plus TE (Table 6). When methiozolin was not applied, plots treated with biostimulant and SF reached 90% recovery at equivalent times but 1 to 3 wk faster than plots that did not receive additional fertility (Table 6).

In all cases, increasing fertility reduced turfgrass recovery time relative to the standard program. These data suggest that turfgrass managers can improve recovery time of creeping bentgrass greens by 1 to 3 wk by adding 7 kg $ha^{-1}$ of N-P-K to existing greens fertility programs. Methiozolin reduced turfgrass recovery time at one location where a severe drought occurred. These data suggest that turfgrass stress should be avoided when methiozolin programs are used for annual bluegrass control. Creeping bentgrass treated with biostimulants recovered equivalent to or faster than SF in all cases. In the presence of methiozolin treatments, TE reduced $T_{90}$ recovery time by 0.25 to 0.5 wk at two locations and increased $T_{90}$ recovery time by 0.1 wk at one location. Otherwise, plots treated with SF plus TE were equivalent to SF-only plots. Further research needs to be conducted to better explain how methiozolin may affect root recovery following stress-induced root loss.

## Practical Implications

Since its recent registration, methiozolin has been used extensively to control annual bluegrass (*Poa annua*) in creeping bentgrass (*Agrostis stolonifera*) putting greens by golf course superintendents. Although treatment programs are designed to control annual bluegrass slowly to avoid compromising putting quality, environmental conditions, or overapplication of methiozolin can hasten the speed of control. Voided putting surfaces must be rapidly repaired or rejuvenated. Our work indicates that methiozolin does not slow the lateral spread of creeping bentgrass as measured by canopy cover, with the exception of one location where dry conditions prevailed. Additionally, our work demonstrates that biostimulant and synthetic fertilizer applications speed expansion of creeping bentgrass to cover canopy voids on greens. Furthermore, turf managers can continue or initiate plant growth regulator treatments using TE during the void recovery phase with little impact to time required for complete canopy recovery. This research contributed to language on the methiozolin label prohibiting intensive mechanical disturbance, such as core aerification, and allowing use of TE in conjunction with methiozolin treatments.

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## References

Acuña A, Gardner D, Villalobos L, Danneberger K (2022) Effects of plant biostimulants on seedling root and shoot growth of three cool-season turfgrass species in a controlled environment. Int Turf Soc Rec J 14:416–421

Beasley JS, Branham BE, Ortiz-Ribbing LM (2005) Trinexapac-ethyl affects Kentucky bluegrass root architecture. HortScience 40:1539–1542

Beck LL, Cooper T, Hephner AJ, Straw CM, Henry GM (2013) Effect of preemergence herbicides on the recovery of bermudagrass from spring dead spot. Appl Turfgrass Sci doi: 10.1094/ATS-2013-0328-01-RS

Bigelow C, Ervin E, Zhang X, Nichols A (2010) Creeping bentgrass putting green cultivation recovery as affected by pre-stress conditioning with liquid fertilizer and biostimulant programs in the cool-humid region. Appl Turfgrass Sci doi: 10.1094/ATS-2010-0727-01-BR

Brosnan JT, Calvache S, Breeden GK, Sorochan JC (2013) Rooting depth, soil type, and application rate effects on creeping bentgrass injury with amicarbazone and methiozolin. Crop Sci 53:655–659

Brosnan JT, Breeden GK, Thoms AW, Sorochan JC (2014) Effects of preemergence herbicides on the establishment rate and tensile strength of hybrid bermudagrass sod. Weed Technol 28:206–212

Ervin EH, Zhang X (2007) Influence of sequential trinexapac-ethyl applications on cytokinin content in creeping bentgrass, Kentucky bluegrass and hybrid bermudagrass. Crop Sci 47:2145–2151

Ervin EH, Ok CH, Fresenberg BS, Dunn JH (2002) Trinexapac-ethyl restricts shoot growth and prolongs stand density of 'Meyer' zoysiagrass fairway under shade. HortScience 37:502–505

Flessner ML, Wehtje GR, McElroy JS, Howe JA (2015) Methiozolin sorption and mobility in sand-based rootzones. Pest Manag Sci 71:1133–1140

Gao Y, Li D (2012) Foliar fertilization by tank-mixing with organic amendment in creeping bentgrass. HortTechnology 22:157–163

Johnson BJ, Murphy TR (1995) Effect of paclobutrazol and flurprimidol on suppression of *Poa annua* spp. *reptans* in creeping bentgrass (*Agrostis stolonifera*) greens. Weed Technol 9:182–186

Johnson BJ, Murphy TR (1996) Suppression of perennial subspecies of annual bluegrass (*Poa annua* spp. *reptans*) in a creeping bentgrass (*Agrostis stolonifera*) green with plant growth regulators. Weed Technol 10:705–709

Jones M, Christians NE (2009) Lateral spread and divot recovery of creeping bentgrass cultivars in non-mowed and mowed settings. Iowa State Research Progress Reports Paper 347. Ames: Iowa Statue University Extension and Outreach

Jones MA, Christians NE (2012) Lateral spread and dry matter partitioning of creeping bentgrass cultivars. Crop Sci 52:393–399

Kahn W, Rayirath UP, Subramanian S, Jithesh MN, Rayorath P, Hodges DM, Chritchley AT, Craigie JS, Norrie J, Prithiviraj B (2009) Seaweed extracts as biostimulants of plant growth and development. J Plant Growth Regul 28:386–399

Karcher DE, Richardson MD, Landreth JW, McCalla JH Jr (2005) Recovery of bermudagrass varieties from divot injury. Appl Turfgrass Sci doi: 10.1094/ATS-2005-0117-01-RS

Karcher DE, Richardson MD (2003) Quantifying turfgrass color using digital image analysis Crop Sci 43:943–951

McCann SE, Huang B (2007) Effects of trinexapac-ethyl foliar application on creeping bentgrass responses to combined heat and drought stress. Crop Sci 47:2121–2128

McIntosh MS (1983) Analysis of combined statistics. Agron J 75:153–155

Murphy JA, Reike PE, Erickson AE (1993) Core cultivation of a putting green with hollow and solid tines. Agron J 85:1–9

Petrovsky J (2019) Methiozolin effects on annual bluegrass control at various seasonal timings and creeping bentgrass injury in shade. M.S thesis. Auburn, AL: Auburn University. 86 p.

Rademacher W (2000) Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. Annu Rev Plant Physiol 51:501–531

Rana SS, Askew SD (2018) Measuring canopy anomaly influence on golf putt kinematics: does annual bluegrass influence ball roll behavior? Crop Sci 58:911–916

Rossi FS Grant JA (2009) Long term evaluation of reduced chemical pesticide management of golf course putting turf. Int Turf Soc Rec J 11:77–90

Schmidt RE, Ervin EH, Zhang X (2003) Questions and answers about biostimulants. Golf Course Maintenance June:91–94

Tucker BJ, McCarty LB, Liu H, Wells CE, Reike JR (2006) Mowing height, nitrogen rate and biostimulant influence root development of field grown 'TifEagle' bermudagrass. HortScience 41:805–807

Venner KA, Hart S, Askew S, Mansue CJ (2012) Use of methiozolin for annual bluegrass (Poa annua L.) control on creeping bentgrass (*Agrostis stolonifera*) greens. Page 95 in Proceedings of the 66th Annual Meeting of the Northeastern Weed Science Society. Philadelphia, Pennsylvania, January 3–6, 2012

Walker KS, Bigelow CA, Hardeback GA (2003) Creeping bentgrass fairway divot recovery as affected by irrigation frequency, cultivar and divot mixture seed additions: 2003. Annual Report of the Purdue University Turfgrass Science Program. West Lafayette, IN: Purdue University

Wherley B, Sinclair TR (2009) Growth and evapotranspiration response of two turfgrass species to nitrogen and trinexapac-ethyl. HortScience 44:2053–2057

Xu Y, Huang B (2010) Responses of creeping bentgrass to trinexapac-ethyl and biostimulants under summer stress. HortScience 45:125–131

Zhang X, Ervin EH (2004) Cytokinin-containing seaweed and humic acid extracts associated with creeping bentgrass leaf cytokinins and drought resistance. Crop Sci 44:1737–1745

Zhang XZ, Ervin EH (2008) Impact of seaweed extract-based cytokinins and zeatin riboside on creeping bentgrass heat tolerance. Crop Sci 48:364–370

Zhang X, Ervin EH, Evanylo GK, Haering KC (2009) Impact of biosolids on hormone metabolism in drought-stressed tall fescue. Crop Sci 49: 1893–1901

Zhang X, Ervin EH, Schmidt RE (2003) Physiological effects of liquid applications of a seaweed extract and a humic acid on creeping bentgrass. J Am Soc Hort Sci 128:492–496

Zhang X, Summer P, Ervin EH (2013) Foliar amino acid-based fertilizer impact on creeping bentgrass drought resistance. International Turf Soc Rec J 12:1–7