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Methiozolin rate and application frequency influence goosegrass (*Eleusine indica*) and smooth crabgrass (*Digitaria ischaemum*) control in turf

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Abstract

Methiozolin is labeled for goosegrass and smooth crabgrass control in golf course putting greens, but no peer-reviewed literature exists regarding this use. Greenhouse experiments were conducted evaluating goosegrass and smooth crabgrass response to increasing rates of methiozolin as affected by weed growth stage. In general, as weed growth stage increased, the methiozolin rate required to reduce weed biomass 90% (WR_{90}) increased. Goosegrass was more sensitive to preemergence-applied methiozolin than smooth crabgrass, and the WR_{90} was 30.4 and 118 g ai ha^{-1} for goosegrass and smooth crabgrass, respectively. However, smooth crabgrass was generally more sensitive to postemergence-applied methiozolin than goosegrass. Subsequent field studies were conducted to evaluate goosegrass and smooth crabgrass control with methiozolin applied singularly or sequentially at standard preemergence timings. Results indicated methiozolin applied singularly or sequentially at the label-recommended rate (500 g ha^{-1}) is not persistent enough to provide season-long control of goosegrass and smooth crabgrass. Ten field studies were conducted in Alabama, California, Florida, and Virginia to evaluate frequent methiozolin application programs with the objective of providing selective, season-long goosegrass and smooth crabgrass control. Results from these studies indicate methiozolin can be safely applied to hybrid bermudagrass and creeping bentgrass putting greens despite exceeding the yearly maximum use rate for putting greens (2,500 g ha^{-1}) with some treatments. Methiozolin effectively controlled smooth crabgrass throughout the growing season in California and Virginia when 10 biweekly applications were applied at 250 g ha^{-1} or higher. In Florida, methiozolin did not acceptably (80%) control goosegrass regardless of application rate. In Virginia, methiozolin acceptably controlled goosegrass only when applied at rates and frequencies that exceeded the maximum yearly methiozolin usage rate. These data indicate that methiozolin has the potential to control smooth crabgrass preemergence when applied frequently, but does not provide acceptable goosegrass control at labeled rates.

Introduction

Hybrid bermudagrass and creeping bentgrass are the most commonly utilized turfgrass species for golf course putting greens in the United States (Lyman et al. 2007). Goosegrass and smooth crabgrass are problematic in golf course putting greens partly because of discontinuous germination and lack of selective herbicide options (Chauhan and Johnson 2008; Fidanza et al. 1996). Although six herbicides are labeled for use on hybrid bermudagrass or creeping bentgrass putting greens for goosegrass and smooth crabgrass control, each has limitations in turf selectivity or weed control efficacy.

Bensulide, dithiopyr, and oxadiazon are labeled for hybrid bermudagrass and creeping bentgrass; whereas they control goosegrass and smooth crabgrass, they also routinely injure turf and have selected for resistant weed populations in many areas (Bhowmik and Bingham 1990; Hart et al. 2004; Johnson 1982, 1987; McElroy et al. 2017). Oxadiazon plus bensulide reduced hybrid bermudagrass root biomass by approximately 15% and slowed spring transition in 1 yr of a study conducted in South Carolina (McCullough et al. 2007). In creeping bentgrass putting greens, oxadiazon plus bensulide can unacceptably injure creeping bentgrass, especially during hot weather (Johnson 1987). Multiple goosegrass populations have developed resistance to oxadiazon on bermudagrass golf fairways in the northern transition zone (McElroy et al. 2017). Several dithiopyr products were once labeled for use on creeping bentgrass and hybrid bermudagrass putting greens, but allowances for use on greens were removed from the labels of most products because of the potential for turf loss when applying root-inhibiting herbicides to stressed turfgrass (Bhowmik and Bingham 1990; Hart et al. 2004).

In hybrid bermudagrass putting greens, pendimethalin and foramsulfuron are both labeled to control goosegrass, smooth crabgrass, or both. Although pendimethalin is effective for goosegrass and smooth crabgrass control (Bhowmik and Bingham 1990; Johnson 1993, 1996a), herbicide-resistant weed populations have reduced its effectiveness in recent years (McCullough et al. 2013; Russell et al. 2022). Foramsulfuron can selectively suppress goosegrass in bermudagrass turf with multiple applications to immature plants (Busey 2004), but control is often poor (<70%) (Breeden et al. 2017; Brosnan et al. 2009; McCullough et al. 2012). Carfentrazone + 2,4-D + MCPP + dicamba (SpeedZone®) has reduced goosegrass coverage in bermudagrass [*Cynodon dactylon* (L.) Pers.], especially when application intervals were more frequent than allowed by the label (Leibhart et al. 2014). Although SpeedZone® does not have specific information that distinguishes between use patterns on greens compared to other types of managed bermudagrass, the product is registered for use on hybrid bermudagrass turf in golf-course systems and does not prohibit use on greens (Anonymous 2020).

In creeping bentgrass putting greens, recent research has developed effective programs for crabgrass and goosegrass control with topramezone and siduron (Brewer and Askew 2021), but neither of these products is currently registered for use on creeping bentgrass greens. Thus, available products for creeping bentgrass or hybrid bermudagrass putting greens are either too injurious for routine use or have been rendered ineffective due to development of resistant weed populations. This lack of commercially viable herbicidal control options necessitates the development of new goosegrass and smooth crabgrass control methods for putting green systems.

Methiozolin was registered in 2019 for selective control of annual grassy weeds in hybrid bermudagrass and creeping bentgrass putting greens (Koo et al. 2014). Although the product label indicates methiozolin selectively controls goosegrass and smooth crabgrass (Anonymous 2021), currently no peer-reviewed literature exists regarding its use for goosegrass and smooth crabgrass control. Data presented upon filing the methiozolin patent indicate methiozolin can control goosegrass and large crabgrass (*Digitaria sanguinalis* L. Scop.) preemergence for 4 wk when applied preemergence to bare ground (Koo and Hwang 2013). Methiozolin has a considerable margin of safety when used on creeping bentgrass putting greens (Askew and McNulty 2014; Brosnan et al. 2013; Hoisington et al. 2014), and recent reports suggest that the product can be safely used on actively growing hybrid bermudagrass putting greens (Peppers et al. 2023). The relatively short persistence of methiozolin (Hwang et al. 2013) suggests that low-dose, frequent application programs may be needed to maintain season-long weed control as has been shown with other herbicides (Brewer and Askew 2021).

Collars and green edges often undergo traffic stress and become composed of mixed turf species and increased weed infestation, especially in the transition zone and southern United States (Dernoeden 2013). Demand for methiozolin in southern markets has mostly been associated with use on these areas, because methiozolin has the safety profile to span multiple turf species, allows for spray overlap onto greens, and addresses herbicide-resistant weeds with a new mode of action (Brabham et al. 2021; K. Han, personal communication). More information is needed to develop treatment programs that offer commercially acceptable weed control and turf safety on green edges and collars. The objectives of this research were to (i) evaluate goosegrass and smooth crabgrass response to various methiozolin rates at numerous growth stages, (ii) evaluate methiozolin for goosegrass and smooth crabgrass control when applied at traditional preemergence application timings, and (iii) evaluate low-dose, frequent methiozolin application programs for season-long weed control and turfgrass safety across varying climatic regions of the United States. We hypothesize that goosegrass and smooth crabgrass will be less susceptible to methiozolin at later growth stages. We also hypothesize that single preemergence applications of methiozolin made at traditional preemergence timings will be inferior to low-dose, frequent application programs for season-long control of goosegrass and smooth crabgrass.

Materials and Methods

Goosegrass and Smooth Crabgrass Response to Increasing Methiozolin Rates as Affected by Weed Growth Stage

Two greenhouse studies were conducted in Blacksburg, VA (37.22° N, 80.41° W) in winter 2022–2023 to evaluate goosegrass and smooth crabgrass response to increasing methiozolin rates as influenced by weed growth stage. Both studies were repeated in time and space for a total of 2 site-yr. Trials were arranged as a randomized complete block design with four replications and 60 treatments that included an embedded six by five by two factorial arrangement with six levels of methiozolin (Poacure®; Moghu Research Center Ltd, Daejeon, South Korea) rate (0, 125, 250, 500, 1,000, and 2,000 g ai ha^{-1}), five levels of weed growth stage (preemergence, one- to two-leaf, three- to four-leaf, one tiller, and two to three tillers), and two levels of weed species (goosegrass and smooth crabgrass). All treatments received herbicide application simultaneously regardless of species or growth stage. This was accomplished by staggering weed seed planting dates to ensure that weeds were at the appropriate growth stage at the scheduled time of application. Approximately 10 to 15 weed seeds were seeded into 4.4- by 7.6-cm pots containing a 1:2 native soil to sand mixture by volume. The native soil utilized in this study was a Groseclose-Urban land complex loam (clayey, mixed, mesic Typic Hapludults) with a pH of 6.1 and 3.6% organic matter. Approximately 1 wk prior to methiozolin application, all but three representative plants were removed from pots receiving a postemergence treatment to allow for consistency in weed growth stage at the time of application. All soil mixtures contained 25 kg ha^{-1} of a slow-release fertilizer (19-6-12) (Sta-Green Indoor and Outdoor All-Purpose Food Fertilizer; Gro Tec, Inc,.Modoc, IN) to prevent nutrient deficiencies throughout the duration of the study. Approximately 1.9 mm of irrigation was supplied twice daily to prevent moisture stress, and supplemental lighting of 900 μmol m^{-2} s^{-1} photosynthetically active radiation was set to a 14-h daylength throughout the duration of the studies. Greenhouse day/night temperatures

Table 1. Herbicide rate and application timing from herbicides applied at standard preemergence timings and frequencies.

Herbicide[a]	Rate	Application timings 2020	2022
	kg ai ha^{-1}		
Nontreated		–	–
Bensulide	9.0	May 4	April 11
Bensulide + oxadiazon	1.7 + 6.7	May 4	April 11
		June 2	May 20
Methiozolin	0.50	May 4	April 11
Methiozolin	1.0	May 4	April 11
		Jun 2	May 20
Siduron	3.4	May 4	April 11
		May 25	April 25
		June 2	May 10
		June 16	May 20

[a]All herbicides were soil incorporated with approximately 6.4 mm of irrigation within 1 h following application according to methiozolin label recommendations.

were maintained at 30 C/24 C. All treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 374 L ha^{-1} at 331 kPa fitted with TTI11006 nozzles (TeeJet Technologies, Spraying Systems Co., Wheaton, IL). Immediately following methiozolin applications, approximately 6.4 mm of irrigation was administered via overhead sprinklers to wash methiozolin from the foliage to the soil to enhance methiozolin uptake according to label instructions. At 4 wk following methiozolin application, aboveground biomass data were collected and dried at 50 C for 72 h, then weighed. Biomass data were converted to a percent reduction relative to the nontreated check of the same growth stage within a given replication. The relationship between methiozolin rate and biomass reduction data were fitted separately by growth stage to a three-parameter Gompertz model using Equation 1:

$$WR = a \times e^{\left(-b\left(e^{-k\times r}\right)\right)} \quad [1]$$

where WR is the predicted biomass reduction, e is the natural log, a is an estimated parameter that controls the rate of weight reduction as methiozolin rate increases, b and k are estimated parameters, and r is the methiozolin rate. Estimated a, b, and k values were used to determine methiozolin rate required to achieve 90% biomass reduction (WR_{90}) using Equation 2:

$$WR90 = \left(\frac{\log(-\left(\frac{\left(\log\left(\frac{90}{a}\right)\right)}{b}\right)}{k}\right) \quad [2]$$

where WR_{90} is the estimated methiozolin rate required to reduce goosegrass or smooth crabgrass biomass 90%, and a, b, and k are the estimated parameters from Equation 1. Resulting WR_{90} data were subjected to ANOVA with sums of squares partitioned to reflect replicate, trial, weed species, growth stage, weed species by growth stage, trial-by-weed species, trial-by-growth stage, and trial-by-weed species-by-growth stage. Appropriate means were separated with Proc GLM in SAS 9.4 (SAS Institute, Cary, NC) using Fisher's protected LSD test at $\alpha = 0.05$.

Goosegrass and Smooth Crabgrass Control from Methiozolin Applied at Standard Preemergence Timings and Frequencies

Four field studies were conducted in Blacksburg, VA at the Virginia Tech Turfgrass Research Center (37.22 N, 80.41° W) between 2020 and 2022 evaluating preemergence goosegrass and smooth crabgrass control, and creeping bentgrass putting green safety. Trials were arranged as randomized complete block designs with six treatments and four replications. The six herbicide treatments and initiation timings that were evaluated are listed in Table 1. All treatments were applied using the aforementioned CO_2-pressurized backpack sprayer. Following application, approximately 6.4 mm of irrigation was applied to the treated areas to facilitate herbicide-to-soil contact according to methiozolin label instructions. Goosegrass control was evaluated on two adjacent sites of a fallow putting green in 2020 and 2022 that are hereafter referred to as TRC1 and TRC4, respectively. Smooth crabgrass control was evaluated at TRC1 as well as two 'L93' creeping bentgrass putting greens located approximately 100 m apart that were maintained at approximately 3.8 mm in height and hereafter referred to as TRC2 and TRC3 for trials conducted in 2020 and 2022, respectively. All trials sites had a sand-based rootzone meeting United States Golf Association specifications (USGA 2018). Visually evaluated and grid-intersect-based percent weed coverage (196 assessments per plot) was collected at all locations, and turfgrass injury was evaluated on the creeping bentgrass–containing locations. All ratings were collected biweekly following trial initiation until early September. Percent weed control was expressed as percent weed coverage reduction relative to the nontreated. Turfgrass injury was evaluated on 0% to 100% scale, where 0% = no turfgrass injury observed, 30% equals maximum acceptable turfgrass injury, and 100% equals complete reduction in visible turfgrass stand. Data were subjected to ANOVA using Proc GLM in SAS 9.4 with sums of squares partitioned to reflect the effects of replicate, trial, treatment, and trial-by-treatment. Trial was considered random, and mean squares associated with treatment were tested by the mean square associated with trial-by-treatment (McIntosh 1983). Appropriate means were separated using Fisher's protected LSD at $\alpha = 0.05$.

Evaluation of Low-Dose, Frequent-Application Methiozolin Programs for Goosegrass and Smooth Crabgrass Control Across Varying Climatic Regions

Ten studies were conducted between 2022 and 2023 in Alabama, California, Florida, and Virginia to evaluate goosegrass and smooth crabgrass control, and creeping bentgrass and hybrid bermudagrass tolerance to low-dose, frequent methiozolin application programs. Site descriptions and application data are listed in Table 2. All studies were arranged as randomized complete block designs with nine treatments and four replications. Methiozolin-containing treatments were initiated at three distinct timings to determine if herbicide-program performance was dependent on initial weed growth stage. Treatments are presented in Table 3 in addition to a nontreated control. These treatment timings were the standard preemergence for a given location; a delayed preemergence made when first germination is expected (DPRE); and an early-postemergence timing made when cotyledons, but not tillering plants, could be found in turf (EPOST). Six of the treatments included methiozolin applied in sequence. Such treatments included methiozolin at 125, 250, and 500 g ha^{-1} 10 times over 20 wk when initiated at the preemergence timing, 250 and 500 g ha^{-1} eight times over 16 wk when initiated at the DPRE

Table 2. Site and application description of studies evaluating frequent methiozolin application programs for goosegrass and smooth crabgrass control, and creeping bentgrass and hybrid bermudagrass tolerance.

Site	Trial location	GPS coordinates	Year	Turfgrass species	Cultivar	Weed species targeted	Initiation date	Application volume
								L ha^{-1}
AU1	Auburn, AL	32.57° N, 85.49° W	2022	Creeping bentgrass	'Penncross'	Smooth crabgrass	April 20, 2022	374
AU2	Auburn, AL	32.57° N, 85.49° W	2022	Hybrid bermudagrass	'TifEagle'	Goosegrass	April 20, 2022	374
FL1	Gainesville, FL	29.40° N, 82.16° W	2022	Hybrid bermudagrass	'TifDwarf'	Goosegrass	April 13, 2022	815
FL2	Gainesville, FL	29.40° N, 82.16° W	2023	Hybrid bermudagrass	'TifDwarf'	None	May 30, 2023	815
FL3	Davie, FL	26.08° N, 80.23° W	2022	Hybrid bermudagrass	'TifEagle'	Goosegrass	March 14, 2022	815
UCR1	Riverside, CA	33.96° N, 117.33° W	2022	Hybrid bermudagrass	'GN-1'	Smooth crabgrass	March 20, 2022	815
UCR2	Riverside, CA	33.96° N, 117.33° W	2022	Creeping bentgrass	'Pure Distinction'	None	March 20, 2022	815
VT1	Blacksburg, VA	37.22° N, 80.41° W	2022	Creeping bentgrass	'L93'	Smooth crabgrass	April 13, 2022	374
VT2	Blacksburg, VA	37.22° N, 80.41° W	2023	Creeping bentgrass	'L93'	Smooth crabgrass	April 13, 2023	374
VT3	Radford, VA	37.15° N,80.52° W	2022	Creeping bentgrass	'L93'	Goosegrass	April 26, 2022	374

Table 3. Herbicide programs and initiation timings of low-dose, frequent herbicide application programs for goosegrass and smooth crabgrass control.

Herbicide[a]	Rate	Initiation timing[b]	Total no. of applications
	kg ai ha^{-1}		
Nontreated	–	–	
Bensulide[c]	11.2	PRE	2
Bensulide + oxadiazon	6.72 + 1.68	PRE	2
Methiozolin	0.125	PRE	10
Methiozolin	0.250	PRE	10
Methiozolin	0.500	PRE	10
Methiozolin	0.250	DPRE	8
Methiozolin	0.500	DPRE	8
Methiozolin	0.500	EPOST	6

[a]All herbicides were soil incorporated with approximately 6.4 mm of irrigation within 1 h following application according to label recommendations.
[b]Treatment initiation timings were the standard preemergence (PRE) for a given location, a delayed preemergence made when germination is expected, but emergence has not occurred (DPRE), and an early postemergence timing made when cotyledons, but not tillering plants, could be found in turf (EPOST).
[c]Bensulide alone and bensulide plus oxadiazon treatments were applied PRE and 6 wk after the initial application.

timing, and 500 g ha^{-1} six times over 12 wk when initiated at the EPOST timing. Two comparison herbicide programs included bensulide at 11.2 kg ha^{-1} or bensulide plus oxadiazon at 6.72 plus 1.68 kg ha^{-1} each applied twice at 6-wk intervals.

For trial locations where weed coverage was insufficient for confident target weed control assessment, only turfgrass response data were collected. Goosegrass control, smooth crabgrass control, creeping bentgrass tolerance, and hybrid bermudagrass tolerance were evaluated at two, three, five, and five locations, respectively. Weed coverage was visually assessed biweekly throughout the season and using grid-intersect counts during the final data collection event. Turfgrass injury was evaluated as 0% equals no turfgrass injury observed, 100% equals complete reduction in visible turfgrass stand, and 30% equals maximum commercially acceptable turfgrass injury. To account for repeated measures over time, turfgrass injury data were expressed as the number of days over an injury threshold of 20% (DOT_{20}) and maximum observed injury for each experimental unit. These injury DOT_{20} values were calculated assuming linear trends in changes to turfgrass injury between assessment dates. Similarly, weed control data were expressed as the number of days with weed control at or above 80% (DOT_{80}), which has been deemed commercially acceptable (Cutulle et al. 2013), and weed control at the conclusion of the trial derived from the aforementioned grid-intersect counts. Days over threshold values (Brewer et al. 2021; Cox et al. 2017) use temporal trends in turfgrass injury and weed control to reflect duration of responses that are important to turf managers. Data were subjected to ANOVA using PROC GLM in SAS 9.4 with sums of squares partitioned to reflect replicate, trial, treatment, and trial-by-treatment. Trial was considered random, and mean squares associated with treatment were tested by the mean square associated with trial-by-treatment (McIntosh 1983). Appropriate means were separated using Fisher's Protected LSD at $\alpha = 0.05$.

Results and Discussion

Goosegrass and Smooth Crabgrass Response to Increasing Methiozolin Rates as Affected by Weed Growth Stage

The main effects of weed species and growth stage and their interaction was significant ($P < 0.001$) for WR_{90} and not

Table 4. Influence of weed growth stage and weed species on methiozolin rate required to reduce goosegrass and smooth crabgrass biomass 90% (WR_{90}).

Growth stage	WR_{90}	
	Smooth crabgrass	Goosegrass
	g ai ha^{-1}	
Preemergence	118 d[a]**[b]	30 c**
One- to two-leaf	235 d	346 b
Three- to four-leaf	521 c**	1,548 a**
One- to two-tiller	1,278 b	>2,000[c] –
Three- to four-tiller	1,954 a	>2,000 –

[a]Different letters following means indicate significant differences between means within a given species.
[b]Means followed by ** indicate significant difference between weed species within a given growth stage.
[c]Goosegrass WR_{90} for one- to two-tiller and three- to four-tiller goosegrass was incalculable due to insufficient methiozolin rates for 90% weight reduction.

dependent on trial ($P > 0.05$). The methiozolin rate needed to reduce smooth crabgrass biomass 90% approximately doubled with each change in smooth crabgrass growth stage (Table 4). In the case of goosegrass, the methiozolin rate needed to control one- to two-leaf plants was over 10 times more than that needed to control plants preemergence. Likewise, goosegrass plants at the three- to four-leaf stage or later stages required 52 to more than 67 times more methiozolin to cause 90% weight reduction compared to germinating goosegrass seedlings. When applied preemergence, goosegrass WR_{90} was extremely low (30 g ha^{-1}) and approximately four orders of magnitude less than that of smooth crabgrass. However, smooth crabgrass was considerably more susceptible to methiozolin than goosegrass when the product was applied postemergence.

Decreased preemergence sensitivity of smooth crabgrass compared to goosegrass may have been due to dissimilar germination time and periodicity, which was delayed approximately 4 d compared to that of goosegrass (data not shown). This delayed germination timing for smooth crabgrass could have allowed for more methiozolin dissipation in the soil leading to a potentially lower overall concentration of methiozolin during germination. A similar trend of differential response to foliar herbicide between smooth crabgrass and goosegrass has been reported for dithiopyr (Enache and Ilnicki 1991; Johnson 1996b). Dithiopyr is primarily preemergence-applied to smooth crabgrass, but has appreciable postemergence activity when smooth crabgrass is in immature growth stages that decreases as smooth crabgrass growth stage increases (Enache and Ilnicki 1991; Reicher et al. 1999). However, whereas dithiopyr may effectively control goosegrass preemergence, it has no appreciable postemergence goosegrass efficacy (Johnson 1996b).

Goosegrass and Smooth Crabgrass Control from Methiozolin Applied at Standard Preemergence Timings and Frequencies

In the three smooth crabgrass control trials, the trial-by-treatment effect was significant ($P < 0.001$) for ratings taken in early July when TRC2 was included in a combined analysis, but not when only TRC1 and TRC3 were included ($P = 0.8685$). Therefore, smooth crabgrass control data were separated into the pooled effect of TRC1 + TRC3 and TRC2. This interaction is likely due to higher smooth crabgrass control from sequential applications of methiozolin at TRC2 where smooth crabgrass cover was 28% compared to 66% ± 5% at the other two locations (data not shown). In early July at TRC2, sequential applications of methiozolin controlled smooth crabgrass 88% and equivalent to bensulide, oxadiazon plus bensulide, and siduron, whereas single applications of methiozolin controlled smooth crabgrass 45%, and less than other treatments (Table 5). In early July at TRC1 and TRC3, methiozolin applied once or twice controlled smooth crabgrass 33% and 62%, respectively, and less than any other herbicide evaluated.

For ratings taken at the conclusion of the trial in September, the trial-by-treatment interaction was insignificant ($P = 0.4412$); therefore, smooth crabgrass control data are pooled across all locations. At the conclusion of the trial, the addition of a sequential methiozolin application improved smooth crabgrass control relative to a single methiozolin application (Table 5). Single and sequential methiozolin applications controlled smooth crabgrass 33% and 64%, respectively, comparable to oxadiazon plus bensulide, but less effective than bensulide and siduron. Oxadiazon plus bensulide was the only treatment that injured creeping bentgrass in any of the studies, but injury was never more than 30% at any location (data not shown).

For the two sites where goosegrass control was evaluated, the trial-by-treatment interaction was significant ($P < 0.001$) for goosegrass control ratings taken in early July, and data are presented separately by trial (Table 5). This trial-by-treatment interaction may be attributed to bensulide and siduron partially controlling goosegrass at TRC1 but not controlling goosegrass at TRC4 (Table 5). Based on previous literature, bensulide and siduron do not control goosegrass acceptably (Bingham and Schmidt, 1967; Brewer and Askew 2021; Johnson 1982). Goosegrass control with bensulide and siduron at this location may be due to sporadic goosegrass emergence throughout the growing season at TRC1, where young seedlings were still present in early July. Goosegrass appeared to emerge more consistently and earlier in the growing season at TRC4 (data not shown), which likely led to better control. In early July at TRC1, single applications of methiozolin controlled goosegrass 17% similar to bensulide alone and siduron. Sequential methiozolin applications were more effective than single applications and controlled goosegrass 59% and similar to oxadiazon plus bensulide (Table 5). In early July at TRC4, single applications of methiozolin controlled goosegrass more effectively than siduron and bensulide. Single and sequential applications of methiozolin controlled goosegrass 44% and 69%, respectively, in early July at TRC4.

For ratings taken at the conclusion of the trial (early September), the trial-by-treatment interaction was insignificant ($P = 0.1210$); therefore, data are pooled across both locations. At the conclusion of the trial, oxadiazon plus bensulide controlled goosegrass more than any other treatment and was the only treatment that controlled goosegrass >80% (Table 5). Sequential methiozolin applications controlled goosegrass 55% at the conclusion of the trial and was superior to single methiozolin applications, bensulide alone, and siduron, which all controlled goosegrass <35%.

Results from these studies indicate that methiozolin offers preemergence goosegrass and smooth crabgrass suppression with no visible injury to creeping bentgrass putting greens. However, methiozolin did not control either smooth crabgrass or goosegrass >80% at trial conclusion. In one location, sequential methiozolin applications controlled smooth crabgrass >80% in early July, indicating that methiozolin has potential for short-term smooth crabgrass control, but more frequent applications may be needed to extend the duration of control given methiozolin's limited

Table 5. Influence of preemergence-applied herbicides on goosegrass and smooth crabgrass control in early July and early September.[a,b]

	Weed control in early July				Weed control in early September	
	Smooth crabgrass		Goosegrass		Smooth crabgrass	Goosegrass
Herbicide	TRC1 + TRC3	TRC2	TRC1	TRC4	All locations	All locations
	%					
Bensulide	99 a[c]	100 a	38 b	0 c	97 a	32 c
Bensulide + oxadiazon	90 a	90 a	58 a	88 a	73 bc	81 a
Methiozolin	33 c	45 b	17 b	44 b	33 d	32 c
Methiozolin fb methiozolin	62 b	88 a	59 a	69 a	64 c	55 b
Siduron	94 a	87 a	12 b	0 c	80 b	20 c

[a]Abbreviation: fb, followed by.
[b]Weed control data collected in early July was assessed visually, whereas weed control data collected in early September was derived via grid-intersect counts.
[c]Different letters following means indicate significant differences between means within a given trial site.

persistence in soil (Hwang et al. 2013). Results from the greenhouse rate response screen (Table 4) further suggest that low doses of methiozolin could effectively be incorporated into a frequent-application strategy.

Evaluation of Low-Dose, Frequent Application Methiozolin Programs for Goosegrass and Smooth Crabgrass Control Across Varying Climatic Regions

Across five trial locations that contained hybrid bermudagrass and an additional five trial locations that contained creeping bentgrass, neither turf species was injured by any methiozolin-containing treatment program (data not shown). Although hybrid bermudagrass was also not injured by other treatments (data not shown), the treatment main effect for injury DOT_{20} was significant for creeping bentgrass ($P < 0.001$) and not dependent on trial ($P > 0.05$) (data not shown). Bensulide plus oxadiazon was the only treatment that unacceptably injured creeping bentgrass at any location and had 24 DOT_{20} (data not shown), which is consistent with previous reports of creeping bentgrass susceptibility to this herbicide combination (Johnson 1982, 1987). These results are also consistent with previous reports of hybrid bermudagrass tolerance to methiozolin when applied during periods of active growth at labeled rates (Peppers and Askew 2023) and with creeping bentgrass tolerance to methiozolin when treated in fall or spring (Askew and McNulty 2014; Brosnan et al. 2013; Hoisington et al. 2014).

The effect of trial-by-treatment on smooth crabgrass DOT_{80} was significant ($P < 0.001$); therefore, smooth crabgrass DOT_{80} data are presented separately by the three locations that were infested with smooth crabgrass. This interaction between trial locations is likely due to differential treatment efficacy between trials for treatments initiated at the DPRE and EPOST timings. Treatments applied at DPRE and EPOST timings less effectively controlled smooth crabgrass at UCR1, which was possibly due to increased early-season temperatures between UCR1 and both VT trial locations. Furthermore, crabgrass emergence was delayed at the VT2 trial location resulting in lower potential for DOT_{80} accumulation relative to UCR1 and VT1.

Bensulide alone and preemergence-initiated methiozolin applied at 500 g ha^{-1} controlled smooth crabgrass over an 80% threshold for 84 to 112 d depending on location and equivalent to the highest observed DOT_{80} (Table 6). Bensulide plus oxadiazon, DPRE-initiated methiozolin applied at 500 g ha^{-1}, and preemergence-initiated methiozolin applied at 250 g ha^{-1} were statistically similar to the best performing treatments at VT1 and VT2, but not at UCR1. In general, methiozolin controlled smooth crabgrass more effectively with earlier-initiated treatment programs. When initiated EPOST, methiozolin applied at 500 g ha^{-1} had 0 to 65 DOT_{80} depending on location and was similar to or less than preemergence-initiated methiozolin applied at 125 g ha^{-1}.

At VT2, smooth crabgrass DOT_{80} was limited to 84 d, but treatments trends were similar to other locations. When treatment programs were initiated later, smooth crabgrass DOT_{80} decreased. However, the magnitude of smooth crabgrass DOT_{80} difference between treatments was generally less. This may be due to differences in creeping bentgrass putting green management between years. Fertility included approximately 2.5 and 4.9 kg N ha^{-1} applied every 2 wk at VT1 and VT2, respectively. This increase in fertility increased creeping bentgrass vigor, and delayed smooth crabgrass emergence for 4 wk at VT2 (data not shown), thus compressing the number of days available to accumulate DOT_{80}.

AT UCR1, preemergence-initiated methiozolin applied at 500 g ha^{-1} and bensulide alone were the only treatments that controlled smooth crabgrass greater than 80% for 112 d, which was the highest DOT_{80} value possible at this trial location (Table 6). With preemergence-initiated methiozolin, smooth crabgrass DOT_{80} decreased stepwise as methiozolin rate decreased. Smooth crabgrass DOT_{80} was similar when treated with preemergence-initiated methiozolin applied at 250 g ha^{-1} and bensulide plus oxadiazon. Methiozolin did not acceptably control smooth crabgrass when application programs were initiated at DPRE and EPOST timings. This reduction in acceptable control is likely due to the difference in temperatures between the two locations. The average high temperatures for the duration of the trials at UCR1 and VT were 31 C and 26 C, respectively (data not shown). Increased temperatures at UCR1 likely accelerated methiozolin degradation. Increases in temperature can speed herbicide dissipation in soil, resulting in reduced preemergence efficacy (Zimdahl and Gwynn 1977; Zimdahl et al. 1984).

The effect of trial-by-treatment on smooth crabgrass control at the conclusion of the trial was insignificant ($P > 0.05$) between VT1 and VT2, but significant between UCR1 and VT locations ($P < 0.001$). Therefore, smooth crabgrass control at the conclusion of the trial is separated into the pooled effect of VT1 + VT2 and UCR1.

At the conclusion of the trials conducted at the VT locations, preemergence-initiated methiozolin applied at 250 and 500 g ha^{-1}, bensulide alone, and bensulide plus oxadiazon were the only treatments that acceptably controlled (>80%) smooth crabgrass (Table 6). Preemergence-initiated methiozolin applied at 125 g ha^{-1}, DPRE-initiated methiozolin applied at 250 g ha^{-1}, and EPOST-

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Table 6. Influence of herbicide application program on creeping bentgrass maximum observed injury, goosegrass, and smooth crabgrass days of 80% or greater control (DOT_{80}), and end-of-season control.[a]

Herbicide	Rate	Initiation timing[c]	Creeping bentgrass Maximum injury	Smooth crabgrass DOT_{80} UCR1	Smooth crabgrass DOT_{80} VT1	Smooth crabgrass DOT_{80} VT2	Smooth crabgrass End-of-season control[b] UCR1	Smooth crabgrass End-of-season control[b] VT[d]	Goosegrass DOT_{80} FL3	Goosegrass DOT_{80} VT3	Goosegrass End-of-season control FL3	Goosegrass End-of-season control VT3
	kg ai ha^{-1}		—%—	—No. of days—			—%—		—d—		—%—	
Bensulide	11.2	PRE[e]	0 b[f]	112 a	112 a	84 a	99 a	99 ab	0	14 ab	29	36 b
Ben + oxad[g]	6.72 + 1.68	PRE	23 a	78.9 b	109 ab	84 a	95 a	92 ab	0	40 a	34	86 a
Methiozolin	0.125	PRE	1 b	7.11 c	38.4 d	58 b	44 b	52 d	0	0 b	33	29 b
Methiozolin	0.250	PRE	2 b	60.5 b	109 ab	79 a	91 a	83 ab	0	14 ab	44	35 b
Methiozolin	0.500	PRE	1 b	112 a	112 a	84 a	99 a	98 ab	0	42 a	33	86 a
Methiozolin	0.250	DPRE	2 b	0 c	80.1 bc	73 b	32 b	55 cd	0	15 ab	22	42 ab
Methiozolin	0.500	DPRE	3 b	0 c	111 ab	84 a	33 b	74 bc	0	45 a	16	70 ab
Methiozolin	0.500	EPOST	1 b	0 c	64.7 cd	33 c	22 b	43 d	0	15 ab	25	44 ab

[a]Weed control DOT_{80} were calculated assuming linear trends in changes to weed control between bi-weekly assessment dates.
[b]End-of-season weed control data were derived via grid-intersect counts.
[c]Treatment initiation timings were the standard preemergence (PRE) for a given location, a delayed preemergence made when germination is expected, but emergence has not occurred (DPRE), and an early postemergence timings made when cotyledons, but not tillering plants, could be found in turf (EPOST).
[d]The end-of-season control data for VT1 and VT2 were pooled.
[e]Bensulide alone and bensulide plus oxadiazon treatments were applied PRE and 6 wk after the initial application.
[f]Different letters following means indicate significant differences between means within a given trial site.
[g]Abbreviation: Ben + oxad, bensulide plus oxadiazon.

initiated methiozolin applied at 500 g ha^{-1} controlled smooth crabgrass 52%, 55%, and 43%, respectively at the conclusion of the trials at VT. Similar to results at VT, at the conclusion of the trial at UCR1, preemergence-initiated methiozolin applied at 250 and 500 g ha^{-1}, bensulide alone, and bensulide plus oxadiazon controlled smooth crabgrass greater than 80% (Table 6). However, dissimilar to the trials conducted at VT, all other treatments controlled smooth crabgrass similarly and less than 44%.

These data indicate methiozolin cannot control smooth crabgrass in a biweekly application program at 500 g ha^{-1} or less throughout the growing season if applications are not initiated at preemergence timings. Although methiozolin reduced smooth crabgrass biomass 90% when applied preemergence at approximately 120 g ha^{-1} in greenhouse rate-response studies (Table 4), methiozolin applied biweekly at 125 g ha^{-1} did not acceptably control smooth crabgrass throughout the growing season (Table 6). This lack of control suggests that methiozolin dissipates rapidly and biweekly applications are inadequate for season-long smooth crabgrass control at rates less than 250 g ha^{-1}.

The effect of trial-by-treatment on goosegrass DOT_{80} and goosegrass control at the conclusion of the trial was significant ($P < 0.001$); therefore, data are presented separately. These interactions were due to a lack of treatment effect at FL3. At FL3, no treatment controlled goosegrass greater than 80% throughout the duration of the trial, and at the conclusion of the trial, the treatment main effect was insignificant ($P > 0.05$) (Table 6). At VT3, the treatment main effect was significant ($P < 0.001$), but highly variable goosegrass density resulted in excess residual error and little statistically significant treatment difference. Attempts were made to discern the influence of annual bluegrass population density on goosegrass control, and a linear regression of annual bluegrass cover against goosegrass control from all methiozolin-treated plots explained 49% of the variability (data not shown). As our treatments were applied during warm summer months to target summer annual grasses, methiozolin controlled existing annual bluegrass rapidly, leaving areas devoid of turf as in other studies (Venner et al. 2023). In general, as initial annual bluegrass (*Poa annua* L.) coverage increased, goosegrass control with methiozolin-containing treatments at the conclusion of the trial decreased (data not shown).

At VT3, preemergence and DPRE-initiated methiozolin applied at 500 g ha^{-1}, and bensulide plus oxadiazon provided the highest goosegrass DOT_{80} values (Table 6). At the conclusion of the trial, preemergence-initiated methiozolin applied at 500 g ha^{-1}, and bensulide plus oxadiazon were the only treatments that controlled goosegrass greater than 80%. Methiozolin treatments applied at 250 g ha^{-1} or less controlled goosegrass less than preemergence-initiated methiozolin treatments applied at 500 g ha^{-1} and bensulide plus oxadiazon regardless of application timing. These data indicate that methiozolin cannot control goosegrass greater than 80% when applied in a biweekly program at less than 500 g ha^{-1}. Additionally, no methiozolin treatment program controlled goosegrass greater than 80% at the conclusion of the trial when applied at rates less than the maximum yearly use rate for golf course putting greens (2,500 g ha^{-1}).

Based on the results of these studies, methiozolin has the potential to control smooth crabgrass. However, 10 biweekly preemergence-initiated methiozolin applications at 250 g ha^{-1} was the only methiozolin program that effectively controlled smooth crabgrass throughout the growing season while not exceeding the maximum annual methiozolin use rate for putting greens. Conversely, these results indicate methiozolin cannot effectively control goosegrass at use rates below the yearly maximum allowable rate when applied biweekly throughout the growing season. Field results were inconsistent with greenhouse results, in which goosegrass was more sensitive to preemergence-applied methiozolin than smooth crabgrass. Susceptibility of these weed species to postemergence-applied methiozolin, in conjunction with methiozolin chemical properties may offer explanation for these disparate results. Goosegrass and crabgrass (*Digitaria* spp.) can germinate from depths of 6 to 8 cm (Benvenuti et al. 2001; Chauhan and Johnson 2008; Hoyle et al. 2013). Methiozolin does not move below 2 cm deep within normal putting green soils (Flessner et al. 2015), and methiozolin's water solubility (3.4 mg L^{-1}) and logK_{ow} value (3.9) indicates that it has a high capacity for retention in the upper portion of the soil (Koo et al. 2010). A portion of goosegrass and smooth crabgrass plants may germinate below methiozolin. For methiozolin to control these deeper emerging plants, the methiozolin soil concentration must be sufficient to control these weeds via foliar activity. Results from the greenhouse study indicate that smooth crabgrass is more susceptible to postemergence-applied methiozolin than goosegrass, which may partially explain the disparate results between the greenhouse and field studies. Future research should evaluate this potential basis for selectivity in the field.

Based on the results of these studies, we can conclude that, as growth stage increases, more methiozolin is required to control smooth crabgrass and goosegrass, with goosegrass being more sensitive to preemergence-applied methiozolin than smooth crabgrass and smooth crabgrass being more sensitive to postemergence-applied methiozolin than goosegrass. Single preemergence methiozolin applications made at 500 g ha^{-1} are insufficient to control smooth crabgrass and goosegrass throughout the duration of the growing season. Hybrid bermudagrass and creeping bentgrass putting greens are highly tolerant of biweekly methiozolin application programs applied at rates of 500 g ha^{-1} or less. These frequent methiozolin application programs have potential to control smooth crabgrass and goosegrass greater than 80% throughout the duration of the growing season. However, maximum yearly methiozolin use rate restrictions limit methiozolin's potential to control goosegrass throughout the growing season.

Practical Implications

Although the methiozolin label suggests the product controls goosegrass and smooth crabgrass, instructions regarding rates or application timings are not listed. These data confirm methiozolin's preemergence efficacy on goosegrass and smooth crabgrass but suggest that frequent application strategies are needed to maintain commercially acceptable weed control for a significant portion of the growing season. This study offers new information regarding safety of applying methiozolin to creeping bentgrass and hybrid bermudagrass putting green turf during summer in southern climates. Frequent methiozolin applications can offer season-long smooth crabgrass control without exceeding annual use restrictions when treatments are initiated preemergence. These data do not support methiozolin for season-long goosegrass control without exceeding maximum yearly use rates. Future research should evaluate tank mixtures or rotational programs that utilize methiozolin with other herbicides for season-long goosegrass control on putting greens.

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