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Long-Term Roughstalk Bluegrass Control in Creeping Bentgrass Fairways

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Methiozolin is an isoxazoline herbicide that selectively controls annual bluegrass in cool-season turf and may control roughstalk bluegrass, another weedy *Poa* species that is problematic in many turfgrass systems. However, the majority of research to date is limited to evaluating methiozolin efficacy for annual bluegrass control in creeping bentgrass putting greens. Research was conducted comparing various application regimes of methiozolin and other herbicides for long-term roughstalk bluegrass control in creeping bentgrass golf fairways. Methiozolin-only treatments did not injure creeping bentgrass or reduce normalized difference vegetative index (NDVI) at 2 golf course locations based on 20 evaluation dates over a 2.5-yr period. The 2.5-yr average turf quality generally declined as roughstalk bluegrass control increased due to transient turf cover loss. At 1 yr after last treatment, methiozolin at 1500 g ai ha^{-1} applied four times in fall reduced roughstalk bluegrass cover 85%. This was equivalent to methiozolin at 1000 g ha^{-1} applied four times in fall, but greater than low rates of methiozolin applied four times in spring or twice in fall and spring. Amicarbazone, primisulfuron, and bispyribac-sodium alone either did not effectively reduce roughstalk bluegrass cover, or did so at the expense of increased creeping bentgrass injury. Results of this study suggest that methiozolin alone or tank-mixed with amicarbazone or primisulfuron is an effective long-term approach for selectively controlling roughstalk bluegrass in creeping bentgrass.
Nomenclature: Amicarbazone; bispyribac-sodium; methiozolin; 5-(2,6-difluorobenzyl)oxymethyl-5-methyl-3-(3-methylthiophen-2-yl)-1; 2-isoxazoline; code names: EK-5229, SJK-03, and MRC-01, prmisulfuron, annual bluegrass, *Poa annua* L.; roughstalk bluegrass, *Poa trivialis* L.; creeping bentgrass, *Agrostis stolonifera* L.
Key words: Creeping bentgrass injury, grid count, line-intersect sampling, long-term weed control normalized difference vegetative index, roughstalk bluegrass control, turfgrass quality.

Roughstalk bluegrass is a light-green perennial grassy weed that forms distinct patches in turfgrass stands due to its stoloniferous growth habit and color and textural differences (Beard 1973). Roughstalk bluegrass looks similar to annual bluegrass and is generally more problematic in higher-cut turf (lawns, fairways, athletic fields). Annual bluegrass is a nuisance in all turfgrass situations, but is most problematic on golf putting greens (Bell et al. 1999). Roughstalk bluegrass can outcompete major cool-season turfgrasses during spring and fall, but is subject to stress-related injury during hot/dry summers and cold winters, which decreases aesthetics and increases management costs (Carrow and Duncan 1998; Christians 2004). These characteristics make roughstalk bluegrass a troublesome weed on golf courses, athletic fields, and home lawns. Selective control options for roughstalk bluegrass in cool-season turfgrass are limited.

Although cultural practices and plant growth regulators can be used to suppress roughstalk bluegrass (Thompson et al. 2016), effective and long-term control relies primarily on herbicides. Postemergence roughstalk bluegrass control in cool-season turf is limited to spot treatment with nonselective herbicides, such as glyphosate, followed by (fb) reseeding with desired turfgrasses (Liskey 1999; Morton et al. 2007). Mueller-Warrant (1990) reported late-winter to late-spring applications of fenoxaprop controlled roughstalk bluegrass in perennial ryegrass, but efficacy varied among seasons, and applications made before winter were found to be ineffective. Late-spring applications provided better roughstalk bluegrass control, but increased injury to perennial ryegrass (Mueller-Warrant 1990). Mueller-Warrant (1990) found that the fenoxaprop rates that were needed to control roughstalk bluegrass in perennial ryegrass were

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high and potentially injurious to creeping bentgrass as per the herbicide label (Anonymous 2011). This suggests that the usefulness of fenoxaprop in creeping bentgrass golf fairways is limited.

Morton et al. (2007) evaluated bispyribac-sodium and sulfosulfuron for roughstalk bluegrass control in creeping bentgrass. Turfgrass and weed response were variable and inconclusive due to differences in cultivar sensitivity, application timings, and temperatures across years and locations. Increased efficacy of bispyribac-sodium and sulfosulfuron in response to warmer temperatures has been reported by several researchers (Lycan and Hart 2006; McCullough and Hart 2006). Thompson et al. (2016) evaluated bispyribac-sodium, paclobutrazol, and tank-mixtures of amicarbazone and mesotrione for roughstalk bluegrass control and noted that only bispyribac-sodium controlled roughstalk bluegrass. Summer applications of bispyribac-sodium at 74 g ai ha^{-1} applied three times at 2-wk intervals controlled roughstalk bluegrass 14% to 90%, depending on location, when assessed 3 to 4 months after initial treatment (Thompson et al. 2016). In lawn-height turf (~7.6 cm), McNulty and Askew (2011) reported 90% roughstalk bluegrass control with sequential applications of bispyribac-sodium at 74 g ha^{-1} 4 wk after treatment (WAT), but no control was evident 1 yr later.

Although not labeled for use in turf, primisulfuron at 26.3 g ha^{-1} was reported to control roughstalk bluegrass 83% at 3 WAT (Post et al. 2013). Landry et al. (2011) reported better control (70%) of annual and roughstalk bluegrass with amicarbazone than with bispyribac-sodium and sulfosulfuron. However, amicarbazone at 0.5 kg ha^{-1} injured creeping bentgrass 65% and reduced stand density 45% 3 WAT. By 6 WAT, turf injury was less than 20% in response to all rates of amicarbazone used in the experiment.

Methiozolin is a recent isoxazoline herbicide developed by Moghu Research Center (Yuseong, Daejeon, South Korea) for controlling annual bluegrass on putting greens (Koo et al. 2014). Researchers in South Korea (Hong and Tae 2013; Koo et al. 2014) and the United States (Askew and McNulty 2014; McCullough et al. 2013) have reported that methiozolin is safe for use in all major cool- and warm-season turfgrass species. Although little is known about methiozolin efficacy for roughstalk bluegrass control in fairway-height turf (~1.3 cm), preliminary research at Virginia Tech and in South Korea has shown that methiozolin has a promise for roughstalk bluegrass control (McNulty and Askew 2011). Post et al. (2013) reported that methiozolin tank-mixed with primisulfuron effectively controlled annual bluegrass and roughstalk bluegrass. Methiozolin, at 1,000 g ha^{-1} applied three times in fall and spring, controlled roughstalk bluegrass >90% without injuring Kentucky bluegrass over a 3-yr period at Pine Ridge Country Club in South Korea (SJ Koo, personal communication).

Limited research is available on application timings and rates of methiozolin, alone or tank-mixed with currently available herbicides, for long-term roughstalk bluegrass control in creeping bentgrass turf managed at heights typical of golf fairways or athletic fields. In a multiyear study, McCullough and Hart (2011) found that sequential summer applications of bispyribac-sodium and sulfosulfuron suppressed roughstalk bluegrass cover in a creeping bentgrass fairway. However, cover suppression was apparent only during months of treatment application, and roughstalk bluegrass regrowth in fall following sequential summer applications of bispyribac-sodium and sulfosulfuron resulted in no roughstalk bluegrass cover reduction 10 months after the last treatment of a 2-yr application program. To our knowledge, this is the only peer-reviewed report of long-term roughstalk bluegrass control. Therefore, field trials were conducted at Virginia Tech to evaluate creeping bentgrass injury, cover, and normalized difference vegetative index (NDVI); roughstalk bluegrass control, cover, and NDVI; and overall turfgrass NDVI and quality following applications of several herbicides and tank-mixtures at different timings over a 2.5-yr period.

Materials and Methods

Field trials were initiated on October 22, 2013, on creeping bentgrass cv. 'L-93' fairways at the Pete Dye River Course of Virginia Tech (PDRC) in Radford, Virginia, and the Highland Course of Primland Resort (HCPR) in Meadows of Dan, Virginia. The creeping bentgrass fairway at PDRC was maintained between 13 and 17 mm, and that at HCPR was maintained at 10 mm. The soil at PDRC was a Wheeling sandy loam (fine-loamy, mixed, active, mesic Ultic Hapludalfs) with 20% sand, 30% silt, 50% clay, pH of 6.2, and 6% (w/w) organic matter, and the soil at HCPR was an Evard-Cowee complex with 45% sand, 30% silt, 25% clay, pH of 6.5, and 6% (w/w) organic matter. Standard cultural practices for golf course fairway

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maintenance were utilized at both locations. Although turfgrass management practices at both locations were aimed at providing good growing conditions for creeping bentgrass fairways, the overall intensity of management operations at the resort-level golf course in Meadows of Dan was much higher than that at Virginia Tech's golf course in Radford.

The experiments at each location were arranged in a randomized complete block design with three replications. Plot sizes at PDRC and HCPR were 1.8- by 1.8-m and 1.8- by 6.1-m, respectively. The complete list of herbicide treatments and application regimes is summarized in Table 1. Treatments also included a nontreated check for comparison. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with TTI11004 nozzles (Teejet Technologies, Springfield, IL 62703), which delivered 281 L ha^{-1} of spray solution at 290 kPa. All herbicide treatments were applied at 2-wk intervals within a given season, and the treatment programs were implemented both spring and fall for two consecutive years. Whenever applicable, methiozolin-only treatments were watered in with 5-mm irrigation before the foliage could dry, because methiozolin activity is dependent on root uptake and acropetal mobility (Koo et al. 2014). After treatment with primisulfuron or amicarbazone alone or tank-mixed with methiozolin, the trial area was kept irrigation-free for at least 12 hr. When methiozolin and bispyribac-sodium were sprayed at the same application timing, methiozolin-only treatments were applied and watered in first followed by bispyribac-sodium application.

Data were collected from each site on a biweekly interval in fall and spring for a total of 20 evaluations over the trial duration. Data collected included visually-estimated and line-intersect cover assessments and visually-estimated injury assessments for creeping bentgrass and control assessments for roughstalk bluegrass. Visual estimations of injury and control were made on a 0% to 100% scale based on a reduction in healthy, green tissue compared with nontreated areas, where 0% was no injury, 30% was maximum acceptable injury, and 100% was complete loss of all green tissue and death of plants (Frans et al. 1986). Because roughstalk bluegrass becomes more conspicuous in spring, both line-intersect and visual estimations were used to assess plant cover. Plant cover was assessed with the line-intersect method on the entire plot at 81 intersections per square meter in each of the three spring seasons during the trial duration.

Overall turf quality data were also assessed at each rating date on a 1 to 9 scale, where 9 was ideal turf quality, 6 was minimally acceptable turf quality, and 1 was a complete loss of green turf. Turf NDVI was collected at all rating dates using a multispectral analyzer (Crop Circle™ Model ACS-210, Holland Scientific Inc., 6001 South 58th Street, Lincoln, NE 68516). In addition to whole-plot assessment, NDVI data were also collected separately for creeping bentgrass and roughstalk bluegrass by collecting spectral reflectance data on separate 4.91-cm^2 areas of species of interest. Separate NDVI ratings were collected for different species with a hand-held spectroradiometer (Spectral Evolution PSR-1100, Spectral Evolution, 1 Canal St, Lawrence, MA 01840).

The average response of all 20 evaluation dates over the 2.5-yr trial duration and the final response at 1 yr after last treatment (YALT) were analyzed separately for each response. Data for each response variable were tested for normality using PROC UNIVARIATE and Shapiro-Wilk statistic in SAS software (version 9.2, SAS Institute, 100 SAS Campus Drive, Cary, NC 27513-2414), and homogeneity of variance was confirmed by visually inspecting plotted residuals and other metrics using the DIAGNOSTIC option of PROC PLOT in SAS. Homogeneity of variance was further assessed using Levene's test where one-way ANOVAs for main effects or all possible combinations of factorial levels were tested using the HOVTEST WELCH option in the MEANS statement of PROC GLM in SAS. When needed, data were log or arcsin square-root transformed to meet the assumptions of ANOVA. In cases where transformation was needed, data were back-transformed for presentation clarity. A similar approach for determining data normality and homogeneity of variance to meet assumptions of ANOVA has also recently been used by other researchers (Brewer et al. 2016; Rana and Askew 2016). All measured responses were subjected to a combined ANOVA using PROC GLM in SAS with the sum of squares partitioned to reflect the effects of the block, and also trial/location, herbicide program, and their interactions. Main effects and interactions were tested using mean square error associated with the random variable interaction (McIntosh 1983). Appropriate means were separated using Fisher's protected LSD at 5% level of significance. To test the correlation of visually estimated plant cover with cover evaluated using the line-intersect method, plant cover data were also subjected to PROC CORR in

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Table 1. List of herbicide treatments and application programs used in the study to evaluate long-term roughstalk bluegrass control in creeping bentgrass golf fairways at Highland Course of Primland Resort in Meadows of Dan, VA, and Pete Dye River Course of Virginia Tech in Radford, VA.[a]

Herbicide treatments[b]						
Common Name	Trade/code name	Manufacturer	Application rate	Fall apps yr^{-1} ×2[c]	Spring apps yr^{-1} ×2[c]	Application timing
			— g ai ha^{-1} —			
Methiozolin	MRC-01 25 EC	Moghu Research Center, Daejeon, South Korea	1,000	4	0	F 13, F 14
Methiozolin	MRC-01 25 EC	Moghu Research Center	1,500	4	0	F 13, F 14
Methiozolin	MRC-01 25 EC	Moghu Research Center	1,000	0	4	S 13, S 14
Methiozolin	MRC-01 25 EC	Moghu Research Center	1,500	0	4	S 13, S 14
Methiozolin	MRC-01 25 EC	Moghu Research Center	1,000	2	2	F 13 fb S 14, F 14 fb S 15
Methiozolin	MRC-01 25 EC	Moghu Research Center	1,500	2	2	F 13 fb S 14, F 14 fb S 15
Amicarbazone	Xonerate® 70 WDG	Arysta LifeScience North America, Cary, NC	98.0	0	2	S 14, S 15
Bispryibac-sodium	Velocity® 17.6 SG	Valent U.S.A Corporation, Walnut Creek, CA	24.7	2	2	F 13 fb S 14, F 14 fb S 15
Primisulfuron	Beacon® 75% WDG	Syngenta Crop Protection, Greensboro, NC	26.3	0	2	S 14, S 15
M fb M+ P	MRC-01 + Beacon®	Moghu Research Center + Syngenta Crop Protection	1,000 fb 1,000 + 26.3	2	2	F 13 fb S 14, F 14 fb S 15
M fb M + A	MRC-01 + Xonerate®	Moghu Research Center + Arysta LifeScience North America	1,000 fb 1,000 + 98.0	2	2	F 13 fb S 14, F 14 fb S 15

[a] Abbreviations: 13, year 2013; 14, year 2014; A, amicarbazone; app, application; F, fall; fb, followed by; M, methiozolin; P, primisulfuron; S, spring.

[b] All treatments were applied with a CO_2-pressurized backpack sprayer equipped with TTI11004 nozzles, which delivered 281 L ha^{-1} of spray solution at 290 kPa. Whenever applicable, methiozolin-only treatments were watered in with 5 mm of irrigation before the foliage could dry, because methiozolin activity is dependent on root uptake and acropetal mobility (Koo et al. 2014). When tank-mixed with primisulfuron or amicarbazone, the trial area was kept irrigation-free for at least 12 hr. When methiozolin and bispyribac-sodium were sprayed at the same application timing, methiozolin-only treatments were applied and watered in first followed by bispyribac-sodium application.

[c] The symbol ×*2* after *fall* or *spring app* yr^{-1} indicates that the given herbicide application was repeated the following season or application timing for two consecutive years, for a total of eight applications for methiozolin-containing and bispyribac-sodium treatments and four applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals.

SAS to determine the Pearson's correlation coefficient among the two plant cover assessment methods used in the study.

Results and Discussion

When averaged over all plots, creeping bentgrass initial cover was 93% and 50%, while roughstalk bluegrass initial cover was 7% and 50% at HCPR and PDRC, respectively (data not shown). Creeping bentgrass average cover had a significant trial-by-treatment interaction ($P = 0.0360$); therefore, data were separated by trial (Table 2). At HCPR, methiozolin applied only in fall at either rate, or split between fall and spring at 1,500 g ha^{-1}, yielded an average creeping bentgrass cover of 89% to 90%. This was higher than that of plots treated with amicarbazone and bispyribac-sodium alone (Table 2). At PDRC, all methiozolin-containing treatments produced creeping bentgrass cover of 64% to 78%, which was higher than that of the nontreated check but equivalent to comparison treatments (Table 2). Regardless of trial, none of the spring-only methiozolin treatments produced creeping bentgrass cover greater than non-methiozolin treatments (Table 2).

For each of the three spring assessments, the visual plant cover ratings for creeping bentgrass and roughstalk bluegrass were highly correlated with the quantitative plant cover assessed via the line-intersect method. Regardless of plant species, the Pearson correlation coefficient between visual and quantitative cover assessments was ≥ 0.93 (data not shown); this is consistent with other peer-reviewed research (Elmore et al. 2013; Gannon et al. 2015; Hoyle et al. 2013).

At 1 YALT, creeping bentgrass cover (evaluated with the line-intersect method) had a significant trial-by-treatment interaction ($P = 0.0043$); therefore, data were separated by trials (Table 2). All methiozolin-containing treatments maintained creeping bentgrass cover ≥81% at HCPR and ≥77% at PDRC, higher levels than those of the nontreated checks (Table 2). The inherent high creeping bentgrass cover with little to no injury observed in the majority of the treatments may explain the lack of treatment differences at HCPR and the significant trial-by-treatment interaction for creeping bentgrass average and 1 YALT cover among the two trial locations (Tables 2 and 3).

Creeping bentgrass injury had a significant trial-by-treatment interaction ($P < 0.0001$); therefore, injury data were separated by trials (Table 3). Methiozolin-only treatments did not injure creeping bentgrass regardless of application rate and timing (Table 3). Hoisington et al. (2014) reported that methiozolin rates of 500 to 2,600 g ha^{-1} reduced creeping bentgrass growth by 50%, and rates of 600 to 4,500 g ha^{-1} caused 25% turf injury averaged over eight creeping bentgrass cultivars, depending on location and evaluation timing. However, the Hoisington et al. (2014) study did not include creeping bentgrass cv. 'L-93', which was used in the current study. In addition, Hoisington et al. (2014) made methiozolin applications 7 and 12 wk after seeding creeping bentgrass cultivars in the greenhouse, while in our study, field applications were made on a well-established creeping bentgrass fairway. Other researchers have reported minimal injury to greens-height creeping bentgrass cv. 'Pencross' in response to sequential methiozolin applications (Brosnan et al. 2013; Xiong et al. 2015). Methiozolin has also been reported safe for 110 varieties of Kentucky bluegrass, another preferred cool-season turfgrass for golf fairways and athletic fields, at rates needed to control annual bluegrass and other winter annual weeds (Rana and Askew 2016).

Although only primisulfuron- and bispyribac-sodium-containing treatments injured creeping bentgrass in both trials, the possible source of the trial-by-treatment interaction was the higher injury observed following bispyribac-sodium applications at PDRC (Table 3). Average creeping bentgrass injury following bispyribac-sodium applied at 24.7 g ha^{-1} was 20% at PDRC, but was only 12% at HCPR (Table 3). Peak creeping bentgrass injury following fall applications of bispyribac-sodium was 78% at PDRC, but was 46% at HCPR (data not shown). Higher creeping bentgrass injury at PDRC than at HCPR cannot be definitively explained, but the inconsistency may be due to differences in turf management between sites. McCullough and Hart (2006) reported injury to creeping bentgrass cv. 'L-93' in response to bispyribac-sodium when grown in growth chambers. More injury was observed at 10 C than at 20 and 30 C. Average monthly temperatures between HCPR and PDRC did not vary by more than 3 C in any month over the 2.5-yr study duration (data not shown). The differences in creeping bentgrass response to bisypyribac-sodium across trials could be an artifact of overall greater management intensity at HCPR than at PDRC. For example, mowing height was at least 3 mm lower at HCPR than it was at PDRC.

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Table 2. Average green cover observed in 20 evaluations of creeping bentgrass and roughstalk bluegrass over a 2.5-yr period and at 1 yr after last treatment (YALT), where fall and/or spring herbicide programs were applied for two consecutive years.[a]

Herbicide program[b]				2.5-yr average cover[c]				Cover 1 YALT[c]		
				AGSST		POATR		AGSST		
Fall	Apps yr^{-1}	Spring	Apps yr^{-1}	HCPR	PDRC	HCPR	PDRC	HCPR	PDRC	POATR
				%						
NTC	-	-	-	85	51	12	43	70	62	33
M low	4	M low	0	89	72	5	10	90	91	10
M high	4	M high	0	89	67	2	7	95	96	5
M low	0	M low	4	87	67	7	27	90	78	16
M high	0	M high	4	87	68	7	26	90	86	12
M low	2	M low	2	86	64	7	20	81	77	21
M high	2	M high	2	90	78	4	8	87	95	9
M low	2	M low + P	2 + 2	87	66	3	7	94	87	10
M low	2	M low + A	2 + 2	90	77	5	12	91	88	11
P	0	P	2	86	62	7	27	85	52	26
A	0	A	2	81	61	10	34	72	55	37
B	2	B	2	81	61	7	16	72	80	16
			$LSD_{0.05}$	7	13	2	11	10	15	8

[a] Abbreviations: A, amicarbazone at 98 g ai ha^{-1}; AGSST, *Agrostis stolonifera* L. (creeping bentgrass); B, bispyribac-sodium at 24.7 g ha^{-1}; LSD, Fisher's protected LSD at 5% level of significance; M low, methiozolin at 1,000 g ha^{-1}; M high, methiozolin at 1,500 g ha^{-1}; Apps yr^{-1}, number of applications per year; HCPR, creeping bentgrass fairway site at Highland Course of Primland Resort in Meadows of Dan, VA; NTC, nontreated check; P, primisulfuron at 26.3 g ha^{-1}; PDRC, creeping bentgrass fairway site at Pete Dye River Course of Virginia Tech in Radford, VA; POATR, *Poa trivialis* L. (roughstalk bluegrass); YALT, year after last treatment.

[b] For both studies (HCPR and PDRC), herbicide programs were applied in two consecutive years for a total of eight applications for methiozolin-containing and bispyribac-sodium treatments and four applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals.

[c] Plant cover was visually estimated by species as percent green tissue on a 0% to 100% scale and averaged over 20 evaluations made during a 2.5-yr period. Cover at 1 YALT was based on line-intersect counts where species present at each of 794 and 239 intersects were assessed in 3.34- and 11.1-m^2 plots at HCPR and PDRC, respectively, on April 29, 2016. For both creeping bentgrass and roughstalk bluegrass, 2.5-yr average and 1 YALT cover had a significant trial-by-treatment interaction ($P < 0.05$); therefore, cover data were separated by trials.

Fall applications of bispyribac-sodium at 24.7 g ha^{-1} caused creeping bentgrass greater and more persistent injury than did spring applications (data not shown). Spring applications of bispyribac-sodium at 24.7 g ha^{-1} injured creeping bentgrass ≤15% 2 wk after the second spring application. Higher persistent creeping bentgrass injury in response to fall-applied bispyribac-sodium could be attributed to the fact that the late-fall and winter temperatures during and after treatment were lower than the temperatures in the spring. Higher creeping bentgrass sensitivity to bispyribac-sodium at lower temperatures has been previously reported under growth chamber (McCullough and Hart 2006) and field (Lycan and Hart 2006) conditions.

The highest creeping bentgrass injury from primisulfuron at 26.3 g ha^{-1} alone and tank-mixed with methiozolin applied in spring was 32% 2 wk after the initial spring treatment and 40% 2 wk after the second spring treatment. However, the injury was transient, and creeping bentgrass recovered completely within 4 wk after the second treatment (data not shown). To our knowledge, no peer-reviewed reports have documented primisulfuron injury to creeping bentgrass. Amicarbazone at 98 g ha^{-1} did not injure creeping bentgrass in the current study; however, amicarbazone can cause significant injury to creeping bentgrass under warmer temperatures (McCullough et al. 2010). McCullough et al. (2010) reported creeping bentgrass cv. 'L-93' injury of 4% to 19% at 4 wk and 6% to 44%, depending on location, 6 to 8 wk after sequential fall applications of amicarbazone at 100 g ha^{-1}. However, the same rate of amicarbazone applied in spring injured creeping bentgrass ≤5% 2 to 4 WAT, with complete recovery by 6 to 8 WAT, depending on location (McCullough et al. 2010).

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Table 3. Average creeping bentgrass injury, creeping bentgrass and roughstalk bluegrass normalized difference vegetative index (NDVI), and turf quality following 20 evaluations over a 2.5-yr period and turf quality at 1 yr after last treatment (YALT), where fall and/or spring herbicide programs were applied for two consecutive years.[a]

Herbicide program[b]				Avg. injury[c]		Avg. NDVI[d]			Turf quality[e]			
				AGSST			POATR		2.5-yr avg.		1 YALT	
Fall	Apps yr^{-1}	Spring	Apps yr^{-1}	HCPR	PDRC	AGSST	HCPR	PDRC	HCPR	PDRC	HCPR	PDRC
				—%—		—Scale from 0 to 1—			—Scale from 1 to 9—			
NTC	–	–	–	0	0	0.7036	0.7093	0.7091	6.5	5.7	7.9	6.8
M low	4	M low	0	0	0	0.7038	0.6285	0.6078	6.3	5.5	8.0	7.8
M high	4	M high	0	0	0	0.7069	0.6213	0.6113	6.2	5.1	8.2	8.1
M low	0	M low	4	0	0	0.7079	0.6689	0.7098	6.3	5.8	7.9	7.2
M high	0	M high	4	0	0	0.6942	0.6452	0.6824	6.3	5.9	7.8	7.6
M low	2	M low	2	0	0	0.6960	0.6266	0.6511	6.1	5.3	7.6	7.2
M high	2	M high	2	0	0	0.6987	0.6285	0.6120	6.3	5.4	7.7	8.1
M low	2	M low + P	2 + 2	4	4	0.6833	0.6021	0.5646	5.9	4.2	8.1	7.7
M low	2	M low + A	2 + 2	0	0	0.6993	0.6259	0.6486	6.5	5.5	7.8	7.9
P	0	P	2	8	6	0.6929	0.6345	0.6904	6.3	5.8	7.9	6.6
A	0	A	2	0	0	0.7168	0.6793	0.6628	6.5	5.7	7.4	6.6
B	2	B	2	12	20	0.6807	0.6449	0.6013	6.2	5.0	7.2	7.7
			$LSD_{0.05}$	1	2	0.0157	0.0301	0.0350	0.2	0.5	0.5	0.6

[a] Abbreviations: A, amicarbazone at 98 g ai ha^{-1}; AGSST, *Agrostis stolonifera* L. (creeping bentgrass); B, bispyribac-sodium at 24.7 g ha^{-1}; LSD, Fishers protected LSD at 5% level of significance; M low, methiozolin at 1,000 g ha^{-1}; M high, methiozolin at 1,500 g ha^{-1}; Apps yr^{-1}, number of applications per year; HCPR, creeping bentgrass fairway site at Highland Course of Primland Resort in Meadows of Dan, VA; NDVI, normalized difference vegetative index; NTC, nontreated check; P, primisulfuron at 26.3 g ha^{-1}; PDRC, trial at Pete Dye River Course of Virginia Tech in Radford, VA; POATR, *Poa trivialis* L. (roughstalk bluegrass); YALT, year after last treatment.

[b] For both studies (HCPR and PDRC), herbicide programs were applied in two consecutive years for a total of eight applications for methiozolin-containing and bispyribac-sodium treatments and four applications for primisulfuron and amicarbazone alone. Within a season, all herbicide treatments were applied at 2 wk intervals.

[c] Creeping bentgrass injury was visually estimated as percent reduction in green tissue on a 0% to 100% scale, where 0% indicated no reduction in green tissue and 100% indicated no green tissue. The injury estimates were averaged over 20 evaluations made during a 2.5-yr period. Creeping bentgrass average injury had a significant trial-by-treatment effect ($P < 0.0001$); therefore, injury data were separated by trials.

[d] Creeping bentgrass and roughstalk bluegrass NDVI data were collected using a spectroradiometer (Spectral Evolution PSR-1100) and averaged over 20 evaluations made during a 2.5-yr period. Creeping bentgrass and roughstalk bluegrass average NDVI had a significant trial-by-treatment interaction ($P < 0.05$); therefore, NDVI data were separated by trials. At 1 YALT, the overall plot and species-wise NDVI in treated plots was not different than that of the nontreated checks (data not shown).

[e] Turf quality was assessed on a 1 to 9 scale, where 9 was ideal turf quality, 6 was minimally acceptable turf quality, and 1 was a complete loss of green turf. The 2.5-yr average quality represents turf quality measurements averaged over 20 evaluations made during a 2.5-yr period and the final evaluation made on April 29, 2016. Both average and 1 YALT turf quality measurements had a significant trial-by-treatment interaction ($P < 0.05$); therefore, turf quality data were separated by trial.

Roughstalk bluegrass average cover had a significant trial-by-treatment interaction ($P < 0.0001$); therefore, cover data were separated by trials (Table 2). In all treatments except amicarbazone at 98 g ha^{-1} applied alone at PDRC, roughstalk bluegrass cover was lower than it was in the nontreated check (Table 2). Regardless of trial, treatments containing fall applications of methiozolin reduced roughstalk bluegrass cover more than spring-only applications did, except methiozolin at 1,000 g ha^{-1} applied twice in fall fb twice in spring (Table 2). Plots treated with bispyribac-sodium at 24.7 g ha^{-1} had 7% and 16% average roughstalk bluegrass cover at HCPR and PDRC, respectively, which constituted a 63% and 42% cover reduction compared to the nontreated check (Table 2). However, better roughstalk bluegrass cover reduction with bispyribac-sodium at PDRC came at the expense of higher and

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unacceptable creeping bentgrass injury. This was especially true for fall applications, which injured creeping bentgrass ≥60%, 4 times the injury level caused by the spring applications (data not shown). Bispyribac-sodium efficacy for controlling roughstalk bluegrass in creeping bentgrass has been reported by other researchers, but trends were inconsistent and dependent on creeping bentgrass cultivars, trials, and temperature (McCullough and Hart 2006; McCullough and Hart 2011; Morton et al. 2007; Thompson et al. 2016).

At 1 YALT, roughstalk bluegrass cover had a significant treatment effect ($P = 0.0009$) but no trial-by-treatment interaction ($P = 0.1446$); therefore, data were pooled over trials (Table 2). Methiozolin at 1,500 g ha^{-1} applied only in fall yielded roughstalk bluegrass cover of 5%, which was equivalent to all treatments containing fall applications of methiozolin (9% to 11%), except methiozolin at 1,000 g ha^{-1} applied twice in fall fb twice in spring (Table 2). Methiozolin applied in spring yielded roughstalk bluegrass cover equivalent to fall-only applications of methiozolin at 1,500 g ha^{-1} only when the higher rate was used (Table 2). No other peer-reviewed research has evaluated roughstalk bluegrass response to methiozolin over a period of 2.5 yr and at 1 YALT. At 1 YALT, spring-only applications of methiozolin at 1,000 g ha^{-1} and split applications of bispyribac-sodium had 16% roughstalk bluegrass cover, which was greater than fall-only applications of methiozolin at 1,500 g ha^{-1} but equivalent to the rest of the treatments containing fall applications of methiozolin (Table 2). Over a 3-yr-long study, McCullough and Hart (2011) observed significant roughstalk bluegrass suppression with summer applications of bispyribac-sodium; however, roughstalk bluegrass regrew during fall months, thus long-term control was poor.

Creeping bentgrass 2.5-yr average NDVI had a significant treatment effect ($P = 0.0052$), but no trial-by-treatment interaction ($P = 0.7735$), whereas, roughstalk bluegrass average NDVI had a significant trial-by-treatment interaction ($P = 0.0002$). Therefore, creeping bentgrass NDVI was pooled over trials, but roughstalk bluegrass NDVI was separated by trial (Table 3). Plots treated with bispyribac-sodium and primisulfuron tank-mixed with methiozolin had average creeping bentgrass NDVI of 0.6807 and 0.6833, respectively, which was lower than that of the nontreated check. Lower creeping bentgrass NDVI readings in response to bispyribac-sodium and primisulfuron tank-mixed with methiozolin applications were consistent with creeping bentgrass average injury data (Table 3). All treatments in each trial, except amicarbazone alone at HCPR, resulted in roughstalk bluegrass NDVI values significantly lower than those of the nontreated check (Table 2). In addition, the majority of fall-applied methiozolin treatments that reduced roughstalk bluegrass average cover the most also resulted in lower NDVI compared to spring-only applications of methiozolin (Tables 2 and 3).

Average and 1 YALT turf quality had significant trial-by-treatment interactions ($P < 0.0001$); therefore, data were separated by trials (Table 3). Regardless of trials, the nontreated check was equivalent to the highest turf quality. Comparatively better quality of the nontreated plots was attributed to injured or dying roughstalk bluegrass observed in the treated areas. The majority of treatments at HCPR produced turf quality higher than the minimally-acceptable level of 6.0; however, none of the treatments produced turf quality higher than 5.9 at PDRC. These variations may be due to differences between HCPR and PDRC in management intensity and roughstalk bluegrass density within fairways. Moreover, the majority of plant response evaluations were collected during late fall/early winter or early spring, when turf was either undergoing or recovering from winter dormancy or injury, and control from herbicide treatments was greatest. At 1 YALT, regardless of trial, all treatments had a turf quality ≥6.6, which is higher than the minimally acceptable level of 6.0 (Table 3). At HCPR, all treatments, except amicarbazone and bispyribac-sodium alone yielded turf quality ≥7.7 (Table 3). Although the intensity of management practices at HCPR hindered the ability to better separate treatments for turf quality, 7 out of 11 herbicide treatments at PDRC yielded turf quality ≥7.6 and higher than the nontreated check (Table 3).

Results from this study suggest that fall applications of methiozolin generally control roughstalk bluegrass better than spring-only applications. Methiozolin alone, at the rates evaluated, did not injure creeping bentgrass regardless of application rate or timing. For effective and consistent long-term roughstalk bluegrass control with safety to fairway-height creeping bentgrass, methiozolin at 1,500 g ha^{-1} applied four times in fall or twice in fall fb twice in spring at 2-wk intervals for two consecutive years is effective. When using rate of 1,000 g ha^{-1}, methiozolin should be either applied all in fall or applied twice in fall fb twice in spring with amicarbazone (primisulfuron is not yet registered for use in turf) for two consecutive years. Care should be taken to avoid creeping bentgrass varieties and temperature conditions during and after applications that could result in unacceptable creeping bentgrass injury by amicarbazone. Amicarbazone and primisulfuron alone applied in spring and bispyribac-sodium applied twice in fall fb twice in spring for two consecutive years were either ineffective or inconsistent at selectively and safely controlling roughstalk bluegrass in creeping bentgrass.

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