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Methiozolin and Cumyluron for Preemergence Annual Bluegrass (*Poa annua*) Control on Creeping Bentgrass (*Agrostis stolonifera*) Putting Greens

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Methiozolin and cumyluron are experimental herbicides that are reported to control annual bluegrass PRE or POST; however, no studies have compared these new herbicides to currently-registered herbicides for annual bluegrass control on putting greens over multiple years. Studies were conducted on three Virginia putting greens for 2 yr to compare methiozolin and cumyluron each at two rates to bensulide and bensulide plus oxadiazon at labeled rates for effects on annual bluegrass and creeping bentgrass cover, turf injury, normalized difference vegetative index (NDVI), turf quality, and annual bluegrass seedhead suppression. Methiozolin, cumyluron, bensulide, and bensulide plus oxadiazon did not significantly injure creeping bentgrass putting green turf, reduce quality, or reduce NDVI. Only methiozolin at 500 or 750 g ai ha^{-1} and cumyluron at 8,600 g ai ha^{-1} reduced area under the progress curve (AUPC) for annual bluegrass cover following four treatments over 2 yr applied in spring and fall each year. A concomitant increase in creeping bentgrass cover AUPC was also observed from the three treatments that reduced annual bluegrass cover. Methiozolin also reduced annual bluegrass seedhead cover at least 85% 1 mo after spring treatments and more than all other treatments except cumyluron at 8,600 g ha^{-1} (66%). These studies suggest that single treatments of methiozolin in spring and fall will not rapidly control existing annual bluegrass but can slowly reduce populations over time, presumably by preventing new seedling emergence. Methiozolin and cumyluron appear to be more effective than currently available herbicides bensulide and bensulide plus oxadiazon for PRE annual bluegrass control and seedhead suppression on golf putting greens.
Nomenclature: Bensulide; cumyluron; methiozolin; oxadiazon; annual bluegrass, *Poa annua* L.; creeping bentgrass, *Agrostis stolonifera* L.
Key words: AUPC, NDVI, seedhead suppression, turfgrass quality.

Methiozolin y cumyluron son herbicidas experimentales reportados para el control de *Poa annua* en PRE o POST. Sin embargo, ningún estudio ha comparado a lo largo de múltiples años estos nuevos herbicidas con herbicidas registrados actualmente para el control de *P. annua* en putting greens. Se realizaron estudios en tres putting greens en Virginia durante 2 años, para comparar los efectos de methiozolin y cumyluron, cada uno a dos dosis, con bensulide y bensulide más oxadiazon a dosis de etiqueta, sobre la cobertura de *P. annua* y *Agrostis stolonifera*, el daño en el césped, el índice de diferencia vegetativa normalizada (NDVI), la calidad del césped, y la supresión de inflorescencias de *P. annua*. Methiozolin, cumyluron, bensulide, y bensulide más oxadiazon no dañaron significativamente los putting greens del césped *A. stolonifera*, ni redujeron la calidad o NDVI. Solamente methiozolin a 500 ó 750 g ai ha^{-1} y cumyluron a 8,600 g ai ha^{-1} redujeron el área de progreso de la curva (AUPC) para la cobertura de *P. annua* después de cuatro tratamientos a lo largo de 2 años, aplicados en la primavera y el otoño, cada año. Se observó un crecimiento concomitante en la cobertura AIPC del césped *A. stolonifera* para los tres tratamientos que redujeron la cobertura de *P. annua*. Methiozolin también redujo la cobertura de inflorescencias de *P. annua* al menos 85% 1 mes después de los tratamientos y más que todos los demás tratamiento excepto cumyluron a 8,600 g ha^{-1} (66%). Estos estudios sugieren que un solo tratamiento de methiozolin en la primavera y el otoño no controlará rápidamente *P. annua* existente, pero puede reducir las poblaciones lentamente a lo largo del tiempo, presumiblemente al prevenir la emergencia de nuevas plántulas. Methiozolin y cumyluron parecen ser más efectivos que los herbicidas actualmente disponibles, bensulide y bensulide más oxadiazon, para el control PRE y la supresión de inflorescencias de *P. annua* en putting greens de golf.

Methiozolin [5-(2,6-difluorobenzyl)oxymethyl-5-methyl-3-(3-methylthiophen-2-yl)-1,2-isoxazoline; code names, EK-5229, SJK-03, MRC-01] is a new isoxazoline herbicide under development by Moghu Research Center (Yuseong, Daejeon, Korea) for use on turfgrass in the United States and other

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countries. A derivative of 5-benzyloxymethyl-1,2-isoxazoline compounds patented by Hong et al. (2002), methiozolin was first published by Hwang et al. (2005) and was reported to have rice (*Oryza sativa* L.) selectivity and herbicidal activity on a number of annual weeds. Koo et al. (2013) at Moghu Research Center discovered specificity of methiozolin for annual bluegrass control in turfgrass and started developing the herbicide, primarily for use on golf putting greens in several markets worldwide. Methiozolin was registered for use in Korea turfgrass in March 2010. Research in South Korea and the United States has shown methiozolin to be safe on almost all major turfgrass species used in the United States, including common bermudagrass [*Cynodon dactylon* (L.) Pers.], hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt Davy], seashore Paspalum (*Paspalum vaginatum* Sw.), zoysiagrass (*Zoysia japonica* Steud.), Kentucky bluegrass (*Poa pratensis* L.), tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.], creeping bentgrass, and perennial ryegrass (*Lolium perenne* L.) (Hong and Tae 2013; Koo et al. 2013; McCullough et al. 2013; McNulty and Askew 2011). Methiozolin has controlled annual and roughstalk bluegrass (*Poa trivialis* L.) POST and was safe to creeping bentgrass, perennial ryegrass, Kentucky bluegrass, and tall fescue in Virginia (McNulty and Askew 2011). In Korea, PRE herbicidal activity was noted on annual bluegrass, crabgrass (*Digitaria* spp.), goosegrass [*Eleusine indica* (L.) Gaertn.], and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (Koo et al. 2013). On golf putting greens, fall applications of methiozolin controlled emerged annual bluegrass in both sand- and soil-based putting greens in Texas and Tennessee (Brosnan et al. 2013). In Georgia, POST annual bluegrass control from winter or spring applications were rate-dependent and higher in winter, although only initial annual bluegrass response was measured because ratings were taken only 4 wk after the last treatment (McCullough et al. 2013). Most field research to date has evaluated POST annual bluegrass control from multiple treatments applied in fall at 500 to 1,000 g ai ha^{-1} with subsequent evaluations the following spring or within 1 to 2 mo after the last treatment (Brosnan et al. 2013; McCullough et al. 2013). No studies have evaluated long-term effects of methiozolin on golf putting greens.

Cumyluron is a substituted urea herbicide currently registered in Japan and sold for use on golf putting greens to control annual bluegrass (Calhoun and Hathaway 2009). In a 2003 patent, cumyluron was said to inhibit weed growth in turf at rates between 500 and 30,000 g ha^{-1} (Tomita and Tonaka 2003). In 2006, Marubeni Agrotec Corporation and its subsidiary, Helena Chemical Company, initiated research to explore potential of cumyluron to control annual bluegrass on golf putting greens and fairways in the United States. The first demonstration of cumyluron efficacy for annual bluegrass control in U.S. turf was in research conducted at Michigan State University from 2006 to 2008 (Calhoun and Hathaway 2009). Other researchers also noted significant reduction in annual bluegrass population when evaluated several months or even years after treatment initiation on creeping bentgrass fairways and putting greens (Askew et al. 2009; McCalla et al. 2010). Cumyluron was reviewed by the U.S. EPA in 2012 and was not granted U.S. registration status. In addition, the U.S. EPA listed cumyluron in 2008 as with "suggestive evidence of carcinogenic potential" in a report published late in 2012 (EPA 2012). Following this EPA decision, research interest in cumyluron for U.S. turfgrass decreased, although the product is still marketed in Japan. Golf course superintendents in Japan have noted good PRE control of annual bluegrass and reductions in annual-type populations over time on putting greens (Yuji Kamiya, Maruwa Biochemical Co., LTD., personal communication).

Currently in the United States, only bensulide, dithiopyr, and oxadiazon may be applied to creeping bentgrass putting greens for annual bluegrass control. Bensulide was evaluated for PRE weed control in creeping bentgrass turf in the early 1960s where it was found to control seeded crabgrass on creeping bentgrass putting greens (Bingham and Schmidt 1967). Bensulide, however, was found to accumulate in putting green soil such that 10 kg ha^{-1} were extracted from the top 2.5 cm of soil and nearly 1.0 kg ha^{-1} was extracted below 12 cm deep after four annual applications of 16.8 kg ha^{-1} (Bingham and Schmidt 1967). In other research, bensulide controlled 72 to 77% and 4 to 18% of the annual and perennial phenotype of annual bluegrass, respectively, following 4 yr of treatments at current maximum label-recommend-

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ed rates of 33 kg ha^{-1} yr^{-1} (Callahan and McDonald 1992). Although these rates are twice those found to accumulate soil residues by Bingham and Schmidt (1967), the authors did not observe creeping bentgrass injury after 4 yr of use (Callahan and McDonald 1992). In other work, bensulide applied in fall reduced 'L93' creeping bentgrass putting green cover and reduced creeping bentgrass root mass 20% when applied at 11 kg ha^{-1} (Hart et al. 2004). Although a few studies suggest that high rates of bensulide applied three to four times per year for several successive years can control annual bluegrass, most golf superintendents use the product less frequently or at below the maximum labeled rate due to experience with creeping bentgrass injury or root loss (SD Askew, personal observation). When applied once or twice per year at between 8.0 to 11 kg ha^{-1}, bensulide controls annual bluegrass only 0 to 41% (Callahan and McDonald 1992).

The expected-use pattern of methiozolin on golf putting greens varies by demography but includes a target application rate of 500 to 1,000 g ai ha^{-1} and two to five applications per year for POST control (Moghu 2014). Once existing annual bluegrass is controlled, a proposed "maintenance program" that includes 500 g ai ha^{-1} applied once in spring and once in fall to prevent new seedling recruitment during primary annual bluegrass germination periods is recommended (SJ Koo, personal communication). In the current study, our objective was to determine how methiozolin, applied at recommended PRE rates and timings, compares to other PRE herbicides currently used on golf putting greens in a similar pattern, and to cumyluron, another experimental product with the same intended use for effects on annual bluegrass and creeping bentgrass cover over time, annual bluegrass seedhead suppression, creeping bentgrass injury, and turf quality and normalized difference vegetative index (NDVI).

Materials and Methods

Three field studies were initiated on March 17, 2009 on three golf putting greens in Virginia. One trial was established on the practice putting green at Gypsy Hill Golf Course near Staunton, VA (GH) and two trials were conducted on holes 7 (SW7) and 10 (SW10) at Spotswood Country Club in Harrisonburg, VA. Greens for all three trials were constructed of native soil in 1966, 1961, and 1961 at GH, SW7, and SW10, respectively. At all sites, repeated topdressing with U.S. Golf Association-specification sand over several years has produced a root zone in the upper six inches of 70 to 73% sand, 15 to 18% silt, and 5 to 8% clay. The pH and CEC was 7.1 and 9.6, respectively at GH; 7.0 and 8.8, respectively at SW7; and 7.2 and 10, respectively at SW10. Creeping bentgrass at all three locations was 'Penncross' overseeded in recent years with 'L93' and mown at 3.0 to 3.4 mm. Fertility at all locations was based on soil-test recommendations and administered by the golf course superintendent according to normal maintenance practices. Annual nitrogen (N) fertility was 250, 122, and 122 kg N ha^{-1} at GH, SW7, and SW10, respectively. Annual bluegrass infestation at all three sites was approximately 42% with less than 5% exhibiting the perennial phenotype (La Mantia and Huff 2011). Studies were arranged as randomized complete block designs with three replications. Treatments included cumyluron (HM 9930 450 g ai L^{-1} Flowable, Helena Chemical Company, Collierville, TN) at 6,450 and 8,600 g ai ha^{-1}; methiozolin (MRC-01 250 g ai L^{-1} Emulsifiable Concentrate, Moghu Research Center, Daejeon, South Korea) at 500 and 750 g ai ha^{-1}; bensulide (Bensumec 4LF 480 g ai L^{-1}, PBI Gordon Corporation, Kansas City, MO) at 9,000 g ai ha^{-1}; and a granular product containing bensulide plus oxadiazon (Goosegrass/Crabgrass Control 6.56 G, Anderson's Golf Products, Maumee, OH) at 8,600 and 2,150 g ai ha^{-1}, respectively. Bensulide and bensulide plus oxadiazon represent industry standards because they are the only two herbicides widely marketed for PRE annual bluegrass control on creeping bentgrass putting greens in the United States. These two herbicides were applied at recommended rates in spring and fall per label instruction. Application times for all treatments and at all locations were March 17, 2009, October 9, 2009, March 16, 2010, and October 11, 2010 (Figure 1). Cumyluron rates were equal to and slightly higher than rates expected to be commercialized in the United States when this study was initiated and based on previous research studies conducted in Virginia and on use patterns in Japan (Askew et al. 2009; Calhoun and Hathaway 2009). Methiozolin rates were at and slightly higher than the lowest rates reported by the

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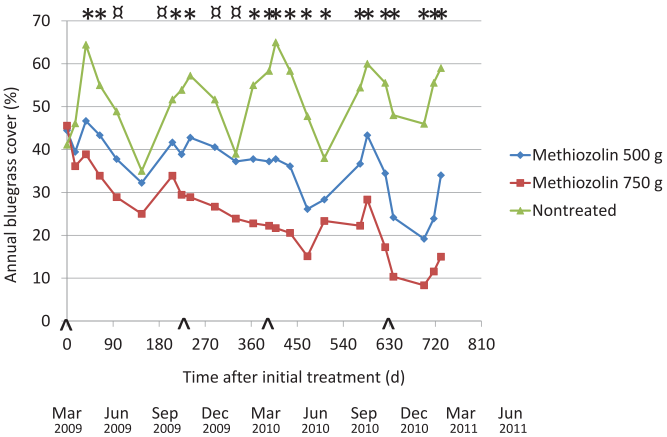

Figure 1. Annual bluegrass cover over time as influenced by two rates of methiozolin applied once each spring and fall over 2 yr and averaged over three golf putting green sites in Virginia. A "*" and a "¤" denote both methiozolin rates and only the high rate, respectively are significantly lower than the nontreated control ($P < 0.05$). Arrows on the X axis indicate treatment times.

manufacturer to have POST activity on annual bluegrass (SJ Koo, personal communication). These trials included the first field applications of methiozolin on U.S. soil and lower use rates were chosen both to ensure turfgrass safety and in keeping with the objective to test PRE annual bluegrass control against competitors. Sprayable herbicides were applied in 280 L ha^{-1} using a CO_2-pressurized sprayer with flat-fan 6502 spray nozzles (Teejet Technologies, Springfield, IL 62703) operated at 4.8 km h^{-1} and 276 kPa in a hooded turf sprayer with a 0.7-m-wide spray swath. Granular herbicides were strewn over plots by shaking granules through a perforated container. Plots were 1.0 m by 2.6 m with a treated area of 0.7 m by 2.0 m and nontreated borders of 0.3 m left and right and 0.6 m front and back. Herbicides were incorporated with 2.5 mm irrigation approximately 6 h after treatment.

Data were collected 24 times over an approximately 2.5 year period and spaced approximately evenly with a bias toward more assessments in spring and late fall (Figure 1). With few exceptions, data assessed at each evaluation time included NDVI using a multispectral analyzer (Crop Circle™ Model ACS-210, Holland Scientific Inc., 6001 South 58th Street, Lincoln, NE 68516), visual and line intersect assessment of annual bluegrass and creeping bentgrass cover, visual estimation of annual bluegrass seedhead suppression and creeping bentgrass injury, and visual estimation of turf quality. Visual assessment of annual bluegrass and creeping bentgrass cover was estimated at all 24 evaluation dates and line intersect cover assessment (150 intersections per plot) was taken once each spring and each fall and at study conclusion. Visual estimations of creeping bentgrass injury were taken at all evaluation dates on a 0 to 100% scale based on an estimation of the reduction in green tissue compared to the nontreated areas where 0 is no injury, 30% is maximum acceptable injury, and 100% is complete loss of all green tissue in plots and apparent death of plants (Frans et al. 1986). Turf quality was assessed at all evaluation dates and based on a 1 to 9 scale where 9 is ideal turf quality, 6 is minimally acceptable turf quality, and 1 is complete loss of green turf. Due to equipment unavailability, NDVI was assessed on 16 of the 24 evaluation dates. The multispectral analyzer was oriented to scan an area 45 cm wide and across the 2.0-m treated length of each plot and recorded approximately 30 measurements per plot, which were averaged. At GH, putting greens did not receive seedhead suppression chemicals, and it was possible to evaluate influence of treatments on annual bluegrass seedhead density in 2 yr at that location. Percent seedhead cover of annual bluegrass in each plot was visually estimated at 38 and 31 d after spring treatment in 2009 and 2010, respectively, and based on a percentage cover of visible seedheads on existing annual bluegrass in the plot.

Creeping bentgrass injury and annual bluegrass seedhead suppression data from the nontreated check were deleted to stabilize variance. To control for variance structure in repeated measures over time, data were transformed to the area under the progress curve (AUPC) (Askew et al. 2013). This type of data transformation is often used for summary of data over longer time periods or where variability in measured responses is periodic (e.g., disease incidence) (Campbell and Madden 1990). The area under the resulting curves was calculated by the Equation 1:

$$AUPC = \sum_{i=1}^{n-1} [(y_1 + y_{i+1})/2](t_{i+1} - t_i) \qquad [1]$$

where y_i is response variable y at the ith observation, t_i is days after initial application at the ith

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observation, and n is the number of observations. Response variables (y) included annual bluegrass cover, annual bluegrass injury, creeping bentgrass cover, NDVI, and turfgrass quality. The AUPC was calculated for each plot, and resulting transformations were determined to be normal using the NORMAL option in PROC UNIVARIATE and Shapiro-Wilk statistic. Data were subjected to ANOVA in SAS® 9.1 with sums of squares partitioned to reflect effects of treatment and locations, which were considered random. Main effects and interactions were tested using mean square error associated with the random variable interaction (McIntosh 1983). Appropriate means were separated with Fisher's Protected LSD test at P = 0.05. The same procedures were used for data analyzed separately by date where AUPC transformation was not required.

Results and Discussion

Annual Bluegrass Response. Annual bluegrass seedhead suppression was assessed only at GH in spring 2009 and 2010 because both SW7 and SW10 were treated with mefluidide in a program to prevent seedhead development. The effect of treatment was significant ($P < 0.001$) but the year by treatment interaction was not significant ($P = 0.1468$). Data were averaged over the 2 yr for presentation (Table 1). Bensulide did not significantly suppress seedhead cover and bensulide plus oxadiazon suppressed seedheads 43%. Cumyluron suppressed seedheads 33 and 66% when applied at 6,450 and 8,600 g ha^{-1}, respectively, and was not different than bensulide plus oxadiazon. Methiozolin suppressed seedheads 85 to 87% depending on rate and more than all treatments except the high rate of cumyluron (Table 1). Only one peer-reviewed study has reported seedhead suppression with methiozolin (Koo et al. 2013). In that study, annual bluegrass plants were transplanted from a Kentucky bluegrass fairway and maintained at fairway height in greenhouse pots. Methiozolin applied at 500 to 2,000 g ha^{-1} reduced annual bluegrass panicle numbers 42 to 81% in a curvilinear response (Koo et al. 2013). In Virginia, methiozolin applied to 4-cm perennial ryegrass turf increased annual bluegrass seedhead suppression 6% for each 100 g ha^{-1} increase in rate when assessed 4 wk after application (McNulty and Askew 2011). These studies in Korea and Virginia suggest that an asymptote for seedhead suppression is reached between methiozolin rates of 1,000 and 2,000 g ai ha^{-1} when applied to fairway- or lawn-height turf. To date, no studies have reported methiozolin effects on annual bluegrass seedhead suppression at putting green mowing heights. In the current study, methiozolin at 500 g ha^{-1} suppressed annual bluegrass seedheads on putting greens (Table 1) similar to seedhead suppression levels in fairways or lawns that required 1,000 to 2,000 g ha^{-1} (Koo et al. 2013; McNulty and Askew 2011). In another Virginia study conducted on two golf putting greens spatially separated by 225 km, methiozolin applied at 1,120 g ha^{-1} suppressed annual bluegrass seedheads 65, 85, and 97% when applied 2, 1, and 2 plus 1 mo before assessment, respectively, and it was superior to ethephon plus trinexapac ethyl (Askew and Smith 2012). Thus, methiozolin might control seedheads on putting greens at rates lower than needed on fairways or higher-cut turfgrass.

When averaged over all plots at each location, initial annual bluegrass cover was 41, 41, and 45% at GH, SW7, and SW10, respectively (data not shown). Annual bluegrass cover in the nontreated check fluctuated seasonally, approximately between 35 and 65%, with peaks in late April and early November and troughs in August and January (Figure 1). Methiozolin initially had a subtle impact on annual bluegrass cover, but reduced cover as much as 25% compared to the nontreated check in the first 3 mo after treatment (Figure 1). Methiozolin did not appear to control existing annual bluegrass, but reduced annual bluegrass population expansion in spring and fall (Figure 1), presumably by reducing seedling recruitment via PRE activity. Causality of cover reduction could not be determined due to difficulty in discerning new seedling recruitment from recovering shoots of mature annual bluegrass plants at greens height. The GR_{50} of annual bluegrass treated PRE with methiozolin was reported by Koo et al. (2013) to be 23 g ha^{-1} and the minimum rate needed for complete PRE control was approximately 75 g ha^{-1}. Over 60% of applied methiozolin degrades after 30 d of aerobic exposure to sandy clay loam soil, but degradation, which is primarily microbial, slows after 30 d, and over 15% of applied herbicide remains after 120 d (Hwang et al. 2013). Thus, methiozolin is rapidly degraded compared to other

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Table 1. Effects of several herbicides on spring seedhead suppression averaged over 2 yr at Gypsy Hill Golf Course near Staunton, VA (GH) and area under the progress curve (AUPC) of annual bluegrass cover, creeping bentgrass cover, creeping bentgrass injury, and turf normalized difference vegetative index (NDVI) and quality, based on 16 to 24 measurements over 731 d between March 17, 2009 and March 18, 2011 and averaged over three locations.[a]

		Annual bluegrass		Creeping bentgrass			
Herbicide	Rate	Seedhd. Sup.	Cover	Cover	Injury	NDVI	Quality
	g ai ha^{-1}	%[b]	AUPC[c]				
Bensulide	9,000	5	37,117	35,257	393	532	2,418
Bensulide + Oxadiazon	8,600 + 2,150	43	37,389	34,880	361	531	2,398
Cumyluron	6,450	33	33,150	39,074	379	534	2,431
Cumyluron	8,600	66	29,714	42,759	552	531	2,417
Methiozolin	500	85	26,753	45,728	362	532	2,427
Methiozolin	750	87	17,606	54,933	492	530	2,456
Nontreated check	—	—	38,214	34,188	—	530	2,388
LSD (0.05)	—	25	2,370	2,389	NS	NS	NS

[a] Abbreviations: Seedhd. Sup., Seedhead Suppression; NS, Not Significant.

[b] Annual bluegrass seedhead suppression was visually estimated as a percentage reduction in the amount of seedheads observed on existing annual bluegrass in each plot at 38 and 31 d after spring treatments in 2009 and 2010, respectively at GH only.

[c] AUPC was calculated for respective data from each experimental unit over time from the 24 evaluation times for cover, injury, and quality and 16 evaluation times for NDVI. A cumulative value was created for each experimental unit and subjected to ANOVA and mean separation. By comparison, if annual bluegrass and creeping bentgrass cover were each 50% at every evaluation date, the AUPC would equal 36,550 for both species. If the injury and NDVI values were averaged over the experiment duration, the injury values would be less than 1% and NDVI values would range from 0.72 to 0.73. Both NDVI and quality were assessed on a whole-plot basis and are influenced by both creeping bentgrass and annual bluegrass.

herbicides, with a reported half life of 49 d in a dark, laboratory condition (Hwang et al. 2013), but its specificity for annual bluegrass control is such that PRE control could conceivably last for 2 to 3 mo. At the study conclusion after 2 yr, annual bluegrass cover was 59, 34, and 15% in plots of the nontreated check, methiozolin at 500 g ha^{-1}, and methiozolin at 750 g ha^{-1}, respectively (Figure 1). Annual bluegrass cover from other treatments at the study conclusion was 49, 42, 49, and 56% from cumyluron at 6,450 g ha^{-1}, cumyluron at 8,600 g ha^{-1}, bensulide, and bensulide plus oxadiazon, respectively (data not shown). Both methiozolin rates and cumyluron at 8,600 g ha^{-1} were the only treatments that reduced annual bluegrass cover significantly compared to the nontreated check at study conclusion (data not shown).

The interaction of location by treatment was insignificant for annual bluegrass cover AUPC ($P = 0.0865$) and data were averaged over location (Table 1). Bensulide and bensulide plus oxadiazon did not reduce AUPC for annual bluegrass cover compared to the nontreated check (Table 1). A stepwise reduction in AUPC for annual bluegrass cover was observed in descending order from the following treatments: cumyluron at 6,450 g ha^{-1}, cumyluron at 8,600 g ha^{-1}, methiozolin at 500 g ha^{-1}, and methiozolin at 750 g ha^{-1} (Table 1). These data suggest methiozolin and higher rates of cumyluron can slowly decrease population levels of the annual type of annual bluegrass over a multiyear period when treatments are applied just prior to spring and fall seedling emergence of annual bluegrass.

Turf and Creeping Bentgrass Response. The interaction of location by treatment was insignificant for creeping bentgrass cover AUPC ($P = 0.0962$), so data were pooled over locations for mean separation (Table 1). Trends in creeping bentgrass cover AUPC generally mirrored those of annual bluegrass cover. As annual bluegrass cover AUPC decreased, creeping bentgrass cover AUPC increased, with significant increases for cumyluron and methiozolin but not for bensulide or bensulide plus oxadiazon (Table 1).

Herbicide treatments in this study did not significantly impact creeping bentgrass injury AUPC ($P = 0.1751$), turf quality AUPC ($P = 0.2035$), or NDVI AUPC ($P = 0.2668$) at any location (Table 1). In the case of NDVI, a

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significant location effect occurred ($P < 0.001$) but the location by treatment interaction was not significant ($P = 0.8164$). The location effect on NDVI (data not shown) presumably occurred due to higher annual nitrogen fertility at GH (250 kg N ha^{-1}) compared to SW7 and SW10 (122 kg N ha^{-1}). It is not surprising that none of the herbicides used in this study significantly injured putting green turf because the rates used have been reported safe to similar turf in previous research (Calhoun and Hathaway 2009; Callahan and McDonald 1992; Koo et al. 2013).

These data suggest that single treatments of methiozolin in spring and fall will not rapidly control existing annual bluegrass, but might slowly reduce populations over time, presumably by preventing new seedling emergence. Methiozolin also suppresses annual bluegrass seedheads on golf putting greens in spring. Methiozolin and cumyluron appear to be more effective than currently available herbicides bensulide and bensulide plus oxadiazon for PRE annual bluegrass control on golf putting greens.

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