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Herbicide effects on dormant and postdormant hybrid bermudagrass putting green turf

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Research Article

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Abstract

Herbicide resistance coupled with a dearth of selective herbicide options has increased the complexity of annual bluegrass control in hybrid bermudagrass putting greens. Cumyluron, endothall, and methiozolin are herbicides that control annual bluegrass by inhibiting novel sites of action compared with the herbicides currently used for turfgrass management in the United States. However, peer-reviewed literature contains no information on hybrid bermudagrass putting green tolerance to these herbicides. Sixteen field studies were established on eight golf greens in Midlothian, VA, in 2021 and 2022 to evaluate effects of cumyluron, endothall, methiozolin, pronamide, and trifloxysulfuron on bermudagrass spring transition. The 16 studies were split equally between initiation during full dormancy versus mid-spring transition. Methiozolin applied at 500 and 1,000 g ai ha^{-1} typically increased the heat units (growing degree days with a base temperature of 15 C) required for hybrid bermudagrass to visibly achieve 90% green coverage (T_{90}) when applied to fully dormant hybrid bermudagrass. This delay in green coverage was more pronounced at sites where hybrid bermudagrass vigor was seemingly reduced via abiotic stressors. Endothall was generally more injurious than all other treatments when applied to hybrid bermudagrass during mid-transition. Endothall applied at 840 g ai ha^{-1} injured hybrid bermudagrass for 0 to 9 d over a threshold of 30% (DOT_{30}), depending on location. In two site-years characterized by increased abiotic stress, methiozolin applied at 1,000 g ai ha^{-1} caused 44 DOT_{30}. Cumyluron never injured hybrid bermudagrass by more than 30% or delayed T_{90} regardless of application timing. These results indicate that methiozolin should be applied only within labeled rates to actively growing hybrid bermudagrass putting greens, cumyluron can be safely applied at 6,450 g ai ha^{-1} to dormant or actively growing bermudagrass greens, and endothall applications should be limited to dormant bermudagrass greens unless transient phytotoxicity is acceptable.

Introduction

During winter dormancy, hybrid bermudagrass putting greens are susceptible to invasion from annual bluegrass because hybrid bermudagrass is not actively growing (Johnson 1980). Few herbicide options exist to control annual bluegrass in hybrid bermudagrass putting greens. Currently, pendimethalin, pronamide, and sulfonylurea herbicides such as trifloxysulfuron and foramsulfuron may be used to control annual bluegrass. However, herbicide resistance is widespread among annual bluegrass populations, especially in the southern and transitional zones of the United States (Brosnan et al. 2020). During the winter dormancy of hybrid bermudagrass is the best time to control annual bluegrass, both to preserve the aesthetics and playability of the turf surface (Callahan and McDonald 1992). However, many annual bluegrass populations have evolved resistance to mitotic-inhibiting herbicides such as pendimethalin and pronamide (Breeden et al. 2017; Brosnan et al. 2014; Isgrigg et al. 2002; McCullough et al. 2017). Additionally, it has been well documented that annual bluegrass has become resistant to acetolactate synthase inhibitors in areas where hybrid bermudagrass is grown (Brosnan et al. 2015, 2016; McElroy et al. 2013). Therefore, new herbicidal options are needed for annual bluegrass control in hybrid bermudagrass putting greens.

Methiozolin (categorized by the Weed Science Society of America [WSSA] as a Group 30 herbicide) was registered in 2019 for preemergence (PRE) and postemergence (POST) control of annual bluegrass in hybrid bermudagrass putting greens. The novel mode of action of methiozolin is via inhibition of fatty acid thioesterase (FAT; Brabham et al. 2021). Annual bluegrass control with PRE and POST applications of methiozolin is commercially acceptable and is well documented in peer-reviewed literature (Askew and McNulty 2014; Brosnan et al. 2013, 2017; Hoisington et al. 2014; McCullough et al. 2013).

Cumyluron is also a FAT-inhibiting herbicide (Johnen et al. 2022) that controls annual bluegrass before it emerges (Askew and McNulty 2014; Reicher et al. 2015). Limited peer-reviewed information exists regarding cumyluron usage; however, the patent indicates that it inhibits annual bluegrass germination at rates of 500 to 30,000 g ai ha^{-1} (Tomita and Tonaka

2003). Although the safety of creeping bentgrass putting greens has been well documented with methiozolin and cumyluron use (Askew and McNulty 2014; McCullough et al. 2013), peer-reviewed literature does not include information on hybrid bermudagrass putting green tolerance to these herbicides.

Endothall is a herbicide currently used in the United States to control a variety of aquatic weed species (Skogerboe and Getsinger 2002). Endothall has historically been used on turfgrass in the United States to control annual bluegrass in cool-season turfgrasses (Engel and Aldrich 1960; Turgeon et al. 1972a, 1972b), but herbicide products have not been marketed for use on turfgrass in the United States for several decades. Endothall is currently registered in Australia for annual bluegrass control in turf systems with no restrictions against its use on hybrid bermudagrass golf greens (Anonymous 2020). Endothall's effectiveness to control annual bluegrass has been limited by cool-season turfgrass phytotoxicity (Peppers et al. 2021). Although peer-reviewed studies have not reported endothall effects on bermudagrass turf in managed turf systems, bermudagrass (*Cynodon dactylon* L. Pers.) was 60 times more tolerant to endothall in irrigation water compared to that of annual bluegrass (Koschnick et al. 2005). Endothall is a serine/threonine protein phosphatase inhibitor (WSSA Group 31), which is a novel mode of action in warm-season turfgrass systems (Bajsa et al. 2012; Tresch et al. 2011). This, coupled with previous literature evaluating annual bluegrass control with endothall in cool-season turf (Engel and Aldrich 1960; Turgeon et al. 1972a, 1972b), indicates that endothall may effectively control herbicide-resistant annual bluegrass populations. Barua et al. (2020) found that all annual bluegrass populations screened in Australia were resistant to endothall. However, in the study by Barua et al., the susceptible comparison was controlled by 50% with a single application of endothall at less than half of the rate that was applied thrice to sublethally suppress annual bluegrass seedheads in other studies (Peppers et al. 2021). Therefore, higher dosages of endothall may acceptably control annual bluegrass with lower risks for resistance development. The now-lapsed U.S. federal label for uses of endothall (US EPA 2005) indicates a maximum terrestrial use rate of 2.24 kg ai ha^{-1}, which is approximately 10 times higher than the currently labeled rate in Australia (Anonymous 2020). Although lower label rates may be necessary for cool-season turfgrass tolerance, higher rates appear plausible for use in bermudagrass systems (Koschnick et al. 2005).

The objective of this study was to evaluate the safety of hybrid bermudagrass to cumyluron, endothall, and methiozolin applied in late winter or spring as is typical for targeting emerged annual bluegrass on golf greens. A secondary objective was to evaluate those herbicides applied during full dormancy and during spring transition. Hybrid bermudagrass is generally more susceptible to injury when herbicides are applied during spring transition (Johnson 1976; Reed and McCullough 2014; Reed et al. 2015). We hypothesized that bermudagrass greens will not suffer a delay in spring transition due to applications of cumyluron, methiozolin, and endothall when applied during full dormancy. Additionally, we hypothesize these herbicides will transiently injure hybrid bermudagrass when applied during spring transition.

Materials and Methods

A total of 16 field studies were established on six golf putting greens to evaluate impact of spring-applied herbicides on bermudagrass spring transition. All trials were conducted at the Independence Golf Club Short Course in Midlothian, VA (37.54°N, 77.69°W). The 16 studies were equally split between initial herbicide treatments to full-dormancy versus mid-transition turf. In 2021, the full-dormancy study was established on two greens and the mid-transition study was established on all six greens. In 2022, this trend was reversed yielding eight site-years for each study. Full-dormancy studies were initiated on February 24, 2021, and February 18, 2022. Mid-transition studies were initiated when hybrid bermudagrass green coverage was approximately 50%. These studies were initiated April 7, 2021, and March 17, 2022. A full description of each site-year can be found in Table 1. Site-years D1 through D8 were established during full dormancy, and site-years MT1 through MT8 were established during mid-transition.

Treatments are listed in Table 2, and included three biweekly applications of methiozolin (Poacure®; Moghu Research Center Ltd, Daejeon, South Korea) or pronamide (Kerb®; Corteva Agriscience, Indianapolis, IN) and single treatments of cumyluron (HM-0814; Helena Agri-Enterprises LLC, Collierville, TN), endothall (KFD-211-01; UPL Limited, Mumbai, India), or trifloxysulfuron (Monument®; Syngenta, Basel, Switzerland). A nonionic surfactant (Induce®; Helena Agri-Enterprises LLC) was included with trifloxysulfuron at 0.25% v/v. Treatments were applied to 1.67-m^2 plots using a CO_2-pressurized sprayer calibrated to deliver 374 L ha^{-1} at 289 kPa using TeeJet 11006 TTI nozzles (Spraying Systems Co., Glendale Heights, IL). Following applications of methiozolin, pronamide, and cumyluron, approximately 6.4 mm of postapplication irrigation was applied to wash herbicide from the foliage and to the soil according to the respective herbicide labels. Application timings are listed in Table 2.

In full-dormancy studies, data included visually assessed percent green coverage of hybrid bermudagrass and normalized difference vegetative index (NDVI) assessed via a multispectral analyzer (Crop Circle™ Model ACS-210; Holland Scientific Inc.). The center 0.84 m^2 of each plot was scanned and collected approximately 35 NDVI readings per experimental unit, which were averaged. These data were collected biweekly until >90% bermudagrass green coverage was observed in each plot. Percent green coverage was converted to thermal time required to reach 90% green coverage via nonlinear regressions using the NLIN procedure with SAS software (version 9.4; SAS Institute Inc., Cary NC). Thermal time was based on growing degree days with a base temperature of 15 C (GDD_{15}) (Fluornoy 2017). Daily growing degree days were calculated using Equation 1:

$$Daily\ GDD_{15} = \frac{Temp\ (high) + Temp\ (low)}{2} - 15\ C \qquad [1]$$

Total GDD_{15} accumulation is the sum of daily GDD_{15}, excluding negative values, beginning on the initial application date. Nonlinear regressions to relate thermal time to hybrid bermudagrass green cover were fitted to a two-parameter rectangular hyperbolic model using Equation 2:

$$Y = iGDD/[(1 + iGDD)/a] \qquad [2]$$

where Y is the predicted percent hybrid bermudagrass green coverage, GDD is the accumulated GDD_{15}, i is the percent green coverage per unit GDD as GDD approaches zero, and a is the asymptote for maximum green coverage. Estimated i and a values were used to calculate thermal time required for turf to reach 90% green cover (T_{90}) in each experimental unit using Equation 3:

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Table 1. Putting green information for each site-year.

Site-year	Study year	Cultivar	Age at time of study	Soil pH	Soil organic matter[a]
			years		%
D1/MT5	2021	Mach 1	0.8	6.5	1.3
D2/MT6	2021	Experimental 'JK110521'	3	6.6	0.8
MT1	2021	Experimental 'FAES1302'	4	6.6	1.3
MT2	2021	MiniVerde	3	6.7	1.2
MT3	2021	G12	3	6.7	0.9
MT4	2021	TifEagle	4	6.5	1.4
D3	2022	Experimental 'FAES1302'	5	6.6	1.4
D4	2022	MiniVerde	4	6.3	1.3
D5	2022	G12	4	6.6	1.1
D6	2022	TifEagle	5	6.6	1.4
D7/MT7	2022	Mach 1	2	6.2	1.1
D8/MT8	2022	Experimental 'JK110521'	4	6.3	1.7

[a]Soil organic matter was measured via loss on ignition from the top 6 cm of soil excluding the verdure, and is presented as a percentage of soil dry weight.

Table 2. Herbicide rate and application timings for each study.

		Application timings			
		2021		2022	
Herbicide[a]	Rate[b]	Dormant	Mid-transition	Dormant	Mid-transition
Nontreated	–	–	–	–	–
Cumyluron	6,450	February 24	April 7	February 18	March 17
Endothall	840	February 24	April 7	February 18	March 17
Endothall	1,680	February 24	April 7	February 18	March 17
Methiozolin	500	February 24	April 7	February 18	March 17
		March 10	April 21	March 3	March 30
		March 24	May 5	March 17	April 14
Methiozolin	1,000	February 24	April 7	February 18	March 17
		March 10	April 21	March 3	March 30
		March 24	May 5	March 17	April 14
Pronamide	289	February 24	April 7	February 18	March 17
		March 10	April 21	March 3	March 30
		March 24	May 5	March 17	April 14
Trifloxysulfuron	27.8	February 24	April 7	February 18	March 17

[a]Methiozolin and pronamide were applied three times at 2-wk intervals, all others were applied once. A nonionic surfactant was included with trifloxysulfuron at 0.25% v v^{-1}. Cumyluron, methiozolin, and pronamide were incorporated with 6.4 mm of irrigation immediately after treatment.
[b]All rates are expressed as g ae ha^{-1}.

$$T_{90} = (90a)/(i([a - 90)] \quad [3]$$

where T_{90} is thermal units in GDD_{15}, and *a* and *i* are the estimated parameters from Equation 2. Minimum observed NDVI measurements were recorded for each experimental unit excluding any measurements taken before nontreated turf reached 50% green coverage. Minimum-observed NDVI and T_{90} values were subjected to ANOVA using the GLM procedure (with SAS software) with sums of squares partitioned to reflect site-year, treatment, and site-year by treatment. Treatment mean squares were tested with the mean square associated with site-year by treatment. Treatment means, with the nontreated control excluded, were separated via Fisher's protected LSD at $\alpha = 0.05$. To compare treatment effects to the nontreated control, T_{90} and minimum observed NDVI values of each treatment were subjected to Dunnett's procedure (Dunnett 1955). To determine clusters of site-years that may be pooled, iterative analyses were conducted by systematically excluding different site-years from the ANOVA, and any group of site-years that did not have a significant site-year by treatment interaction were pooled and presented separately alongside other groups or individual site-years.

In mid-transition studies, NDVI readings were collected in a manner similar to that of the full-dormancy study, but percent visually assessed, hybrid bermudagrass injury was recorded rather than green turf cover. In this study, turf was already predominately green at initiation and assessed injury represents stunting, discoloration, and stand reduction caused by treatments. In the dormancy study, by contrast, the rate of hybrid bermudagrass green cover accumulation was a more direct assessment of herbicidal impacts to turf. Percent visible injury data were evaluated as 0% equals no injury, 100% equals complete visible necrosis of hybrid bermudagrass, and 30% equals maximum commercially acceptable injury (Johnson 1995). All data were collected biweekly until injury was no longer present in any plot (approximately 12 wk). Hybrid bermudagrass injury data were converted to number of days above the maximum acceptable injury threshold of 30% (DOT_{30}). These DOT_{30} data were calculated in a manner similar to that by Brewer et al. (2022) in which linear trends in changes to bermudagrass injury between assessment dates were assumed. The DOT_{30} values reflect the duration of unacceptable turfgrass injury that is important for turfgrass managers to understand when choosing a herbicide program. Additionally, maximum hybrid bermudagrass injury was calculated by recording maximum observed injury values from each experimental unit over the span of assessment dates and consist of an assessment of injury severity. Minimum

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Table 3. Influence of herbicides applied to fully dormant hybrid bermudagrass on thermal time to obtain 90% green coverage.[a–e]

Herbicide[f]	Rate	T_{90}		
		Sites D1, D2	Sites D3, D4, D8	Sites D5, D6, D7
	g ae ha^{-1}	——— GDD_{15} ———		
Nontreated	–	60.0	42.9	42.1
Cumyluron	6,450	46.8 d	41.9 d	43.0 b
Endothall	840	53.4 cd	43.9 cd	46.9 b
Endothall	1,680	57.3 cd	45.7 bcd	49.2 b
Methiozolin	500	141* b	48.0 bc	61.3 b
Methiozolin	1,000	303* a	55.0* a	267* a
Pronamide	289	100 bc	49.4 b	49.0 b
Trifloxysulfuron	27.8	50.8 d	45.9 bcd	45.6 b

[a]Abbreviations: GDD_{15}, number of growing degree days with a base temperature of 15 C; T_{90}, thermal time required for green bermudagrass turf to reach 90% green cover.
[b]Data are pooled over site-year groups when the trial by treatment interaction was insignificant ($P > 0.05$).
[c]Sites D1 through D8 were located on eight golf greens comprising six randomly chosen hybrid-bermudagrass cultivars at Independence Golf Club in Midlothian, VA. Hybrid bermudagrass cultivars included 'Mach 1' (D1, D7), 'Experimental JK110521' (D2, D8), 'Experimental FAES1302' (D3), 'Miniverde' (D4), 'G12' (D5), and 'Tifeagle' (D6).
[d]Means separation between treatments, excluding the nontreated control, were determined with Fishers protected LSD ($P < 0.05$).
[e]Treatment means followed by an asterisk (*) indicate significant difference compared to the nontreated check ($P < 0.05$) within a given site-year group based on Dunnett's test.
[f]Methiozolin and pronamide were applied three times at 2-wk intervals, all others were applied once. A nonionic surfactant was included with trifloxysulfuron at 0.25% v v^{-1}. Cumyluron, methiozolin, and pronamide were incorporated with 6.4 mm of irrigation immediately after treatment.

observed NDVI measurements were also recorded for each experimental unit similarly to studies initiated during full dormancy. Minimum observed NDVI, maximum observed injury, and DOT_{30} values were subjected to ANOVA and means were separated as described for the full-dormancy study.

Results and Discussion

Hybrid Bermudagrass Tolerance to Herbicides Applied During Full Dormancy

Data were pooled over any group of site-years that exhibited insignificant trial by treatment interaction ($P > 0.05$). Hybrid bermudagrass T_{90} and minimum NDVI data were separated into three site-year groups including the pooled effect of sites D1 and D2; sites D3, D4, and D8; and sites D5, D6, and D7. Nontreated plots transitioned to green turf consistently across the eight site-years and required 42 to 60 GDD_{15} or 64 to 68 d to achieve 90% green cover depending on site-year (Table 3). Methiozolin was the only herbicide that resulted in increased hybrid bermudagrass T_{90} relative to the nontreated control. The site-year dependence was likely caused by a variable magnitude of bermudagrass response to methiozolin between the three site-year groups. For example, bermudagrass T_{90} following methiozolin at the lower rate was similar to nontreated turf at all sites except the group that contains D1 and D2, which are the two sites from 2021 (Table 3). Temperatures were colder in 2021 during study initiation (data not shown) and may have slowed hybrid bermudagrass development compared with the other sites in 2022. In addition, D1 was recently sprigged less than 1 yr before study initiation. Previous research indicates that recently established hybrid bermudagrass is more susceptible to root damage from root-absorbed herbicides such as methiozolin (Sharpe et al. 1989).

At site D2, however, the reason for the severe delay in T_{90} from methiozolin at the low rate is not apparent other than the aforementioned differences in early-season temperatures between 2021 and 2022. The same green where D2 was located in 2021 provided an adjacent site for D8 in 2022 where methiozolin at either rate caused minimal delay in green cover. Methiozolin applied at a high rate on sites D1 and D2, and sites D5, D6, and D7 caused hybrid bermudagrass to require five to six times more thermal time to reach 90% green cover than at the other three sites. Sites D5 and D6 received approximately 30% and 15% less daily sunlight, respectively, than the other dormant-initiated locations during the trial period based on total number of hours that these locations received direct sunlight, and D7 was less than 2 yr postestablishment at the time the trial initiated. The increased shade stress may have contributed to increased methiozolin injury because many studies have evaluated reduction of hybrid bermudagrass vigor grown in shade (Baldwin et al. 2008; Gaussoin et al. 1988; Trappe et al. 2011). Increased shade has also been attributed to increased methiozolin efficacy in preliminary experiments (Henry et al. 2023).

Additionally, hybrid bermudagrass cultivars may exhibit differential herbicidal susceptibility. McElroy et al. (2005) observed differential bermudagrass cultivar susceptibility to broadleaf herbicides during turfgrass establishment. The PRE herbicide butralin also differentially damages some cultivars of hybrid bermudagrass relative to others (Johnson 1976). However, in those studies, hybrid bermudagrass cultivar and environmental conditions were randomly selected, and conclusions cannot be drawn regarding how these factors influence response to the herbicides that were evaluated. In addition, experimental cultivar 'JK110521' was represented at sites D2 and D8, which statistically separated into different site groups and exhibited differential response to either rate of methiozolin applied to dormant turf (Table 3). Cumyluron and endothall applied to dormant hybrid bermudagrass did not increase hybrid bermudagrass T_{90} relative to nontreated turf at any site-year.

Trends in hybrid bermudagrass T_{90} were corroborated by similar trends in minimum observed NDVI. The minimum observed NDVI in nontreated plots ranged from 0.506 to 0.579 (Table 4). Methiozolin applied at 1,000 g ai ha^{-1} reduced hybrid bermudagrass NDVI relative to the nontreated in all site-years. Methiozolin applied at 500 g ai ha^{-1} significantly reduced hybrid bermudagrass NDVI relative to the nontreated only in site-years D1 and D2. Similar to T_{90} data, no other treatment significantly reduced hybrid bermudagrass minimum NDVI relative to the nontreated control.

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Table 4. Influence of herbicides applied to fully dormant hybrid bermudagrass on hybrid bermudagrass minimum observed normalized vegetative difference index following the first instance of 50% green coverage in nontreated turf.[a–d]

Herbicide[e]	Rate	Minimum observed normalized difference vegetative index		
		D1 and D2	D3, D4, D8	D5, D6, D7
	g ae ha^{-1}	Index 0–1		
Nontreated	–	0.579	0.541	0.506
Cumyluron	6,450	0.576 ab	0.561 A	0.512 a
Endothall	840	0.589 a	0.528 Bc	0.499 a
Endothall	1,680	0.588 a	0.522 C	0.465 b
Methiozolin	500	0.471* c	0.509 Cd	0.464 b
Methiozolin	1,000	0.372* d	0.494* D	0.431* c
Pronamide	289	0.549 b	0.531 Bc	0.487 ab
Trifloxysulfuron	27.8	0.595 a	0.552 Ab	0.509 a

[a]Data are pooled over site-years groups when the trial by treatment interaction was insignificant ($P > 0.05$).
[b]Sites D1 through D8 were located on eight golf greens consisting of six randomly chosen hybrid-bermudagrass cultivars at Independence Golf Club in Midlothian, VA. Hybrid bermudagrass cultivars included 'Mach 1' (D1, D7), 'Experimental JK110521' (D2, D8), 'Experimental FAES1302' (D3), 'Miniverde' (D4), 'G12' (D5), and 'Tifeagle' (D6).
[c]Means separation between treatments, excluding the nontreated control, were determined with Fishers protected LSD ($P < 0.05$).
[d]Treatment means followed by an asterisk (*) indicate significant difference compared to the nontreated check ($P < 0.05$) within a given site-year group based on Dunnett's test.
[e]Methiozolin and pronamide were applied three times at 2-wk intervals, all others were applied once. A nonionic surfactant was included with trifloxysulfuron at 0.25% v/v. Cumyluron, methiozolin, and pronamide were incorporated with 6.4 mm of irrigation immediately after treatment.

Table 5. Influence of herbicides applied to mid-transition hybrid bermudagrass, on hybrid bermudagrass d over 30% injury threshold.[a–d]

Herbicide[e]	Rate	Days over 30% injury threshold		
		MT1, MT2, MT4, MT6	MT3, MT5	MT7, MT8
	g ae ha^{-1}	days		
Cumyluron	6,450	0.0 c	0.23 b	0.0 b
Endothall	840	5.5* b	8.5 b	0.0 b
Endothall	1,680	22* a	35* a	0.14 b
Methiozolin	500	0.0 c	6.1 b	0.0 b
Methiozolin	1,000	0.0 c	44* a	13* a
Pronamide	289	0.0 c	6.8 b	0.0 b
Trifloxysulfuron	27.8	0.17 c	1.7 b	0.0 b

[a]Data are pooled over site-years groups when the trial by treatment interaction was insignificant ($P > 0.05$).
[b]Sites D1 through D8 were located on eight golf greens comprising six randomly chosen hybrid-bermudagrass cultivars at Independence Golf Club in Midlothian, VA. Hybrid bermudagrass cultivars included 'Experimental FAES1302' (MT1), 'Miniverde' (MT2), 'G12' (MT3), 'Tifeagle' (MT4), 'Mach 1' (MT5, MT7), and 'Experimental JK110521' (MT6, MT8).
[c]Means separation between treatments, excluding the nontreated control, were determined with Fishers protected LSD ($P < 0.05$).
[d]Treatment means followed by an asterisk (*) indicate significant difference compared to the nontreated check ($P < 0.05$) within a given site-year based on Dunnett's test.
[e]Methiozolin and pronamide were applied three times at 2-wk intervals, all others were applied once. A nonionic surfactant was included with trifloxysulfuron at 0.25% v/v. Cumyluron, methiozolin, and pronamide were incorporated with 6.4 mm of irrigation immediately after treatment.

Hybrid Bermudagrass Tolerance to Herbicides Applied During Mid-Transition

Data are pooled between site-years when the trial by treatment interaction was insignificant ($P > 0.05$). Hybrid bermudagrass DOT_{30}, maximum observed injury, and minimum NDVI data separated into three groups representing the pooled effect of sites MT1, MT2, MT4, and MT6; MT3 and MT5; and MT7 and MT8. In general, hybrid bermudagrass injury metrics appeared to be more severe at sites MT3 and MT5 (Table 5). Sites MT3 and MT5 may have separated from the other site-years due to higher levels of abiotic stress relative to other site-years. Site-year MT5 was characterized as having relatively immature hybrid bermudagrass (Table 1) and MT3 had approximately 30% less direct sunlight relative to other site-years. For example, MT3 and MT5 were the only site-years where methiozolin at 500 g ai ha^{-1} caused more than 30% injury and produced a significant DOT_{30} (Table 5). Likewise, trifloxysulfuron and pronamide injured bermudagrass by more than 30% for 1.7 d to 6.8 d at MT3 and MT5, and no days at other locations. However, at site-years MT3 and MT5, only endothall and methiozolin applied at 1,680 and 1,000 g ai ha^{-1}, respectively, increased hybrid bermudagrass DOT_{30} relative to the nontreated check. In all site-years, except MT7 and MT8, endothall applied at 1,680 g ai ha^{-1} had significant DOT_{30} values relative to the nontreated control. At site-years MT1, MT2, MT4, and MT6, endothall applied at 840 g ai ha^{-1} injured hybrid bermudagrass by at least 30% for 5.5 d to 8.5 d. Methiozolin applied at 500 g ai ha^{-1} never significantly increased hybrid bermudagrass DOT_{30} relative to the nontreated.

The maximum observed injury caused by herbicides exhibited trends that were similar to that of injury DOT_{30}. For example, endothall at either rate, and methiozolin at 1,000 g ai ha^{-1}, had generally higher maximum injury (Table 6) compared to injury from the other products. Although most of the herbicides caused significant injury to hybrid bermudagrass, relative to the nontreated only endothall at either rate, and methiozolin applied at 1,000 g ai ha^{-1} resulted in unacceptable injury to hybrid bermudagrass. Some trends, however, indicate that when methiozolin injured hybrid bermudagrass by more than 30% the injury was persistent, which is reflected by 13 to 44 DOT_{30} at site-years MT3 and MT5, and MT7 and MT8 (Table 5). Cumyluron never significantly injured hybrid bermudagrass across all site-years.

Endothall applied at 840 and 1,680 g ai ha^{-1} reduced the minimum observed NDVI of hybrid bermudagrass relative to the nontreated in all but 1 site-year along a positive rate-dependent trend (Table 7). Endothall applied at 1,680 g ai ha^{-1} reduced hybrid bermudagrass NDVI greater than any other herbicide in all site-years. Although endothall applied at 840 g ai ha^{-1} resulted in unacceptable injury to hybrid bermudagrass (Table 6), the injury was transient, with hybrid bermudagrass DOT_{30} values never exceeding 9 d (Table 5). These results are consistent with those observed after flumioxazin and oxadiazon were applied during mid-bermudagrass-transition on non–putting green, hybrid bermudagrass (Johnson 1976; Reed and McCullough 2014; Reed et al. 2015). Additionally, these results align with preliminary reports of endothall activity on fairway-height hybrid bermudagrass, in which endothall applications were more injurious to hybrid bermudagrass when applied at higher rates to actively growing hybrid bermudagrass (Peppers and Askew 2022). Methiozolin applied at 1,000 g ai ha^{-1} at site-years MT3 and MT5 was the only treatment outside of endothall to significantly reduce hybrid bermudagrass NDVI relative to the nontreated control. Neither pronamide nor trifloxysulfuron produced significantly reduced minimum observed NDVI relative to the nontreated. Cumyluron did not unacceptably injure hybrid bermudagrass (Table 6) or reduce NDVI (Table 7) at any site-year.

These are the first studies submitted to peer-review that evaluated hybrid bermudagrass putting green tolerance to

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Table 6. Influence of herbicides applied to mid-transition hybrid bermudagrass on maximum observed hybrid bermudagrass injury.[a–d]

Herbicide[e]	Rate	Hybrid bermudagrass injury		
		MT1, MT2, MT4, MT6	MT3, MT5	MT7, MT8
	g ae ha^{-1}		%	
Cumyluron	6,450	0.94 f	8.8 d	0.0 d
Endothall	840	36* b	41* b	7.5* c
Endothall	1,680	71 a	71* a	22* b
Methiozolin	500	5.9 de	21* c	9.4* c
Methiozolin	1,000	17 c	61* a	30* a
Pronamide	289	1.8 ef	27* c	2.5 d
Trifloxysulfuron	27.8	10 d	26* c	18* b

[a]Data are pooled over site-years groups when the trial by treatment interaction was insignificant (P > 0.05).
[b]Sites D1through D8 were located on eight golf greens comprising six randomly chosen hybrid-bermudagrass cultivars at Independence Golf Club in Midlothian, VA. Hybrid bermudagrass cultivars included 'Experimental FAES1302' (MT1), 'Miniverde' (MT2), 'G12' (MT3), 'Tifeagle' (MT4), 'Mach 1' (MT5, MT7), and 'Experimental JK110521' (MT6, MT8).
[c]Means separation between treatments, excluding the nontreated control, were determined with Fishers protected LSD (P < 0.05).
[d]Treatment means followed by an asterisk (*) indicate significant difference compared to the nontreated check (P < 0.05) within a given site-year group based on Dunnett's test.
[e]Methiozolin and pronamide were applied three times at 2-wk intervals, all others were applied once. A nonionic surfactant was included with trifloxysulfuron at 0.25% v v^{-1}. Cumyluron, methiozolin, and pronamide were incorporated with 6.4 mm of irrigation immediately after treatment.

Table 7. Influence of herbicides applied to mid-transition hybrid bermudagrass on minimum observed hybrid bermudagrass normalized difference vegetative index.[a–d]

Herbicide[e]	Rate	Minimum normalized vegetative index		
		MT1, MT2, MT4, MT6	MT3, MT5	MT7, MT8
	g ae ha^{-1}		Index 0–1	
Nontreated	–	0.569	0.536	0.559
Cumyluron	6,450	0.591 a	0.541 a	0.561 a
Endothall	840	0.478* d	0.459* c	0.532 a
Endothall	1,680	0.407* e	0.426* d	0.501* b
Methiozolin	500	0.561 bc	0.511 b	0.555 a
Methiozolin	1,000	0.553 c	0.493* b	0.538 a
Pronamide	289	0.582 ab	0.543 a	0.554 a
Trifloxysulfuron	27.8	0.554 c	0.534 a	0.542 a

[a]Data are pooled over site-year groups when the trial by treatment interaction was insignificant (P > 0.05).
[b]Sites D1 through D8 were located on eight golf greens comprising six randomly chosen hybrid-bermudagrass cultivars at Independence Golf Club in Midlothian, VA. Hybrid bermudagrass cultivars included 'Experimental FAES1302' (MT1), 'Miniverde' (MT2), 'G12' (MT3), 'Tifeagle' (MT4), 'Mach 1' (MT5, MT7), and 'Experimental JK110521' (MT6, MT8).
[c]Means separation between treatments, excluding the nontreated control, were determined with Fishers protected LSD (P < 0.05).
[d]Treatment means followed by an asterisk (*) indicate significant difference compared to the nontreated check (P < 0.05) within a given site-year group based on Dunnett's test.
[e]Methiozolin and pronamide were applied three times at 2-wk intervals, all others were applied once. A nonionic surfactant was included with trifloxysulfuron at 0.25% v v^{-1}. Cumyluron, methiozolin, and pronamide were incorporated with 6.4 mm of irrigation immediately after treatment.

methiozolin, endothall, or cumyluron. Results from these studies indicate that methiozolin is consistently detrimental to hybrid bermudagrass putting greens when applied at twice the label-recommended rate during full dormancy. Trends in the data suggest that abiotic stressors may negatively affect hybrid bermudagrass tolerance to elevated rates of methiozolin; however, no specific conclusions in this regard may be drawn from this study. Endothall injures hybrid bermudagrass when applied at higher rates or during postdormancy transition. Cumyluron can safely be used on hybrid bermudagrass before or during postdormancy transition. These trials were conducted in the northernmost portion of the transition zone where hybrid bermudagrass experiences more extreme cold stress than in the majority of locations in which hybrid bermudagrass is grown. A reduction in hybrid bermudagrass green coverage during spring transition is commonly observed with root-inhibiting herbicides in the northern transition zone (Bingham 1967; Bingham and Shaver 1979; Breuninger and Schmidt 1981). This is primarily due to the increased susceptibility of meristematic root tissue to root-inhibiting herbicides (Bingham 1967). Additionally, bermudagrass roots are mostly lost on fully dormant turf and must be regrown following the initiation of postdormancy growth (DiPaola and Beard 1978). Abiotic stressors also exacerbate herbicide injury on turfgrasses (Bhowmik and Bingham 1990; Hart et al. 2004; Venner et al. 2023), which may explain why hybrid bermudagrass appeared to be more susceptible to endothall, methiozolin, and pronamide at certain site-years. The maximum labeled use rate of methiozolin on putting greens is 500 g ai ha^{-1} (Anonymous 2021), which did not unacceptably injure hybrid bermudagrass at any site-year when applied during mid-transition. These data suggest that methiozolin should be applied only within labeled rates to actively growing hybrid bermudagrass putting greens, cumyluron can be applied anytime during late winter or spring, and endothall applications should be limited to dormant turf treatment unless transient phytotoxicity is acceptable.

Practical Implications

The proliferation of herbicide-resistant annual bluegrass on hybrid bermudagrass greens and associated areas has increased the need for multiproduct admixtures or novel herbicide modes of action. Methiozolin, endothall, and cumyluron control annual bluegrass and some other grassy weeds endemic to hybrid bermudagrass greens, but limited information exists regarding their safety for use in this unique turf system. Endothall and cumyluron are not currently labeled for use on any turfgrass site in the United States. The methiozolin product label indicates that hybrid bermudagrass should be actively growing when the herbicide is applied and use rates should not exceed 500 g ai ha^{-1} on turf managed at greens height (Anonymous 2021). Results of these studies suggest that cumyluron is safe to use on hybrid bermudagrass, regardless of application timing, when applied at 6,450 g ai ha^{-1}. Endothall can be safely applied to hybrid bermudagrass during full dormancy, but high levels (approximately 20% to 80%) of injury may transiently occur when applied to hybrid bermudagrass during mid-transition. These data may have use in driving labeling decisions for endothall and cumyluron, and lead to warnings for methiozolin use on fully dormant hybrid bermudagrass putting greens.

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