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Evaluation of spring-applied endothall for annual bluegrass control in warm-season turf

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Endothall; trifloxysulfuron; annual bluegrass, *Poa annua* L.; hybrid bermudagrass, *Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt Davy. 'Tifway 419' and 'Latitude 36'; manilagrass, *Zoysia matrella* (L.) Merr. 'Cavalier'

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Abstract

Increasing instances of herbicide-resistant annual bluegrass have limited turf managers' options for chemical control. Endothall inhibits serine threonine protein phosphatase, a novel site of action for warm-season turf, and endothall use in hybrid bermudagrass is not extensively reported. Greenhouse studies were conducted to evaluate herbicide-resistant annual bluegrass response to endothall. Five herbicide-resistant annual bluegrass biotypes were treated with increasing endothall rates and compared to two susceptible populations. One glyphosate-resistant annual bluegrass biotype was 2.3- to 3.3-fold more resistant to endothall depending on trial and susceptible biotype, and all other biotypes were endothall susceptible. Four field studies were established from 2022 to 2023 to evaluate the influence of endothall rate and application timing on bermudagrass and manilagrass turf injury and annual bluegrass control. These studies were arranged as a 3 × 4 factorial with three levels of application timing (fully dormant, 50% green, and 100% green) and four levels of herbicide (endothall applied at 1.12, 1.68, and 2.24 kg ai ha^{-1} and trifloxysulfuron applied at 27.8 g ai ha^{-1}). Maximum observed turf injury was dependent on endothall rate and timing and was commercially acceptable (<30%) at the low and middle rates when applied to 100% green bermudagrass and at all rates when applied to dormant turf. When applied to 50% green turf (mid-transition), endothall unacceptably injured warm-season turf regardless of application rate. Endothall controlled annual bluegrass more effectively when applied during mid-transition and 100% green turf than it did when applied during fully dormant turf. When applied at rates of 1.68 and 2.24 kg ai ha^{-1} during mid-transition or at 100% green turf, endothall controlled annual bluegrass 83% to 95%. Results from these studies indicate that endothall selectively controls herbicide-resistant annual bluegrass in warm-season turf but that selectivity and performance depend on application timing.

Introduction

Annual bluegrass resistance to herbicide is widespread in intensively managed turf systems. Currently there are 18 uniquely reported cases of herbicide-resistant annual bluegrass in the United States (Heap 2023), and that is likely underreported based on recent literature (Bowling et al. 2024; Ignes et al. 2023; Rutland et al. 2023). Herbicide-resistant annual bluegrass has proliferated in warm-season turf systems across a variety of herbicide modes of action (MOAs). A recent survey of Tennessee golf courses identified 21%, 64%, 58%, and 97% of annual bluegrass as resistant to glyphosate, foramsulfuron, prodiamine, and simazine, respectively (Brosnan et al. 2020c). Additionally, 4% of these resistant populations exhibited resistance to multiple herbicide MOAs (Brosnan et al. 2020c). Similar surveys in Mississippi and Texas indicate that annual bluegrass herbicide resistance is widespread across the southern United States and that annual bluegrass populations with multiple herbicide resistance are prevalent (Hutto et al. 2004; Singh et al. 2021). In many instances, annual bluegrass evolves resistance to multiple herbicide MOAs when resistant populations are initially managed with a single alternate herbicide (Brosnan et al. 2020a). Furthermore, resistant annual bluegrass populations are more prevalent in warm-season turf systems (Brosnan et al. 2020b; Cross et al. 2015; Isgrigg et al. 2002; Kelly et al. 1999; McElroy et al. 2013; Yu et al. 2018). Owing to the widespread nature of herbicide-resistant annual bluegrass, herbicide options with alternative MOAs are needed to sustain effective annual bluegrass control in warm-season turf systems.

Endothall is currently utilized in the United States as an aquatic herbicide for control of a variety of weed species (Skogerboe and Getsinger 2002). In U.S. turf, endothall was historically used for semiselective control of annual bluegrass in cool-season turfgrasses. In a creeping bentgrass (*Agrostis stolonifera* L.) fairway, three spring applications of endothall applied at 0.56 kg ha^{-1} reduced annual bluegrass coverage by 62% relative to the nontreated (Engel and Aldrich 1960). In Michigan, three biweekly applications of endothall applied at 0.3 and 0.6 kg ai ha^{-1} to Kentucky bluegrass (*Poa pratensis* L.) turf reduced annual bluegrass coverage from 50% to 32% and 17%, respectively (Turgeon et al. 1972a). Endothall's effectiveness for annual bluegrass control, however, has been limited by cool-season turf phytotoxicity (Peppers et al. 2021).

Recent literature has indicated that bermudagrass may be more tolerant than cool-season turf species to endothall applications. Bermudagrass was 57 and 65 times more tolerant to endothall-contaminated irrigation water compared to annual bluegrass and annual ryegrass (*Lolium multiflorum* Lam.), respectively (Koschnick et al. 2005). Additionally, endothall applied at 0.84 and 1.68 kg ai ha^{-1} was not significantly injurious to hybrid bermudagrass putting greens when applied during full winter dormancy (Peppers and Askew 2023). To date, no peer-reviewed literature has evaluated endothall for annual bluegrass control in bermudagrass turf. Endothall is a serine/threonine protein phosphatase inhibitor, which is a novel MOA in turf systems (Bajsa et al. 2012; Tresch et al. 2011). Previous literature has indicated that herbicides with novel MOAs can effectively control herbicide-resistant annual bluegrass populations (Brosnan et al. 2017). Endothall-resistant annual bluegrass has already been reported in Australia. Barua et al. (2020) found that all annual bluegrass populations screened in Australia were resistant to endothall. However, in this study, the susceptible comparison was controlled 50% by a single application of endothall applied at 0.13 kg ai ha^{-1}, which is a much lower rate than has sublethally suppressed annual bluegrass in other studies (Engel and Aldrich 1960; Peppers et al. 2021; Turgeon et al. 1972a). The now-lapsed U.S. federal label for terrestrial uses of endothall (EPA 2005) indicates a maximum terrestrial use rate of 2.24 kg ai ha^{-1}, which is approximately ten times higher than the currently labeled rate in Australia (Anonymous 2020). On the basis of previous literature, we surmise that endothall rates for turfgrass use currently in Australia and formerly in the United States were limited due to concerns of injury to cool-season turf and the product's historical market value. In warm-season turf, especially during dormancy, the potential market value for endothall has likely increased due to developed annual bluegrass resistance to a wide range of formerly viable herbicides. Thus we hypothesized that above-Australian-label endothall dosages may acceptably control herbicide-resistant annual bluegrass with acceptable phytotoxicity to dormant, semidormant, or actively growing bermudagrass turf.

Materials and Methods

Herbicide-Resistant Annual Bluegrass Response to Endothall

Two greenhouse studies were conducted at the Glade Road Research Facility in Blacksburg, VA (37.23°N, 80.44°W), to evaluate herbicide-resistant annual bluegrass response to endothall. Both trials were arranged as randomized complete-block designs with 42 treatments and four blocks. Treatments were arranged as a 7 × 8 factorial with seven levels of annual bluegrass populations and eight levels of herbicide treatment. The six annual bluegrass populations consisted of two known susceptible populations (S1 and S2), two acetolactate synthase (ALS)-inhibitor-resistant populations (ALS1 and ALS2), two glyphosate (5-enolpyruvylshikimate-3-phosphate; EPSP)-resistant populations (EPSP1 and EPSP2), and a population that exhibits resistance to multiple herbicide MOAs (MR). The multiple-resistant annual bluegrass population was putatively resistant to EPSP-, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-, photosystem II (PSII)-inhibiting herbicides. All annual bluegrass populations were collected throughout the state of Virginia and screened for herbicide resistance to a variety of MOAs. The causal mechanisms of resistance are more thoroughly presented in Table 1. The six herbicide levels include five endothall rates (0.5, 1.0, 2.0, 4.0, and 8.0 kg ai ha^{-1}) and a nontreated comparison for every annual bluegrass population.

All populations were seeded into 45 × 30-cm flats containing potting soil (Pro-Mix® BXM General Purpose Growing Medium, Premier Horticulture, Quakertown, PA, USA). After annual bluegrass plants reached the 2-tiller growth stage, the herbicide-resistant annual bluegrass populations were treated with appropriate herbicides to ensure homogeneity of resistant annual bluegrass plants. Populations ALS1, ALS2, and MR were treated with trifloxysulfuron (Monument®, Syngenta Crop Protection, Greensboro, NC, USA) applied at 27.8 g ai ha^{-1} + non-ionic surfactant (Induce, Helena® Chemical Company, Collierville, TN, USA) applied at 0.25% v/v; populations EPSP1 and EPSP2 were treated with glyphosate (Roundup Pro® Concentrate, Monsanto Company, Washington, DC, USA) applied at 1.12 kg ai ha^{-1}. Surviving plants were selected and transplanted into 7.6 × 7.6 × 6.4-cm pots containing a 2:1 sand–to–native soil mixture. The native soil utilized in this study was a Groseclose-Urban land complex loam (clayey, mixed, mesic Typic Hapludults) with pH 6.0 and 3.1% organic matter. All plants were fertilized with 25 kg N ha^{-1} (19-6-12; Sta-Green™ Indoor and Outdoor All-Purpose Food Fertilizer, Gro Tec, Modoc, IN, USA) once approximately 1 wk after germination to maintain proper plant growth. Irrigation was supplied twice daily to prevent plant wilt. Mercury vapor lamps provided 430 μmol m^{-2} s^{-1} of photosynthetically active radiation as supplemental lighting and was set to a 14-h day length throughout the studies. Greenhouse day/night temperatures were maintained at 29/20 C. All treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 375 L ha^{-1} at 330 kPa and fitted with TTI11004 TeeJet® nozzles (TeeJet® Technologies, Springfield, IL, USA). Following applications, all pots were allowed to dry for 4 to 6 h before irrigation was applied. Annual bluegrass plants had approximately 5 to 8 tillers at application. At the conclusion of the trial, 28 d after application, annual bluegrass aboveground biomass was collected and dried at 50 C for 72 h before weighing. Annual bluegrass control data were extrapolated from the aboveground biomass data by comparing all treated plants to the nontreated comparison within a given biotype and replication. The endothall rate required to control annual bluegrass 50% and 90% (C_{50} and C_{90}, respectively) was modeled across all doses in each replicate for a given biotype using a three-parameter sigmoidal model with Equation 1:

$$y = a/\left(1 + e^{\{-[x-xo]/b\}}\right) \quad [1]$$

where y represents percent annual bluegrass control, e is the natural logarithm, x represents the endothall rate, and a, b, and xo represent regression parameters calculated using the PROC NLIN procedure in SAS (version 9.4; SAS Institute, Cary, NC, USA). The resulting C_{50} and C_{90} data were subjected to analysis of variance (ANOVA) using the PROC GLM procedure in SAS 9.4 with sums of squares partitioned to reflect replicate, trial, and biotype, and means were separated with Fisher's protected least significant difference (LSD) test at $\alpha = 0.05$.

Field Evaluation of Annual Bluegrass Control and Turf Tolerance to Endothall

Four field studies were conducted in Blacksburg, VA, between February 2022 and June 2023 to evaluate annual bluegrass and warm-season turf response to endothall. Two field studies, one in 2022 (TRC1) and one in 2023 (TRC2), were conducted on a

Table 1. Herbicide-resistant annual bluegrass biotypes screened for endothall resistance.[a]

Biotype	Location collected	Growing condition	Putative resistance	Target site mutation
S1	Charlottesville, VA	Sports field	None	None detected
S2	Keswick, VA	Golf putting green	None	None detected
ALS1	Lansdowne, VA	Golf fairway	ALS	None detected
ALS2	Lansdowne, VA	Golf tee box	ALS	Trp574-Leu[b]
EPSP1	Chesterfield, VA	Golf fairway	EPSP	Pro106-Ala[c]
EPSP2	Keswick, VA	Golf fairway	EPSP	Pro106-Ala
MR	Laurel, VA	Sports field	ALS, PSII, HPPD, mitosis inhibitor	None detected

[a]Abbreviations: ALS, acetolactate synthase; ALS1/2, ALS-inhibitor-resistant population; EPSP, 5-enolpyruvylshikimate-3-phosphate; EPSP1/2, glyphosate-resistant population; HPPD, 4-hydroxyphenylpyruvate dioxygenase; MR, population with confirmed resistance to four herbicide modes of action; PSII, photosystem II; S1/2, susceptible population.
[b]Annual bluegrass ALS herbicide resistance due to a *Trp574-Leu* mutation was first reported by McElroy et al. (2013).
[c]Annual bluegrass glyphosate resistance due to a *Pro106-Ala* mutation was first reported by Cross et al. (2015).

Table 2. Trial locations and application timings of field-applied endothall.

				Application timing		
Year	Trial	Species	Cultivar	Fully dormant	Mid-transition	100% green
2022	TRC1	Hybrid bermudagrass	Tifway 419	Apr 5	Apr 25	May 12
2022	GRRF1	Manilagrass	Companion	Apr 5	Apr 25	May 12
2023	GRRF2	Hybrid bermudagrass	Latitude 36	Mar 16	Apr 26	May 10
2023	TRC2	Hybrid bermudagrass	Tifway 419	Mar 16	Apr 26	May 10

'Tifway 419' hybrid bermudagrass research fairway maintained at 1.5 cm height at the Virginia Tech Turfgrass Research Center (37.21°N, 80.41°W). Two additional field studies were conducted at the Glade Road Research Facility in 2022 (GRRF1) on 'Cavalier' manilagrass and in 2023 (GRRF2) on a 'Latitude 36' hybrid bermudagrass (Table 2). Both locations at the Glade Road Research Facility were research fairways maintained at 1.3 cm height throughout the study. All field trials were arranged as randomized complete-block designs with 13 treatments and four blocks. Treatments were arranged as a 3 × 4 factorial with three levels of application timing (fully dormant, 50% visible green turf coverage, and 100% visible green turf coverage) and four levels of herbicide treatment. The four levels of herbicide treatment were endothall (Teton®, United Phosphorus, Cary, NC, USA) applied at 1.12, 1.68, and 2.24 kg ai ha^{-1} and trifloxysulfuron (Monument®) applied at 27.8 g ai ha^{-1}. A nontreated comparison was included in all trials. Applications were applied via a CO_2-pressurized sprayer fitted with flat-fan TeeJet® 6503 nozzles (TeeJet® Technologies) and calibrated to deliver 375 L ha^{-1} at 330 kPa. Plots measured 0.9 × 1.8 m in size. Fully dormant, 50% green, and 100% green applications were made on April 5, April 25, and May 12 in 2022, respectively, and on March 16, April 26, and May 10 in 2023, respectively. Annual bluegrass had 80 to 120 tillers at the earliest application timing and >150 tillers at the mid-transition and fully green turf application timings.

Annual bluegrass control and turf green coverage were visually evaluated throughout the study as a percentage, where 0% equals no annual bluegrass control or no visible green turf, 100% equals complete annual bluegrass control or complete green turf coverage, and 80% annual bluegrass control was considered commercially acceptable. Turf injury was extrapolated from green coverage assessment by calculating the percent green coverage reduction in treated plots compared to the nontreated check. At the conclusion of the studies (~June 1), annual bluegrass density was measured via line-intersect grids that included 135 intersects at 5.5-cm increments within the treated portion of each plot. Final assessments of weed control were extrapolated from the line-intersect counts by comparing weed coverage in the nontreated check in each replication with the coverage in each treated plot. Data were subjected to ANOVA with sums of squares partitioned to reflect replicate and trial as random variables; herbicide, application timing, and Herbicide × Application Timing as fixed effects; and all possible interactions of trial with fixed effects. Terms that included trial interactions were tested with the mean square of residual error. The terms herbicide, application timing, and Herbicide × Application Timing were tested with the mean square associated with each term's interaction with trial, as described by McIntosh (1983). Main effects or interactions were pooled over trial only if trial interactions were insignificant. Appropriate means were separated with Fisher's protected LSD test at $\alpha = 0.05$.

Results and Discussion

Herbicide-Resistant Annual Bluegrass Response to Endothall

The trial × biotype interaction was significant for annual bluegrass C_{50} and C_{90} ($P = 0.0077$ and 0.0008, respectively); therefore results are presented separately by trial. The trial interaction was likely due to differences in endothall efficacy between the two trials with respect to the S2 biotype, as this was the only biotype to change the mean rank between trials for either C_{50} or C_{90} (Table 3). Although differences between biotypes other than S2 were similar in both trials, 26% to 53% more endothall was required to control annual bluegrass in Trial 1 compared to Trial 2 for all biotypes except S2 and EPSP2. The average amount of endothall needed to control susceptible annual bluegrass 90% was 1.6 kg ha^{-1} (Table 3). It was surmised that light intensity under greenhouse conditions was less than full sunlight, and this may have reduced endothall performance given the herbicide's MOA (Dodge 1982; Mayasich et al. 1986). In Trial 2, plants were moved outdoors under full sunlight at treatment time and remained for 3 d following treatment, and endothall more effectively controlled all biotypes except S2 and EPSP2. Similar differences occurred between field and greenhouse performances of endothall when 4.5 kg endothall ha^{-1} was required to reduce annual bluegrass foliar length in greenhouse studies in 1972 (Turgeon et al. 1972a).

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Table 3. Influence of biotype on endothall rate required to control annual bluegrass 50% and 90%.[a,b,c,d]

	C_{50}		C_{90}	
	Trial 1	Trial 2	Trial 1	Trial 2
Biotype	g ai ha^{-1}			
S1	2,347 bc	1,595 b	5,392 ab	2,649 b
S2	1,300 c	1,675 b	1,882 c	2,657 b
ALS1	1,810 bc	1,184 b	4,334 a–c	1,842 b
ALS2	1,660 bc	1,310 b	5,209 ab	2,530 b
EPSP1	2,602 b	1,818 b	3,589 bc	2,711 b
EPSP2	4,242 a	3,817 a	6,566 a	6,306 a
MR	2,265 bc	1,477 b	3,481 bc	2,314 b

[a]Abbreviations: ALS, acetolactate synthase; ALS1/2, ALS-inhibitor-resistant population; C_{50}, 50% control; C_{90}, 90% control; EPSP, 5-enolpyruvylshikimate-3-phosphate; EPSP1/2, glyphosate-resistant population; HPPD, 4-hydroxyphenylpyruvate dioxygenase; MR, population with confirmed resistance to four herbicide modes of action; PSII, photosystem II; S1/2, susceptible population.
[b]Letters following means indicate significant differences, according to Fisher's protected LSD test ($\alpha = 0.05$), within a given column.
[c]Biotypes were tested for putative resistance in previous studies, and only survivors of prescreened populations were used in the current study.
[d]Trial 1 remained under greenhouse supplemental lighting conditions throughout the duration of the study. However, annual bluegrass plants in Trial 2 were moved outdoors for 3 d immediately following application to mimic field light intensity.

Only EPSP2 required more endothall to achieve C_{50} than both susceptible populations in both trials (Table 3). Interestingly, EPSP2 and EPSP1 each had a Pro-106-Ala amino acid substitution on EPSPS, but only EPSP2 exhibited endothall resistance. This disparate endothall response in similar EPSP-resistant biotypes that had not been previously exposed to endothall indicates that the Pro-106-Ala substitution does not confer endothall resistance. The endothall resistance mechanism in EPSP2 is unknown. Previous research has indicated that annual bluegrass populations with nontarget site resistance can be resistant to novel MOAs (Brosnan et al. 2017), but there also may be other mechanisms that could explain the resistance of the EPSP2 population to endothall. It should be noted that ALS1 did not have an observed target site mutation and was not resistant to endothall. Non-target-site resistance is most observed in row crop systems but has been reported in annual bluegrass from turf systems. In an Alabama population, annual bluegrass resistance to PSII-inhibiting herbicides was conferred via reduced herbicide absorption and translocation (Syvantek et al. 2016). An annual bluegrass population in Tennessee resistant to multiple herbicide MOAs exhibited increased levels of transporter and metabolic enzymes (Brosnan et al. 2019). ALS1 and EPSP2 may exhibit different resistance mechanisms, leaving open the possibility of a nontarget site mechanism of resistance to endothall in EPSP2.

Field Evaluation of Annual Bluegrass Control and Turf Tolerance to Endothall

Over 90% of bermudagrass winter damage occurred at GRRF2. Therefore turf injury data were not collected at this location. Owing to differences in herbicide speed of activity between endothall and trifloxysulfuron, turf injury data were converted to the maximum observed injury over the assessment period. Maximum turf injury did not differ due to trial ($P \geq 0.1854$). However, the interaction of Herbicide × Application Timing was significant ($P = 0.0002$). Therefore data are pooled over trials, and the Herbicide × Application Timing interaction is shown (Table 4). Herbicides did not unacceptably (>30%) injure fully dormant turf, and only endothall applied at 2.24 kg ai ha^{-1} injured actively growing turf >30%. In general, semidormant turf was more sensitive to endothall than was fully dormant or green turf. These results align with previous literature, as warm-season turf is generally injured more by herbicides applied during postdormancy transition (Dernoeden 1994; Johnson 1976; Peppers and Askew 2023; Reed and McCullough 2014; Reed et al. 2015). Turf injury during postdormancy transition generally increased with endothall rate to as much as 60% (Table 4).

Despite unacceptable maximum injury at any endothall rate during postdormancy transition and the highest rate on green turf, turf recovered to acceptable levels by 14 d after treatment (DAT) for all treatments except the highest endothall rate applied to transitioning turf (Table 4). By 28 DAT, treatments did not injure turf more than 13% (data not shown). Hybrid bermudagrass putting greens responded similarly to endothall application timings and exhibited rapid recovery whenever bermudagrass was injured in other studies (Peppers and Askew 2023). Additionally, warm-season turf demonstrated endothall tolerance relative to historical reports of cool-season turf response (Engel and Aldrich 1960; Peppers et al. 2021; Turgeon et al. 1972a), which is consistent with studies that evaluated turf tolerance to endothall-contaminated irrigation water (e.g., Koschnick et al. 2005).

Although the three-way interaction of Trial × Herbicide × Application Timing on annual bluegrass control at the conclusion of the trial was significant ($P = 0.0495$), the low F-value for the interaction (2.6) compared to the Herbicide × Application Timing main effect ($F = 11.4$, $P = 0.002$) suggests that the interaction explains a small amount of the variance. The three-way interaction was likely significant due to variability in annual bluegrass control with trifloxysulfuron in relation to endothall treatments. For example, at GRRF1, trifloxysulfuron applied during mid-transition controlled annual bluegrass 93% and more than all endothall treatments. At GRRF2, trifloxysulfuron applied during mid-transition controlled annual bluegrass 72% and less than all endothall treatments (data not shown). Additionally, when trifloxysulfuron treatments were removed from the analysis, the trial interaction was no longer significant ($P = 0.7041$), indicating that trifloxysulfuron was the primary cause of the three-way interaction. For these reasons, data were pooled to show the Herbicide × Application Timing interaction, which was also significant ($P < 0.0001$) for clarity and brevity (Table 4).

Endothall applied to fully dormant turf controlled annual bluegrass 49% to 72%, depending on rate, and less at any given rate than when applied during or after postdormancy transition (Table 4). This reduction in endothall efficacy when applied during full dormancy may be attributed to a variety of factors. Temperature and sunlight intensity were inherently lower during the fully dormant applications. Average temperatures at the time of the fully dormant applications were 8 to 9 C, and average temperatures at the time of both later applications were 18 to 23 C (data not shown). Previous research has indicated that herbicide activity is positively correlated to temperature and light intensity (Dodge 1982; Kells et al. 1984; Mayasich et al. 1986; McWhorter and Azlin 1978; Wills and McWhorter 1981). Endothall applied at 1.68 and 2.24 kg ai ha^{-1} to postdormant turf controlled annual bluegrass 88% to 95% and equivalently to or better than trifloxysulfuron (Table 4).

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Table 4. Maximum observed turfgrass injury and end-of-season annual bluegrass control as influenced by herbicide at three application timings (dormant, mid-transition, and 100% green turf).[a,b]

Herbicide	Rate	Maximum observed turf injury				Annual bluegrass control			
		Dormant	Mid-transition	100% green	LSD[c]	Dormant	Mid-transition	100% green	LSD
	g ai ha^{-1}	%							
Endothall	1,120	6 b	32 b	13 bc	11	49 b	77 b	83 c	10
	1,680	28 a	43 b	21 b	17	71 a	88 a	90 ab	9
	2,240	24 ab	60 a	35 a	19	72 a	91 a	95 a	10
Trifloxysulfuron[d]	27.8	18 ab	11 c	3 c	12	83 a	86 a	89 bc	9

[a]Letters following means indicate significant differences, according to Fisher's protected LSD test (α =0.05), within a given column.
[b]Annual bluegrass control was derived via line-intersect counts that included 135 intersects at 5.5-cm increments within the treated portion of each plot. Final assessments of weed control were extrapolated from the line-intersect counts by comparing weed coverage in the nontreated check in each replication with the coverage in each treated plot.
[c]Statistical significance, according to Fisher's protected LSD test (α =0.05), within rows for a given rating metric.
[d]Non-ionic surfactant was included at 0.25% v/v in all trifloxysulfuron treatments.

These results indicate that endothall controls annual bluegrass acceptably at any of the rates tested when applied to fully green turf and injures bermudagrass not more than 21% at rates of 1.68 kg ha^{-1} or lower. Endothall does not injure fully dormant turf, but single treatments are unlikely to acceptably control annual bluegrass at this timing. Endothall should not be applied to bermudagrass during postdormancy transition unless severe but transient injury can be tolerated. To avoid turf injury, it may be possible to make multiple applications of endothall or include other herbicide admixtures. Previous research has indicated that multiple endothall applications at lower rates control annual bluegrass more effectively than do single endothall applications at higher rates (Turgeon et al. 1972a). All annual bluegrass evaluated in this study had >80 tillers at the time of application, and endothall may more effectively control relatively less mature annual bluegrass, as weed growth stage regularly affects herbicide activity (Bellinder et al. 2003; Busey 2004; Peppers et al. 2024; Steckel et al. 1997). Additionally, surfactant was not included with endothall in these studies. Adjuvants like non-ionic surfactants or crop oil concentrates can increase herbicide efficacy (Norsworthy and Grey 2004; Riechers et al. 1994; Sherrick et al. 1986) and may increase annual bluegrass control by a given endothall rate.

Practical Implications

Results from these studies indicate that endothall can provide selective annual bluegrass control in warm-season turf species, even on herbicide-resistant annual bluegrass populations if mid-transition treatments are avoided. Endothall applied at rates of 1.12 and 1.68 kg ai ha^{-1} controls annual bluegrass when applied to fully green turf; however, annual bluegrass is unlikely to be controlled more than 75% when single treatments are applied during dormancy. Turf was most tolerant to endothall when it was applied during full dormancy. To improve weed control while capitalizing on turf safety during dormancy, future research should evaluate herbicide and surfactant admixtures with endothall applied at earlier application timings. To reduce the potential for phytotoxicity on fully green turf, postapplication irrigation should be investigated as a means to reduce foliar injury because endothall is translocated primarily acropetally (Turgeon et al. 1972b). Sequential herbicide applications at lower rates are commonly more effective than single applications at higher rates (Willis et al. 2006) and should be investigated for their potential to improve annual bluegrass control in dormant or green turf and to reduce phytotoxicity in green turf.

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