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Mesotrione and Amicarbazone Tank-mixtures for Annual Bluegrass (*Poa annua*) Control in Cool-season Turfgrass

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Abstract. **Annual bluegrass (*Poa annua* L.) control with postemergence herbicides in cool-season turfgrass is often inconsistent. Amicarbazone and mesotrione have complementary modes of action but have not been evaluated in tank-mixtures for control of mature annual bluegrass in cool-season turfgrass. Field experiments were conducted during 2018 in New Jersey, and in Indiana, Iowa, and New Jersey during 2019 to evaluate springtime applications of amicarbazone and mesotrione for POST annual bluegrass control in cool-season turfgrass. On separate tall fescue (*Festuca arundinacea* Schreb.) and kentucky bluegrass (*Poa pratensis* L.) sites in 2018, three sequential applications of amicarbazone (53 g·ha^{-1}) + mesotrione at 110 to 175 g·ha^{-1} provided >70% annual bluegrass control, whereas three sequential applications of amicarbazone alone at 53 and 70 as well as two sequential applications at 110 g·ha^{-1} provided <15% control at 14 weeks after initial treatment (WAIT). In 2019, results in New Jersey were similar to 2018 where amicarbazone alone provided less control than mesotrione + amicarbazone tank-mixtures. In Indiana, where the annual bluegrass infestation was severe and most mature, tank-mixtures were more effective than amicarbazone alone at 6 WAIT, but at 12 WAIT all treatments provided poor control. In Iowa, where the annual bluegrass infestation was <1 year old, all treatments provided similar control throughout the experiment and by >80% at the conclusion of the experiment. This research demonstrates that sequential applications of mesotrione + amicarbazone can provide more annual bluegrass control than either herbicide alone, but efficacy is inconsistent across locations, possibly due to annual bluegrass maturity and infestation severity.**

Annual bluegrass (*Poa annua* L.) often invades and persists in intensively managed cool-season turfgrass systems (Beard, 1973). A lack of heat, drought, and disease tolerance compared with other cultivated turfgrass species makes it difficult to manage and thus it is often considered a weed (Beard et al., 1978). Annual bluegrass often behaves as a perennial, particularly where cool-season turfgrasses are intensively managed, and preemergence herbicides are not an effective control option (Carroll et al., 2021; Reicher et al., 2017).

Selective postemergence annual bluegrass control in cool-season turfgrass is difficult due to limited efficacy of selective herbicides. Recent herbicide investigations in cool-season turfgrass have focused primarily on amicarbazone, bispyribac-sodium, ethofumesate, and mesotrione. Limited tolerance of cultivated cool-season turfgrasses hampers amicarbazone and bispyribac-sodium efficacy, and these herbicides are typically used at lower rates in sequential application programs (Jeffries et al., 2013; McCullough and Hart, 2008, 2009, 2010; McCullough et al., 2010; McDonald et al., 2006; Patton et al., 2019; Reicher et al., 2015; Shortell et al., 2008; Yu et al., 2013). Similarly, ethofumesate requires sequential applications and is most effective in perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea* Schreb.) where it can be applied at higher rates than in kentucky bluegrass (*Poa pratensis* L.) or creeping bentgrass (*Agrostis stolonifera* L.) (Adams, 1989; Dernoeden and Turner, 1988; Park et al., 2019; Woosley et al., 2003).

Although turfgrass tolerance to amicarbazone and bispyribac-sodium limits efficacy, mesotrione is considerably safer to most cool-season turfgrass species; however, postemergence annual bluegrass control with mesotrione is often difficult to achieve and inconsistent across locations and years (Park et al., 2019; Reicher et al., 2011; Skelton et al., 2012; Sousek and Reicher, 2019). Variable efficacy is often attributed to environmental conditions near the time of application, different annual bluegrass biotypes, and maturity (Gonçalves et al., 2021; McElroy et al., 2004; Reicher et al., 2011; Skelton et al., 2012; Yu and McCullough, 2016). Because of limited efficacy, mesotrione is not labeled for postemergence annual bluegrass control (Anonymous, 2010). Nevertheless, considerable research has been conducted investigating strategies to improve mesotrione efficacy for annual bluegrass control. Investigating frequent low-rate applications, Skelton et al. (2012) found that seven to ten applications of mesotrione at 56 or 84 g·ha^{-1} provided more consistent annual bluegrass control than three to five applications at 110 to 186 g·ha^{-1}. Other research found that N fertilizer applications increased mesotrione activity against annual bluegrass (Elmore et al., 2013b). A program of prodiamine applied preemergence followed by three sequential applications of mesotrione (175 g·ha^{-1}) provided more annual bluegrass control than either herbicide alone in Nebraska (Reicher et al., 2017).

Amicarbazone is a photosystem II (PSII)-inhibiting herbicide and mesotrione is an p-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor (Dayan et al., 2009; Mitchell et al., 2001). These herbicide modes of action are complementary, and tank-mixtures of HPPD and PSII-inhibiting herbicides are often synergistic against weeds of various cropping systems, first reported by Sutton et al. (2002). In turfgrass, Elmore et al. (2013a) found tank-mixtures of amicarbazone and mesotrione were synergistic for annual bluegrass control in greenhouse experiments. Field experiments in an overseeded perennial ryegrass fairway in Tennessee found single applications of mesotrione at 280 g·ha^{-1} provided 78% annual bluegrass control; when mesotrione was tank-mixed with amicarbazone (75 g·ha^{-1}), control increased to 97%. Work of Elmore et al. (2013a) was conducted in Tennessee on juvenile annual bluegrass with 2 to 10 tillers that behaved as an annual, and the researchers suggested that mesotrione + amicarbazone tank-

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mixtures be evaluated on more mature and perennial annual bluegrass. For example, in the work of Elmore et al. (2013a) on juvenile plants, a single mesotrione application at 280 g·ha^{-1} provided more control than sequential mesotrione applications (totaling 560 g·ha^{-1}) on presumably larger and more perennial plants in the work of Reicher et al. (2011, 2017) and Skelton et al. (2012). Yu and McCullough (2016) found multitiller annual bluegrass and kentucky bluegrass metabolized mesotrione twice as rapidly as one-tiller plants. Greater annual bluegrass maturity may explain the lack of mesotrione efficacy observed in cooler climates. Given the limited efficacy of mesotrione in cool-season turfgrass, and improved efficacy of mesotrione + amicarbazone tank-mixtures on juvenile annual bluegrass plants in overseeded bermudagrass (*Cynodon* spp.), the objective of this research was to evaluate the efficacy of mesotrione and amicarbazone tank-mixtures on mature annual bluegrass in cool-season turfgrass.

Materials and Methods

2018 field experiments

An experiment was conducted at the Rutgers Plant Science Research and Extension Farm in Freehold, NJ (lat. 40°13'27.3″N, long. 74°15'09.7″W) on turfgrass naturally infested with annual bluegrass. The experiment was repeated on two sites in adjacent fields, mown weekly during the growing season (April to November) at 4.0 cm and irrigated as necessary to prevent annual bluegrass wilt. The first site was a 2.5-year-old stand of 'Baron' kentucky bluegrass (*Poa pratensis* L.) and the other site was a 2.5-year-old stand of 'Regenerate' tall fescue (*Festuca arundinacea* Schreb.). See Table 1 for more information on the annual bluegrass infestation, which observations suggest most plants in the population behaved as perennials at both sites. The soil was a Holmdel sandy loam (fine-loamy, mixed, active, mesic Aquic Hapludult) with a pH of 6.5. Nitrogen fertilizer (20N–0P–5K; urea nitrogen, 50% from polymer coated urea; LESCO Inc., Cleveland, OH) totaling 100 kg N/ha/yr was applied in the spring and autumn. Fungicides were applied preventatively to prevent diseases common to annual bluegrass. Fungicides were applied on 15 May, 19 and 29 June, 27 July, and 15 Aug. (azoxystrobin, difenoconazole, chlorothalonil, thiophanate-methyl, pyraclostrobin, and fludioxonil fungicide active ingredients were used). Dithiopyr (Dimension 2EW; Dow AgroSciences LLC, Indianapolis, IN) was applied on 30 Apr. and 8 June at 280 g·ha^{-1} for summer annual grass control. Imidacloprid (Merit 75 WSP; Bayer Environmental Science, Cary, NC) was applied at 340 g·ha^{-1} on 8 June for white grub (*Phyllophaga* spp.) control. The degree to which turfgrass management practices (i.e., irrigation, mowing, fertilizer, and fungicide use) or annual bluegrass genetics contributed to perennial annual bluegrass behavior at the site is not known.

Treatments consisted of three amicarbazone-only programs and four amicarbazone + mesotrione tank-mixture programs. Herbicide program details are provided in Table 2. Amicarbazone-only programs were based on the Xonerate 2SC product label for use in cool-season turfgrass. Amicarbazone was applied using Xonerate 2SC (FMC Corp., Philadelphia, PA). Mesotrione was applied using Tenacity (Syngenta Crop Protection, LLC, Greensboro, NC). Mesotrione + amicarbazone were tank-mixed. All treatments were applied with a nonionic surfactant (NIS; Activator 90; Loveland Products Inc., Loveland, CO) at 0.25% v/v per the product label instructions. Treatments were initiated on 26 Apr. 2018 at both sites. Sequential applications were made on 10 May, 17 May, and 22 May. Treatments were applied with water carrier at 410 L·ha^{-1} through a single 8002EVS nozzle using a hand-held CO_2-pressurized (300 kPa) sprayer. Treatments were applied to plots (0.9 m × 3.0 m with a 0.3-m nontreated border between each plot) arranged in a randomized complete block design with four blocks (replicates) at each site. Air temperatures after application are listed in Table 3.

2019 experiments

To evaluate the findings of the 2018 experiments in multiple locations, replicate experiments were conducted in Freehold, NJ, West Lafayette, IN, and Ames, IA, in 2019. Treatments consisted of three sequential applications of various herbicide programs shown in Table 2. Herbicide and NIS materials are the same as described above in 2018 experiments. Herbicide programs were based on the most efficacious mesotrione + amicarbazone programs from the 2018 experiment. When amicarbazone was applied alone in 2018 experiments, annual bluegrass control was unaffected by herbicide rate (53, 70, 110 g·ha^{-1}), but turfgrass injury increased with rate. Therefore, amicarbazone was evaluated only at 53 g·ha^{-1} in 2019 experiments. Amicarbazone and mesotrione alone were included for comparison. The mesotrione + amicarbazone + urea ammonium nitrate (UAN) treatments were based on previous research that found UAN or other pH-reducing adjuvants improved mesotrione efficacy (Idziak and Woznica, 2008; Penner, 2000; Xie et al., 2011). The addition of urea and ammonium sulfate to mesotrione + amicarbazone was based on research that found improved mesotrione efficacy when N fertilizer is applied (Cathcart et al., 2004). In turfgrass, mesotrione controlled crabgrass (*Digitaria* spp.) better when N was applied at ≥ 10 kg·ha^{-1} within 3 d of mesotrione application (Beck et al., 2015; Elmore at al., 2012).

New Jersey. The Freehold, NJ, site was the same as described for 2018 experiments in terms of soil characteristics and turfgrass management regimens. In 2019, the sites were adjacent 'Dauntless' kentucky bluegrass and 'Revenge GLX' perennial ryegrass (*Lolium perenne* L.) stands with natural infestations of annual bluegrass. See Table 1 for more information on the annual bluegrass infestation, which exhibited perennial behavior at the kentucky bluegrass site with a creeping growth habit and cover increase during summer. At the perennial ryegrass site, annual bluegrass exhibited a more upright growth habit and cover decreased during the summer, suggesting weak perennial or annual behavior. The degree to which turfgrass management practices (i.e., irrigation, mowing, and fungicide

Table 1. Site characteristics and annual bluegrass infestation for experiments conducted in Freehold, NJ, in 2018 and in Freehold, NJ, West Lafayette, IN, and Ames, IA, in 2019 to evaluate herbicide programs for postemergence annual bluegrass control.

Location	Yr	Turfgrass species	Annual bluegrass growth habit[z]	Spring annual bluegrass cover (%)[y]	Midsummer annual bluegrass cover (%)	Age of annual bluegrass infestation (yr)[x]	Fungicides applied[w]
Freehold, NJ	2018	Kentucky bluegrass	Creeping	31	62	2.5	Yes
Freehold, NJ	2018	Tall fescue	Creeping	68	86	2.5	Yes
Freehold, NJ	2019	Kentucky bluegrass	Creeping	31	48	2.5	Yes
Freehold, NJ	2019	Perennial ryegrass	Upright	16	10	<1	Yes
West Lafayette, IN	2019	Perennial ryegrass	Creeping	76	41	10	No
Ames, IA	2019	Kentucky bluegrass	Upright	52	34	<1	No

[z]Plants exhibited a creeping growth habit (i.e., elongated, branched stems growing along the ground that develop roots at the nodes) characteristic of *Poa annua* var. *reptans* (Hausskn.) T. Koyama or upright habit (i.e., bunch-type growth habit, no stoloniferous growth) characteristic of *P. annua* subsp. *erecta* (Carroll et al., 2021).

[y]Visual estimate of mean annual bluegrass cover in the nontreated plots on a 0% (no cover) to 100% (complete annual bluegrass cover) scale in April or May and in midsummer (late July or August).

[x]The number of years annual bluegrass had been established at each site before the experiment was initiated.

[w]Fungicides were applied sequentially during the growing season preventatively to control dollar spot (caused by *Clarireedia jacksonii*), brown patch (caused by *Rhizoctonia solani*), and summer patch (caused by *Magnaporthe poae*) diseases.

Table 2. Herbicide treatments applied for postemergence annual bluegrass control in Freehold, NJ, during 2018 and 2019 as well as Ames, IA, and West Lafayette, IN, in 2019. Programs in 2018 were initiated on 26 Apr. on kentucky bluegrass and tall fescue in New Jersey. Programs in 2019 were initiated on 24 Apr. in Indiana on perennial ryegrass; 25 Apr. in New Jersey on kentucky bluegrass, perennial ryegrass, and tall fescue; and on 24 May on kentucky bluegrass in Iowa.

Herbicide	Rate ($g \cdot ha^{-1}$)	Applications (#)	Interval (wk)
2018 Treatments			
Amicarbazone[z]	53	3	2
Amicarbazone	70	3	2
Amicarbazone	110	2	3
Amicarbazone + mesotrione	53 + 110	3	2
Amicarbazone + mesotrione	53 + 140	3	2
Amicarbazone + mesotrione	53 + 175	3	2
Amicarbazone + mesotrione	53 + 280	2	2
2019 Treatments			
Amicarbazone	53	3	2
Mesotrione	175	3	2
Amicarbazone + mesotrione	53 + 110	3	2
Amicarbazone + mesotrione	53 + 140	3	2
Amicarbazone + mesotrione	53 + 175	3	2
Amicarbazone + mesotrione + UAN[y]	53 + 110 + 6.6 L	3	2
Amicarbazone + mesotrione + urea + AMS[x]	53 + 110 + 2.5 kg + 12.5 kg	3	2

[z]All treatments were applied with NIS at 0.25% v/v.
[y]Urea ammonium nitrate (UAN, 30N–0P–0K).
[x]Urea (46N–0P–0K) and ammonium sulfate (AMS, 21N–0P–0K) were dissolved in spray solution.

use) or annual bluegrass genetics contributed to perennial annual bluegrass behavior is not known. An additional experiment was conducted on mature 'Traverse II' tall fescue to evaluate turfgrass tolerance. No annual bluegrass was present on this site. The location, soil, and management were the same as described previously for the 2018 perennial ryegrass and kentucky bluegrass experiments. Plots were sized and arranged in the same way as described for the 2018 experiment. Treatments were applied in the same manner as in the 2018 experiment on 25 Apr., 9 May, and 22 May 2019 to all three sites.

Indiana. Research was conducted at the William H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN (lat. 40°26′31″N, long. 86°55′53″W), on a 10-year-old perennial ryegrass (cultivars unknown) sward mown weekly at 1.3 cm. Annual bluegrass cover decreased slightly from spring to summer but the site was heavily infested (Table 1). The soil was a Starks-Fincastle silt loam (fine-silty, mixed, mesic Aeric Ochraqualf) with a pH of 6.7. Fertilizer was applied at 37 $kg \cdot ha^{-1}$ N on 5 June 2019 (Shaw's 24N–0P–22K Fairways Grade; Knox Fertilizer Company, Knox, IN) but no other fertilizer was added during the experimental period. Irrigation was applied as needed to prevent drought stress. Plots were sized 1.5 × 1.5 m and arranged in a randomized complete block design with four replications. Treatments were applied with water carrier at 815 $L \cdot ha^{-1}$ through a three-nozzle boom equipped with flat fan nozzles (XR8003VS, Teejet; Spraying Systems Co., Glendale Heights, IL) using a CO_2-pressurized (207 kPa) sprayer on 24 Apr., 10 May, and 27 May 2019.

Iowa. Research was conducted at Coldwater Golf Links in Ames, IA (lat. 42°1′36″N, long. 93°37′12″W), on kentucky bluegrass (cultivars unknown) rough mown at 4 cm. The annual bluegrass at the Iowa site was <1 year old, as the site was free of annual bluegrass before a flood in Summer 2018. The flood killed some kentucky bluegrass and allowed annual bluegrass to establish in Fall 2018. Annual bluegrass cover declined slightly from spring to summer at this site, suggesting annual or weak perennial behavior (Table 1). The soil was a Clarion Loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll containing 5.2% organic matter). The site was fertilized with 112 $kg \cdot ha^{-1}$ N annually (Lesco 28N–0P–3K; SiteOne Landscape Supply, Roswell, GA) applied in three applications and supplemented with 2.5 cm irrigation per week. Plots were sized 1.5 × 3.0 m and arranged in a randomized complete block design with four replications. Treatments were applied with water carrier at 420 $L \cdot ha^{-1}$ through flat fan nozzles (XR8003VS, Teejet; Spraying Systems Co.) hand-held CO_2-pressurized (280 kPa) sprayer on 24 May, 7 June, and 24 June.

Data collection. In 2018, annual bluegrass control was estimated visually on a 0% (no injury or control) to 100% (complete necrosis and/or weed absence) scale relative to the nontreated control. Turfgrass (kentucky bluegrass, perennial ryegrass or tall fescue) injury was evaluated visually when it was apparent on a 0% (no injury) to 100% (complete necrosis) scale relative to the nontreated control. Turfgrass injury <20% is generally considered acceptable by turf practitioners. Annual bluegrass cover was evaluated visually on a 0% (no cover) to 100% (complete cover) scale on

Table 3. Air temperatures for weeks following the initial herbicide application at each site. Data were collected from weather stations in Freehold, NJ, in 2018 and Freehold, NJ, West Lafayette, IN, and Ames Iowa in 2019. Air temperatures are presented for the 6 weeks after initial treatments.

	Freehold 2018[z]		Freehold 2019		Indiana 2019[y]		Iowa 2019[x]	
Weeks after initial application	Avg[w] (°C)	Max[v] (°C)	Avg (°C)	Max (°C)	Avg (°C)	Max (°C)	Avg (°C)	Max (°C)
1	14	21	12	18	12	16	19	24
2	18	25	13	18	15	22	23	28
3	16	22	13	19	12	18	20	26
4	17	21	19	26	18	24	20	25
5	20	26	20	26	22	28	23	27
6	19	25	20	27	20	27	26	32

[z]Weather stations maintained by the Rutgers, NJ, Weather Network collected air temperature on 5-min intervals.
[y]On-site weather station maintained by the Purdue Turf Program collected air temperature on 1-h intervals.
[x]Weather station maintained by Iowa Environmental Mesonet collected air temperature on 1-h intervals.
[w]Average air temperature for the entire 7-d period of observation.
[v]Average of the maximum 24-h air temperatures observed for the 7-d period of observation.

the day of initial herbicide application and at the conclusion of the experiment in early autumn. In 2019, annual bluegrass control was not evaluated, but annual bluegrass cover was transformed and expressed as percent reduction (or increase) in cover compared with the initial application date on a plot-by-plot basis. To supplement visual estimates, a grid intersect count was used to determine annual bluegrass cover at the final evaluation in both years at all sites. The presence or absence of annual bluegrass was determined under each intersect. In New Jersey, a 0.8 × 0.9-m grid with 90 intersects was placed twice in each plot for a total of 180 intersects in 2018 and a 0.8 × 0.8-m grid with 80 evenly spaced intersects for a total of 160 intersects in 2019. The grid was placed systematically, the 0.8-m grid width centered within the 0.9-m width of each plot; the grid was first placed one-half of the 3.0 m plot length and then moved to the other half for the second count. In Iowa, counts were conducted using a 0.8 × 0.8-m grid with 49 evenly spaced intersects placed twice in each plot; the grid placed in the same way as described previously for the New Jersey location. Count data were pooled within each plot and not treated as subsamples. In Indiana, a 1.0 × 1.0-m grid with 81 evenly spaced intersects was placed once in the center of each plot. Grid intersect counts were transformed to express annual bluegrass as percent cover. Grid counts and final visual ratings were conducted on 30 Sept. in Indiana at 22 WAIT, 18 Oct. in Iowa (21 WAIT), and 10 Oct. in New Jersey (23 WAIT) in 2019 and on 15 Aug. in 2018 (14 WAIT) at both New Jersey sites.

Statistical analysis. Data from all experiments were analyzed as a single-factor randomized complete block design ($P = 0.05$). Data were not transformed based on residual analysis (Shapiro–Wilk statistic) in SAS (Statistical Analysis Software, Inc., Cary, NC). Analysis of variance was performed using the mixed-model procedure in SAS and Fisher's Protected least significant difference ($P = 0.05$) was used to compare means (Saxton, 2010). Treatment interactions with location were significant ($P < 0.05$), so data from each location are presented separately. Treatment and location effects were fixed and block effects were considered random in the mixed-model analysis.

Results

2018 experiments

Results from the tall fescue and kentucky bluegrass sites are presented separately as significant location-by-treatment interactions were detected ($P < 0.05$).

Annual bluegrass control. Amicarbazone alone controlled annual bluegrass ≤20% at all rating dates at both sites (Table 4). According to grid intersect counts at 14 WAIT, amicarbazone-alone programs did not reduce annual bluegrass cover compared with the nontreated control. In previous research, similarly poor annual bluegrass control was reported from two springtime amicarbazone applications at 100 $g \cdot ha^{-1}$ in Indiana (McCullough et al., 2010).

All mesotrione + amicarbazone tank-mixtures controlled annual bluegrass control more than amicarbazone alone from 4 to 14 WAIT at both sites. Tank-mixtures containing mesotrione at 175 $g \cdot ha^{-1}$ provided more control than at 110 and 140 $g \cdot ha^{-1}$ at 4 WAIT. Tank-mixtures containing mesotrione at 110, 140, and 175 $g \cdot ha^{-1}$ provided similar annual bluegrass control from 6 and 14 WAIT at both sites, suggesting that sequential applications muted effects of rate. The tank-mixture containing mesotrione at 280 $g \cdot ha^{-1}$ provided less control than other tank-mixtures at 6, 9, and 14 WAIT at the tall fescue site but not the kentucky bluegrass site. This indicates three sequential applications provide more control than two, just as Skelton et al. (2012) found. Although a direct statistical comparison cannot be made, treatments generally provided more control at the kentucky bluegrass site. We attribute the efficacy difference to a more severe annual bluegrass infestation at the tall fescue site (68% annual bluegrass cover compared with 32% at the kentucky bluegrass site 0 WAIT) combined with the rhizomatous growth of kentucky bluegrass that competes better with annual bluegrass.

Annual bluegrass grid intersect data support visual estimations. At the kentucky bluegrass site, grid counts determined annual bluegrass cover was 2% to 6% for mesotrione + amicarbazone tank-mixtures and 33% to 42% for amicarbazone alone and the nontreated. At the tall fescue site, annual bluegrass cover according to grid counts was 35% to 36% for tank-mixtures containing mesotrione at 110, 140, and 175 $g \cdot ha^{-1}$ compared with 50% to 58% for amicarbazone alone and the nontreated. Control provided by amicarbazone alone was negligible in both experiments and would not be considered commercially acceptable.

Turfgrass injury. Injury was only assessed in the kentucky bluegrass trial, as tall fescue density was too low to accurately assess injury. Injury was greatest at 4 WAIT and will be discussed but is not presented in a table. Amicarbazone alone at 53 and 70 $g \cdot ha^{-1}$ caused <10% injury at 4 WAIT. The

Table 4. Annual bluegrass control and cover following postemergence herbicide programs in Freehold, NJ, during 2018. Programs in 2018 were initiated on 26 Apr. on 'Baron' kentucky bluegrass and 'Regenerate' tall fescue. Annual bluegrass control was evaluated visually on a 0% (no injury or control) to 100% (complete necrosis and/or weed absence) percent scale relative to the nontreated control.

		Annual bluegrass control (%)[z]								ABG cover reduction (%)[y]		ABG cover (%)[x]	
		4 WAIT		6 WAIT		9 WAIT		14 WAIT		14 WAIT		14 WAIT	
Herbicide	Rate ($g \cdot ha^{-1}$)	KBG	TF	KBG	TF	KBG	TF	KBG	TF	KBG	TF	KBG	TF
Amicarbazone[w]	53	5 d[v]	3 d	11 c	6 c	4 bc	0 d	11 c	10 c	−22 b	−18 c	41 a	50 ab
Amicarbazone	70	16 cd	11 cd	20 b	11 c	10 bc	0 d	10 c	10 c	−78 c	−26 c	39 a	58 a
Amicarbazone	110	20 c	16 c	15 bc	10 c	13 b	0 d	9 c	3 c	−103 c	−24 c	33 a	52 ab
Amicarbazone + mesotrione	53 + 110	38 b	52 b	90 a	94 a	86 a	82 b	92 ab	72 a	83 a	66 a	4 b	36 c
Amicarbazone + mesotrione	53 + 140	44 b	53 b	93 a	91 a	90 a	83 b	94 a	76 a	88 a	64 a	2 b	35 c
Amicarbazone + mesotrione	53 + 175	58 a	70 a	90 a	96 a	94 a	91 a	95 a	78 a	94 a	65 a	2 b	35 c
Amicarbazone + mesotrione	53 + 280	65 a	81 a	85 a	85 b	83 a	71 c	89 b	51 b	76 a	24 b	6 b	46 bc
Nontreated	—	—	—	—	—	—	—	—	—	−99 c	−29 c	42 a	54 ab
P value	***	***	***	***	***	***	***	***	***	***	***	***	

[z]Annual bluegrass control on a 0% (no injury) to 100% (complete necrosis) scale as determined by visual estimates relative to the nontreated control.

[y]Annual bluegrass cover reduction was calculated on a plot-by-plot basis using visual cover estimates as follows: percent cover reduction = {[1 – (annual bluegrass cover at 14 WAIT/annual bluegrass cover at 0 WAIT)] × 100}

[x]Cover was determined by placing a 0.8 × 0.9-m grid with 90 intersects twice in each plot for a total of 180 intersects to determine the presence or absence of annual bluegrass.

[w]Initial applications were made on 26 Apr. 2018. Two sequential applications were made on 10 May and 22 May for treatments containing amicarbazone at 53 and 70 $g \cdot ha^{-1}$. One sequential application was made on 17 May for amicarbazone at 110 $g \cdot ha^{-1}$ and amicarbazone + mesotrione at 280 $g \cdot ha^{-1}$. All treatments included a nonionic surfactant at 0.25% (v/v).

[v]Any two means within a column not followed by the same letter are significantly different according to Fisher's Protected least significant difference test ($P = 0.05$).

ABG = annual bluegrass; KBG = kentucky bluegrass; TF = tall fescue; WAIT = weeks after initial treatment.

***Significant at $P \leq 0.001$.

Table 5. Annual bluegrass cover reduction following sequential postemergence herbicide applications in Freehold, NJ (NJ), West Lafayette, IN (IN), and Ames, IA (IA) during 2019. Initial applications were made on 24 Apr., 25 Apr., and 24 May in New Jersey, Indiana, and Iowa, respectively. Two sequential applications were made at 2-week intervals following the initial application. Experiments were conducted on kentucky bluegrass and perennial ryegrass sites in New Jersey, perennial ryegrass in Indiana, and kentucky bluegrass in Iowa.

		Annual bluegrass cover reduction (%)[z]												Annual bluegrass cover (%)[y]			
		6 WAIT				12 WAIT				Final[x]				Final			
Herbicide	Rate (g·ha^{-1})	NJ KBG	NJ PR	IN	IA	NJ KBG	NJ PR	IN	IA	NJ KBG	NJ PR	IN	IA	NJ KBG	NJ PR	IN	IA
Amicarbazone[w]	53	27 b[v]	28 c	31 d	100 a	2 bc	54 bcd	69 ab	97 ab	27 d	54 d	72 a	97 a	15 a	27	46	9 b
Amicarbazone + mesotrione	53 + 110	70 a	63 a	64 bc	88 a	39 ab	91 a	69 ab	85 b	72 bc	91 a	70 a	81 a	9 bc	17	49	20 b
Amicarbazone + mesotrione	53 + 140	83 a	76 a	59 c	100 a	73 a	80 ab	75 ab	100 a	88 ab	80 abc	77 a	92 a	6 cd	13	38	15 b
Amicarbazone + mesotrione	53 + 175	79 a	75 a	77 a	100 a	90 a	88 a	82 a	100 a	92 a	88 ab	80 a	100 a	3 d	12	38	8 b
Mesotrione	175	32 b	35 bc	27 de	88 a	−37 cd	67 abc	60 bc	100 a	68 c	67 bcd	70 a	100 a	9 abc	17	44	11 b
Amicarbazone + mesotrione + UAN[u]	53 + 110	78 a	59 ab	67 abc	100 a	66 ab	77 ab	76 ab	100 a	77 abc	77 abcd	76 a	91 a	7 cd	16	34	11 b
Amicarbazone + mesotrione + urea + AMS[t]	53 + 110	66 a	58 ab	74 ab	100 a	74 a	53 bcd	75 ab	100 a	73 bc	56 cd	73 a	75 a	9 bc	22	41	17 b
Nontreated	—	7 b	−17 d	17 e	0 b	−77 d	29 d	46 c	18 c	44 d	29 e	56 b	10 b	14 ab	21	52	50 a
P value		***	***	***	***	***	***	**	***	***	***	*	***	**	NS	NS	***

[z]Annual bluegrass cover reduction was calculated on a plot-by-plot basis using visual cover estimates as follows: percent cover reduction = {[1 – (annual bluegrass cover at the indicated interval/annual bluegrass cover at 0 WAIT)] × 100}

[y]Cover as determined by grid intersect counts transformed to be expressed as percent cover.

[x]Final ratings were taken on 10 Oct. 2019 (23 WAIT) in New Jersey, 30 Sept. 2019 (22 WAIT) in Indiana, and 18 Oct. (21 WAIT) in Iowa.

[w]All treatments included a nonionic surfactant at 0.25% (v/v).

[v]Any two means within a column not followed by the same letter are significantly different according to Fisher's Protected LSD test (P = 0.05).

[u]Mesotrione and amicarbazone tank-mixed with urea ammonium nitrate (UAN, 30N–0P–0K) at 6.6 L·ha^{-1}.

[t]Mesotrione and amicarbazone tank-mixed with dissolved urea (46N–0P–0K) at 2.5 kg·ha^{-1} N and ammonium sulfate (AMS, 21N–0P–0K) at 12.5 kg·ha^{-1} N.

KBG = kentucky bluegrass; PR = perennial ryegrass; WAIT = weeks after initial treatment.

NS, *, **, ***Nonsignificant or significant at $P \leq$ 0.05, 0.01, or 0.001, respectively.

110 g·ha^{-1} regimen caused 15% injury, slightly more than the 6% injury reported from a similar regimen evaluated on kentucky bluegrass by McCullough et al. (2010). All amicarbazone + mesotrione combinations caused more injury than amicarbazone (53 g·ha^{-1}) alone. Amicarbazone + mesotrione at 280 g·ha^{-1} caused 34% injury, more than amicarbazone (53 g·ha^{-1}) + mesotrione at 110 and 140 g·ha^{-1}, which caused 21% and 23% injury, respectively.

2019 experiments

Treatment-by-location interactions were detected ($P < 0.05$) on all rating dates. Interactions were also detected in New Jersey data. Thus, data from each location are presented separately.

Annual bluegrass control. The efficacy of amicarbazone + mesotrione tank-mixtures with UAN or urea + AMS was usually not different from the herbicides alone and is not discussed (Table 5). At 6 WAIT, mesotrione + amicarbazone tank-mixtures reduced annual bluegrass cover 59% to 83% in Indiana and at both New Jersey sites. Mesotrione and amicarbazone alone reduced annual bluegrass cover 27% to 35% and were less effective than the tank-mixture. In Iowa, the efficacy of all treatments was 88% to 100% at 6 WAIT.

At 12 WAIT, efficacy across sites was more variable. In Iowa, all treatments reduced annual bluegrass cover by ≥85% and there were generally no differences between treatments. In Indiana, only amicarbazone + mesotrione at 175 g·ha^{-1} reduced annual bluegrass cover more than mesotrione alone; otherwise, there were no differences among treatments. Treatment differences were most evident in New Jersey. At the kentucky bluegrass site in New Jersey, amicarbazone + mesotrione at 140 or 175 g·ha^{-1} reduced annual bluegrass cover by 73% and 90%, respectively, whereas mesotrione alone did not reduce cover compared with the nontreated. At the perennial ryegrass site in New Jersey, amicarbazone alone was less effective than two of the three mesotrione + amicarbazone tank-mixtures 12 WAIT. Mesotrione alone was as effective as the tank-mixtures at the perennial ryegrass site 12 WAIT.

At the final rating date (10 October, 23 WAIT) at both New Jersey sites, trends were similar to those observed 12 WAIT, except that the efficacy of mesotrione alone had improved relative to the tank-mixtures. Amicarbazone tank-mixed with mesotrione at 140 and 175, but not 110 g·ha^{-1} reduced annual bluegrass cover more than mesotrione alone at the kentucky bluegrass site. At the New Jersey perennial ryegrass site, mesotrione alone was as effective as the two of the three tank-mixtures.

In Indiana, there were no differences among herbicide treatments at the final visual and grid count evaluation on 30 Sept. (22 WAIT). The severity of the annual bluegrass infestation and summer decline of annual bluegrass at the Indiana site (annual bluegrass cover was reduced by 46% in the nontreated control at 12 WAIT) may explain the lack of

Table 6. Turfgrass injury following three sequential postemergence herbicide applications in Freehold, NJ, during 2019. Herbicide programs were initiated on 25 Apr. and sequential applications were made on 9 May and 22 May 2019 to separate kentucky bluegrass, perennial ryegrass, and tall fescue sites. Injury was evaluated visually on a 0% (no injury) to 100% (complete necrosis) scale relative to the nontreated control.

		Turfgrass injury (%)					
		Kentucky bluegrass		Perennial ryegrass		Tall fescue	
Herbicide	Rate (g·ha^{-1})	4 WAIT	6 WAIT	4 WAIT	6 WAIT	4 WAIT	6 WAIT
Amicarbazone[z]	53	14 c[y]	6 de	3 b	8 bc	7 d	4 de
Amicarbazone + mesotrione	53 + 110	20 bc	16 bc	11 a	15 ab	18 b	10 bcd
Amicarbazone + mesotrione	53 + 140	23 b	24 ab	15 a	18 a	21 b	13 bc
Amicarbazone + mesotrione	53 + 175	21 b	24 ab	18 a	13 abc	30 a	20 a
Mesotrione	175	3 d	0 e	3 b	5 c	7 d	0 e
Amicarbazone + mesotrione + UAN[x]	53 + 110	30 a	28 a	16 a	16 a	20 b	16 ab
Amicarbazone + mesotrione + urea + AMS[w]	53 + 110	26 ab	10 cd	16 a	10 abc	13 c	9 cd
P value		***	***	***	*	***	**

[z]All treatments included a nonionic surfactant at 0.25% (v/v).

[y]Any two means within a column not followed by the same letter are significantly different according to Fisher's Protected least significant difference test ($P = 0.05$).

[x]Mesotrione and amicarbazone tank-mixed with urea ammonium nitrate (UAN, 30N–0P–0K) at 6.6 L·ha^{-1}.

[w]Mesotrione and amicarbazone tank-mixed with dissolved urea (46N–0P–0K) at 2.5 kg·ha^{-1} N and ammonium sulfate (AMS, 21N–0P–0K) at 12.5 kg·ha^{-1} N.

WAIT = weeks after initial treatment.

*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

treatment differences. No fungicides were applied in Indiana, which likely hastened the decline of annual bluegrass during summer. There were few treatment differences in Iowa, although treatments tended to be more effective in Iowa than Indiana. We attribute this to annual bluegrass immaturity and higher air temperatures at and after herbicide application (Table 3). Amicarbazone activity against annual bluegrass (McCullough et al., 2010; Yu et al., 2013) and mesotrione efficacy in other species (Gonçalves et al., 2020; Johnson and Young, 2002) increases with air temperature.

Turfgrass injury. No injury was observed in Iowa or Indiana (data not presented). Injury observed in New Jersey on kentucky bluegrass in 2019 was similar to what was observed in 2018. Mesotrione alone caused less injury than tank-mixtures of amicarbazone + mesotrione tank-mixtures at 4 and 6 WAIT on all three turfgrass species (Table 6). Injury from amicarbazone and mesotrione alone caused <9% injury, except at 4 WAIT on kentucky bluegrass where amicarbazone caused 14% injury. Injury from amicarbazone + mesotrione tank-mixtures ranged from 10% to 30% and exceeded, at times, the threshold of 20% injury, which is deemed as unacceptable by some turf practitioners. The addition of UAN increased injury to kentucky bluegrass, but not perennial ryegrass or tall fescue. No injury was observed by 8 WAIT (4 weeks after the last application) in any species (data not presented).

This research demonstrates that sequential applications of mesotrione + amicarbazone substantially improves control compared with amicarbazone alone. Improved efficacy from this tank-mixture was reported previously by Elmore et al. (2013a) on juvenile annual bluegrass that was thought to behave as an annual in overseeded bermudagrass. Our research was conducted where annual bluegrass behaved as a perennial due to management and climate. Highlighting the difference in herbicide efficacy, Elmore et al. (2013a) reported one application of amicarbazone at 75 g·ha^{-1} provided substantially more annual bluegrass control than three sequential applications at 53 g·ha^{-1} in this research. Except in Iowa, annual bluegrass control provided by amicarbazone in this research was poor, comparable to previous research evaluating amicarbazone at similar rates for annual bluegrass control in cool-season turf (McCullough et al., 2010). Whether mesotrione + amicarbazone improves control compared with mesotrione alone was less conclusive. In 2019, the tank-mixtures provided more control than mesotrione alone at three of the four sites 6 WAIT, but at only one site by the conclusion of the experiments. Unfortunately, mesotrione was not included as a standard in the 2018 research where mesotrione + amicarbazone provided ≥90% control in kentucky bluegrass. In both 2018 and 2019 in New Jersey, the tank-mixture was most effective at the kentucky bluegrass site which had the most mature annual bluegrass infestation.

Inconsistent annual bluegrass control across locations reported in our research is common. Reicher et al. (2011) reported 71% to 88% annual bluegrass control from three sequential applications of mesotrione at 175 g·ha^{-1} in 1 year and 25% to 52% control when the experiment was repeated. Skelton et al. (2012) reported similarly inconsistent annual bluegrass control across experiments. This inconsistent control may also be due to genetic diversity between populations of this polyploid species (Chen et al., 2015; Mengistu et al., 2000) or annual bluegrass maturity and growth habit, which is not typically reported.

This research indicates that mesotrione + amicarbazone tank-mixtures are often more effective than amicarbazone alone for postemergence annual bluegrass control in the springtime. This tank-mixture was not always more effective than mesotrione alone. Turfgrass managers who experience poor efficacy of amicarbazone or mesotrione alone should consider this tank-mixture if transient turfgrass injury can be tolerated. This research found a tank-mixture of amicarbazone (53 g·ha^{-1}) with mesotrione at 110 g·ha^{-1} applied three times on a 2-week interval is optimal. Higher rates of mesotrione (140 and 175 g·ha^{-1}) increased turfgrass injury in some instances and did not reliably increase annual bluegrass control.

Given the common theme of incomplete annual bluegrass control provided by herbicide programs in this and other research, future work should investigate multiyear herbicide programs for annual bluegrass control in conjunction with management practices that promote turfgrass competition. Mesotrione + amicarbazone tank-mixtures could be applied in the spring and preceded by ethofumesate applications in the autumn. Research should be conducted on mature annual bluegrass and consider management practices including irrigation, fungicide, fertilizer, management, and seeding that promote or prevent summer annual bluegrass decline.

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