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Metamifop Rates, Application Timings, and Broadleaf Herbicide Admixtures Affect Smooth Crabgrass Control in Turf

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Metamifop is an aryloxyphenoxypropionate herbicide under evaluation in the United States for annual grass control in cool-season turfgrasses. Insufficient information is available on the most effective metamifop application timings and mixtures for POST smooth crabgrass control. Field trials conducted in Blacksburg, VA, evaluated metamifop for smooth crabgrass control in existing stands of perennial ryegrass, Kentucky bluegrass, and tall fescue at three rates compared to fenoxaprop, metamifop applied twice at three application intervals, and metamifop in combination with the broadleaf herbicides carfentrazone, 2,4-D plus dicamba plus mecoprop (DDM), and mesotrione. Smooth crabgrass control was equivalent with metamifop at 400 g ai ha^{-1} and fenoxaprop at 195 g ai ha^{-1}. Smooth crabgrass cover was 2% or less, 12 wk after initial treatment, when treated twice with metamifop (300 g ha^{-1}) at a 3-, 6-, or 8-wk interval and significantly better than metamifop applied once. Smooth crabgrass cover was significantly greater at every assessment date in plots treated with metamifop plus DDM than all other metamifop plus broadleaf herbicide admixtures. Metamifop did not appear to significantly injure any turfgrass in these studies, but conclusions about metamifop safety to cool-season turfgrasses cannot be made from these studies due to nonreplication of turfgrass species. According to these data, metamifop is an effective herbicide for controlling smooth crabgrass in cool-season turfgrasses when applied once at 300 or 400 g ha^{-1} or twice at a 3-, 6-, or 8-wk interval. Although metamifop continues to control smooth crabgrass when added to some broadleaf herbicides, smooth crabgrass control was reduced when metamifop was combined with DDM.

Nomenclature: 2,4-D; carfentrazone; dicamba; mesotrione; metamifop; smooth crabgrass, *Digitaria ischaemum* (Schreb.) Schreb. ex Muhl. DIGIS; Kentucky bluegrass, *Poa pratensis* L. POAPR; perennial ryegrass, *Lolium perenne* L. LOLPE, tall fescue, *Lolium arundinaceum* (Schreb.) S.J. Darbyshire FESAR.

Key words: ACCase inhibitor, antagonism, aryloxyphenoxypropionate, weed control.

Metamifop es un herbicida aryloxyphenoxypropionate que está siendo evaluado en los Estados Unidos para el control de gramíneas anuales en céspedes de clima frío. La información disponible es insuficiente acerca de los momentos más efectivos de aplicación de metamifop para el control POST de *Digitaria ischaemum*. Experimentos de campo realizados en Blacksburg, Virginia, evaluaron el control de *D. ischaemum* con tres dosis de metamifop en céspedes establecidos de *Lolium perenne*, *Poa pratensis*, y *Lolium arundinaceum* y se comparó con fenoxaprop, metamifop aplicado dos veces en tres intervalos de aplicación, y metamifop en combinación con los herbicidas de hoja ancha carfentrazone, 2,4-D más dicamba más mecoprop (DDM), y mesotrione. El control de *D. ischaemum* fue equivalente con metamifop a 400 g ai ha^{-1} y fenoxaprop a 195 g ai ha ha^{-1}. La cobertura de *D. ischaemum* fue 2% o menor, 12 semanas después del tratamiento inicial, cuando se trató dos veces con metamifop (300 g ha^{-1}) a intervalos de 3, 6, u 8 semanas y fue significativamente mejor que metamifop aplicado una sola vez. La cobertura de *D. ischaemum* fue significativamente mayor en cada fecha de evaluación en parcelas tratadas con metamifop más DDM que en cualquiera de las otras mezclas de metamifop más otros herbicidas de hoja ancha. Parece que metamifop no dañó significativamente ninguna de las especies de césped estudiadas, pero no se pueden hacer conclusiones acerca de la seguridad de metamifop en céspedes de clima frío a partir estos estudios debido a que no hubo replicaciones por especie de césped. De acuerdo a estos resultados, metamifop es un herbicida efectivo para el control de *D. ischaemum* en céspedes de clima frío cuando se aplica una vez a 300 ó 400 g ha^{-1} o dos veces a intervalos de 3, 6, u 8 semanas.

Metamifop is an aryloxyphenoxypropionate (AOPP) herbicide under development in the United States. Already marketed in nine Asian and six Middle Eastern countries as a POST annual grass herbicide in cereal crops and rice (*Oryza sativa* L.),

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metamifop shows great potential for future expansion to Japan and North America in turf (Flessner and McElroy 2011; Hoyle et al. 2012; Kim et al. 2003a,b; Post and Askew 2010). Metamifop inhibits acetyl-CoA carboxylase (ACCase) (Kim et al. 2003a,b; Senseman 2007), which is the enzyme that catalyzes the first step in fatty acid synthesis (Walker et al. 1988). This enzyme produces phospholipids, which are the building blocks for new membranes and cell growth (Devine et al. 1993). Metamifop, as well as all other members of the AOPP and cyclohexanedione families, is ineffective on dicotyledonous plants (Buhler et al. 1985; Burton et al. 1987; Swisher and Corbin 1982) due to little or no activity against the prokaryotic form of ACCase found only in dicotyledonous plants (Konishi and Sasaki 1994; Konishi et al. 1996).

Several POST herbicides have been registered for crabgrass (*Digitaria* spp.) and other grass weed control in cool-season turf, including fenoxaprop, fluazifop, quinclorac, and mesotrione. However, past research has shown stunting, stand reduction, or transient phytotoxic symptoms to seedling tall fescue and perennial ryegrass, and mature Kentucky bluegrass and creeping bentgrass (*Agrostis stolonifera* L.) with varying application rates and timings of fenoxaprop (Cudney et al. 1997; Dernoeden 1987; Mueller-Warrant 1990; Neal et al. 1990) and fluazifop (Warren et al. 1989). Dernoeden et al. (2003) reported control of pretillering smooth crabgrass (8% cover) with three sequential applications of quinclorac at 0.42 kg ai ha^{-1}. Quinclorac applied mid- to late season has been reported to discolor creeping bentgrass (Dernoeden et al. 2003; Hart et al. 2004), but it is typically safe for use on other cool-season turfgrasses and also controls large crabgrass [*Digitaria sanguinalis* (L.) Scop.] (Reicher et al. 1999). Mesotrione has been shown to suppress smooth crabgrass (Elmore et al. 2012; Goddard et al. 2010) but may injure tall fescue, especially in environments of high humidity (Goddard et al. 2010). Metamifop controls annual grass weeds including barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and crabgrass equivalent to other AOPP herbicides, but appears to be less injurious to cool-season turfgrasses (Flessner and McElroy 2011; Kim et al. 2003a,b; Post and Askew 2010). Metamifop at 300 g ai ha^{-1} controlled smooth crabgrass similarly to fenoxaprop at 100 g ai ha^{-1} at 6 wk after treatment (WAT) on two creeping bentgrass putting greens; however, creeping bentgrass injury with metamifop (300 g ha^{-1}) never exceeded 10%, whereas fenoxaprop at 100 g ha^{-1} injured creeping bentgrass beyond 95% (Post and Askew 2010).

Assuming metamifop will be registered, appropriate application timings, treatment programs, and tank mixtures must be elucidated to maximize herbicide efficacy. Appropriate metamifop application intervals for season-long smooth crabgrass control are not known. Likewise, few studies have evaluated metamifop mixed with herbicides commonly used for broadleaf weed control in turfgrass. Since broadleaf herbicides with various modes of action are often mixed with and may antagonize graminicides (Brommer et al. 2000; Corkern et al. 1998; Culpepper et al. 1998, 1999; Dernoeden and Fidanza 1994; Holshouser and Coble 1990; Jordan et al. 1993; Rhodes and Coble 1984), research is needed to evaluate metamifop and broadleaf herbicide mixtures to test for possible interactions. Based on current, labeled recommendations for metamifop usage in Japan and preliminary studies conducted in the United States, we hypothesized that metamifop would control smooth crabgrass but would likely be antagonized when tank-mixed with a synthetic auxin herbicide similar to previous reports with other AOPP herbicides. Therefore, experiments were conducted to compare different rates of metamifop to fenoxaprop for smooth crabgrass control and turfgrass safety in perennial ryegrass, Kentucky bluegrass, and tall fescue. The second objective was to evaluate the effect of metamifop application intervals on season-long smooth crabgrass control. Thirdly, smooth crabgrass and broadleaf weed control efficacy with metamifop applied in combination with three commonly used broadleaf herbicides was evaluated.

Materials and Methods

Smooth Crabgrass Control with Single Applications. Two field experiments were conducted in Blacksburg, VA, in 2008; research was repeated in 2009. In 2008, one site was located at the Turfgrass Research Center (TRC) on a 10-yr-old stand of 'Kelly' Kentucky bluegrass and the other at the Glade Road Research Facility (GRF) on a 5-yr-old stand of perennial ryegrass (39% 'Federation', 30% 'Partner', and 29% 'Cadence' blend). A third field experiment was also conducted at the TRC in 2009 on a 4-yr-old stand of 'AST7002′ tall fescue. The Kentucky bluegrass, perennial ryegrass, and tall fescue sites were maintained at 3.0, 3.0, and 6.4 cm mowing heights, respectively. All study sites at the TRC were irrigated manually and as needed to prevent turfgrass wilt. The soil at the TRC was a Groseclose-Urban land complex loam (clayey, mixed, mesic Typic Hapludults) with a pH of 6.2. The soil at GRF was a Duffield silt loam (fine-loamy, mixed, active, mesic, Ultic Hapludalfs)-Ernest silt loam (fine-loamy, mixed, superactive, mesic Aquic Fragiudults) complex, with a pH of 6.6. Plots were 2.0 by 2.0 m and arranged in a randomized complete block (RCB) experimental design with three replications. Treatments for these studies included metamifop (SAH-001 10% EC, Summit Agro International Ltd., Tokyo, Japan) applied once at 100, 200, and 400 g ai ha^{-1}, and fenoxaprop (Acclaim® Extra herbicide, Bayer Environmental Science, Research Triangle Park, NC 27709) at 195 g ai ha^{-1}. The metamifop rate range was suggested by the manufacturer, and the fenoxaprop rate was based on the maximum rate for use on a cool-season turfgrass as indicated by the product label. A nontreated check was included for comparison.

Treatments were applied on July 1, 2008, for the Kentucky bluegrass and perennial ryegrass sites and July 3, 2009, for the tall fescue site using a CO_2-pressurized sprayer calibrated to deliver 280 L ha^{-1} at 289 kPa via 11004TTI nozzles (TeeJet® Spraying Systems Co., Wheaton, IL 60189-7900). At the TRC, smooth crabgrass cover in the Kentucky bluegrass was approximately 35% and comprised 10% pretiller seedlings, 70% two- to three-tiller plants, and 20% plants with more than three tillers at trial initiation in 2008. At the GRF in 2008, initial smooth crabgrass cover in the perennial ryegrass was approximately 29% and comprised 15% two- to three-tiller plants and 75% larger than three-tiller plants; the remainder of the smooth crabgrass population was seedlings. In 2009, initial smooth crabgrass cover at the tall fescue site at the TRC was 8% and comprised 90% larger than three- to five-tiller plants with the remainder having less than two tillers.

Treatment effects on smooth crabgrass were evaluated 1, 4, and 8 WAT in both years. Smooth crabgrass control was assessed visually on a scale of 0 to 100, where 0 = no control and 100 = complete plant necrosis. Smooth crabgrass green cover was estimated on each rating date using plant counts taken with a 15- by 15-cm grid (121 intersects) that overlaid each plot (Richardson et al. 2001). Turfgrass injury was assessed visually on a scale of 0 to 100, where 0 = no injury and 100 = complete plant necrosis.

Data were analyzed using the general linear model (GLM) in SAS® 9.2 (SAS Institute Inc, Cary, NC). Data were arcsine square root transformed to improve normality based on the Shapiro-Wilk statistic using the NORMAL option in PROC UNIVARIATE in SAS. Transformed data were subjected to ANOVA using the GLM procedure in SAS. Since trials were considered random, treatment effects were tested using mean square error associated with the treatment by trial interaction (McIntosh 1983). If data transformation was needed to meet the assumptions of ANOVA, data were back-transformed for presentation to improve clarity. Appropriate means were separated with Fisher's protected LSD test at $P = 0.05$. To further validate visually assessed data, smooth crabgrass cover was compared to smooth crabgrass control at 8 WAT using regression analysis.

Application Interval Effects on Smooth Crabgrass Control. Two field experiments were conducted in Blacksburg, VA, in 2011. One study site was at the GRF and the other at a site on the Virginia Polytechnic Institute and State University campus adjacent to Prices Fork Road (PFR), approximately 0.2 km from the GRF. Turfgrass at the GRF site was a 9-yr-old stand of perennial ryegrass (33% 'ASP6004', 32% 'ASP0112', and 32% 'ASP1001 GL' blend) irrigated with an automatic watering system (Toro® TMC-424, Toro, Bloomington, MN), which was adjusted as needed to prevent turf wilt. Turfgrass at the PFR site was a 6-yr-old stand of 'Midnight II' Kentucky bluegrass irrigated manually and as needed to prevent turfgrass wilt. All turfgrass sites were maintained at a 1.9-cm mowing height. The soil at the perennial ryegrass location (GRF) was described previously. Soil at the Kentucky bluegrass location (PFR) was a Groseclose-Urban land complex loam with a 6.1 pH. Nutrients (approximately 0.015 kg N m^{-2} annually) at both locations were applied based on Virginia Polytechnic Institute and State University Extension soil test and cool-season turfgrass maintenance recommendations (Turgeon 2005). Plots at each location were 2.0 by 2.0 m and arranged in an RCB experimental design with three replications. Herbicide treatments consisted of metamifop applied initially on June 16, 2011, at 300 g ai ha^{-1} alone or followed by an additional application at 3, 6, or 8 wk after initial treatment (WAIT). A nontreated check was also included for comparison. Initial treatments at the GRF and PFR were mixed and applied in early morning and afternoon, respectively, on June 16, 2011. At the GRF, smooth crabgrass cover was approximately 41% and comprised 23% pretiller seedlings, 75% two- to three-tiller plants, and 2% plants with more than three tillers. At PFR, smooth crabgrass cover was approximately 44% and comprised 80% two- to three-tiller plants and less than 3% plants with more than three tillers; the remainder of the smooth crabgrass population was seedlings. Treatments were applied using techniques and equipment previously described.

Treatment effects on smooth crabgrass were evaluated at 2, 4, 8, and 12 WAIT. Smooth crabgrass green cover percentage was estimated visually, and smooth crabgrass plant counts were made at each rating date using methods previously described to determine plant density in each plot. Data were analyzed in SAS similarly to previously described methods. Sums of squares were partitioned to reflect main effects and interactions of metamifop rate, application interval timings, and trial. Means were separated as previously described.

Smooth Crabgrass Control as Affected by Broadleaf Herbicide Admixtures. Two field experiments were conducted in Blacksburg, VA, in 2011, one at the GRF and the other at the PFR. These study sites were in close proximity to the aforementioned application interval study sites and had similar soil type, turf variety, and maintenance inputs as previously described. Plots were 2.0 by 2.0 m and arranged in an RCB experimental design with three replications. Herbicide treatments were arranged in a two-by-four factorial design with two levels of metamifop rate (0, 300 g ha^{-1}) and four levels of broadleaf herbicide: none, 2,4-D plus dicamba plus mecoprop (MCPP) (Trimec Turf® herbicide, PBI Gordon Corporation, Kansas City, MO 64101) at 1,500 g ae ha^{-1} (subsequently noted as DDM), carfentrazone (Quicksilver® herbicide, FMC Corporation, Philadelphia, PA 19103) at 33 g ai ha^{-1}, and mesotrione (Tenacity® herbicide, Syngenta Crop Protection, Inc., Greensboro, North Carolina 27419-8300) at 280 g ai ha^{-1}. Herbicide rates were chosen based on the maximum rate recommended for use on a cool-season turfgrass indicated by the product label. Initial treatments were mixed and applied on June 17, 2011. Treatments were applied using a CO_2-pressurized sprayer calibrated to deliver 280 L ha^{-1} at 289 kPa via 11004TTI nozzles. At the GRF, smooth crabgrass cover was approximately 27% and comprised 23% pretiller seedlings, 75% two- to three-tiller plants, and 2% larger than three-tiller plants. At PFR, smooth crabgrass cover was approximately 36% and comprised 80% two- to three-tiller plants and less than 3% plants with more than three tillers; the remainder of the population was seedlings. Treatment effects on smooth crabgrass were evaluated at 2, 4, 8, and 12 WAIT. Data collection, transformation, and ANOVA were conducted similarly to the application intervals study. Sums of squares in ANOVA were partitioned to reflect effects of metamifop and broadleaf herbicide admixture, which were considered fixed. The effect of trial was considered random, and mean squares associated with trial interactions were used to test for significance of fixed effects (McIntosh 1983). If significant, interactions or main effects of metamifop and broadleaf admixtures were separated as previously described.

Results and Discussion

Smooth Crabgrass Control with Single Applications. Trial interactions were not significant ($P > 0.05$) for all three studies, so data were pooled over trial. Treatment effects were significant ($P < 0.05$) for smooth crabgrass control at 1, 2, 4, and 8 WAT and smooth crabgrass green cover at 8 WAT (Table 1). At 8 WAT, metamifop applied once at 400 g ai ha^{-1} controlled smooth crabgrass equivalent to fenoxaprop at 195 g ha^{-1} (88%), and significantly better than metamifop at 100 and 200 g ha^{-1} (Table 1). Visually estimated smooth crabgrass control data were correlated with grid counts at 8 WAT (data not shown). Metamifop at 400 g ha^{-1} and fenoxaprop reduced crabgrass cover by 85%, significantly more than all other treatments (Table 1). Metamifop did not visually injure the turfgrasses at any site, but it should be noted that

Table 1. Smooth crabgrass control and percentage of green cover over time, pooled over three locations, in response to metamifop or fenoxaprop applied once[a] in 2008 and 2009 at the Turfgrass Research Center and Glade Road Research Facility in Blacksburg, VA.

Herbicide[a]	Rate	1 WAT[b] Control[c]	2 WAT Control	4 WAT Control	8 WAT Control	8 WAT Cover[d]
	(g ai ha^{-1})	%				
Metamifop	100	33[e]	40	43	53	27
Metamifop	200	48	68	74	74	16
Metamifop	400	59	83	85	88	8
Fenoxaprop	195	66	90	85	88	8
Nontreated	—	0	0	0	0	53
LSD (0.05)	—	5	5	7	7	5

[a] Initial treatment was applied July 1, 2008, at the perennial ryegrass and Kentucky bluegrass locations and July 3, 2009, at the tall fescue location.

[b] Abbreviations: WAT, weeks after treatment.

[c] Smooth crabgrass control was determined by a scale of 0 to 100, where 0 = no injury and 10 = complete plant necrosis, and compared to the nontreated.

[d] Smooth crabgrass cover was determined using live plant counts (plants m^{-2}) assessed with a 15- by 15-cm grid.

[c] [e] Data were pooled over three locations.

each turfgrass species was only represented once in each location. Therefore, no conclusions relative to turfgrass injury may be drawn from these data.

Based on these data, one application of metamifop at 400 g ha^{-1} controls smooth crabgrass similarly to one application of fenoxaprop at 195 g ha^{-1} for 8 wk. These studies, however, did not test the longevity of control associated with applying these herbicides earlier in the growing season. It is likely that additional applications would be needed to address newly germinated plants emerging throughout the summer (Dernoeden et al. 2003). Although the fenoxaprop rate used in this study was higher than current labeled rates for Kentucky bluegrass, smooth crabgrass control with metamifop at 400 g ha^{-1} was similar.

Application Interval Effects on Smooth Crabgrass Control. Smooth crabgrass counts and cover were not affected by location when treated with metamifop at various application intervals. Since trial interactions were not significant ($P > 0.05$), data were pooled over trial locations. Significant treatment differences ($P < 0.05$) were noted at each evaluation date for both smooth crabgrass density and visually estimated percentage of cover (Table 2). By 12 WAIT, metamifop applied twice at a 3-, 6-, or 8-wk interval reduced smooth crabgrass cover and density significantly better than one initial application (Table 2). These data suggest that two applications of metamifop at 300 g ha^{-1} applied 3, 6, or 8 wk apart reduce smooth crabgrass cover significantly better than one application. However, although one application reduced smooth crabgrass cover significantly better than the nontreated, smooth crabgrass cover with this program was only 2 to 3% more than programs that applied metamifop twice. Derr et al. (1985) observed greater control of pre- to early-tillering stages of large crabgrass with single applications of sethoxydim or fluazifop. In our study, a single application of metamifop reduced smooth crabgrass cover to less than 5%; however, plots that received two applications still had significantly less smooth crabgrass cover (1 to 2%) at 12 WAIT than those only treated once. Hoyle et al. (2012) reported 96% control of three- to five-tiller large crabgrass 3 WAT with one application of metamifop at 200 g ai ha^{-1} in greenhouse conditions. A study by Chism and Bingham (1991) showed that fenoxaprop at 0.28 kg ai ha^{-1} only controlled large crabgrass 81% at 6 WAT, also suggesting that two or more applications of fenoxaprop may be needed to control smooth and large crabgrass for more than 2 mo. Metamifop reduced smooth crabgrass cover and density in this study with one or two applications. Data suggest that under the conditions of these experiments, repeat applications of metamifop are not required to reduce smooth crabgrass cover, but sequential applications may be needed if single applications

Table 2. Smooth crabgrass plant density and percentage of green cover, pooled over two locations, in response to metamifop applied once or followed by sequential applications at 3, 6, and 8 wk after initial treatment at the Glade Road Research Facility and Prices Fork Road sites in Blacksburg, VA, in 2011.

Herbicide[a]	Rate	Timing[b]	2 WAIT[c] Plant density[d,e]	2 WAIT[c] Cover[d,f]	4 WAIT Plant density[d,e]	4 WAIT Cover[d,f]	8 WAIT Plant density[d,e]	8 WAIT Cover[d,f]	12 WAIT Plant density[d,e]	12 WAIT Cover[d,f]
	(g ai ha^{-1})	WAIT	No. m^{-2}	%	No. m^{-2}	%	No. m^{-2}	%	No. m^{-2}	%
Metamifop	300	—	4	1	9	2	14	3	21	4
Metamifop	300 fb[c] 300	3	4	1	3	1	3	1	6	1
Metamifop	300 fb 300	6	4	1	9	2	5	1	12	2
Metamifop	300 fb 300	8	5	1	13	3	16	3	4	1
Nontreated	—	—	98	20	116	23	131	80	123	55
LSD (0.05)	—	—	7	1	7	1	7	1	7	1

[a] Initial treatment was applied June 16, 2011, and 3-, 6-, and 8-wk sequential treatments were applied on July 7, July 28, and August 11, respectively.

[b] Indicates timing of second metamifop application in weeks after initial treatment.

[c] Abbreviations: fb, followed by; WAIT, weeks after initial treatment.

[d] Data were pooled over two locations.

[e] Smooth crabgrass density (live smooth crabgrass plants m^{-2}) was determined by visual grid counts (121 intersects).

[f] Smooth crabgrass cover was determined by visual assessments based on percentage of each plot covered by green smooth crabgrass tissue.

fail to provide adequate reductions in different environments.

Smooth Crabgrass Control as Affected by Broadleaf Herbicide Admixtures. The ANOVA indicated a significant trial-by-metamifop interaction ($P < 0.05$) at 2 and 4 WAT and a significant metamifop-by-broadleaf herbicide interaction ($P < 0.05$) at 4 and 8 WAT. Trial by metamifop-by-broadleaf herbicide and trial-by-broadleaf herbicide interactions were not significant ($P > 0.05$) at any rating date.

The trial-by-metamifop interaction likely resulted from differences in metamifop effects on smooth crabgrass density between sites at 2 and 4 WAT. At 2 WAT, metamifop reduced smooth crabgrass density from 69 to 14 plants m^{-2} at the PFR location and did not significantly reduce population (56 vs. 34 plants m^{-2}) at the GRF (data not shown). A similar trend occurred at 4 WAT when metamifop reduced smooth crabgrass density from 95 to 29 plants m^{-2} only at the PFR location (data not shown). The differences in smooth crabgrass density between trial locations may be due to differences in irrigation frequency between sites. The GRF location was irrigated each night from an automatic system, whereas the PFR location was irrigated manually and less frequently. Increased surface moisture has been shown to promote germination in some annual grasses (Burke et al. 2003; Chauhan et al. 2006). Since only three rainfall events exceeded 6.4 mm in the first month after treatment (data not shown), infrequent surface wetting at the PFR location could have reduced the rate of smooth crabgrass population expansion at that site compared to the daily irrigated GRF site. After 4 WAT, these differences were no longer evident as smooth crabgrass populations continued to expand at the PFR location.

Application of the broadleaf herbicides carfentrazone and DDM did not influence smooth crabgrass density, which increased from approximately 70 to 115 plants m^{-2} over a 12-wk period following study initiation (Figure 1a). Mesotrione is frequently used in cool-season turf as a standard for the control of crabgrass and as an alternative mode of action in broadleaf weed control (Beam et al. 2006; Giese et al. 2005; McCurdy et al. 2009; Willis et al. 2007); however, one mesotrione application at 280 g ai ha^{-1} did not effectively reduce mature smooth crabgrass density in this study, as it was not significantly different from carfentrazone or DDM (Figure 1a). Metamifop reduced smooth crabgrass density by 40 to 60 plants m^{-2} between 2 and 12 WAT (Figure 1b). Tank mixtures of metamifop with carfentrazone or mesotrione did not alter smooth crabgrass density

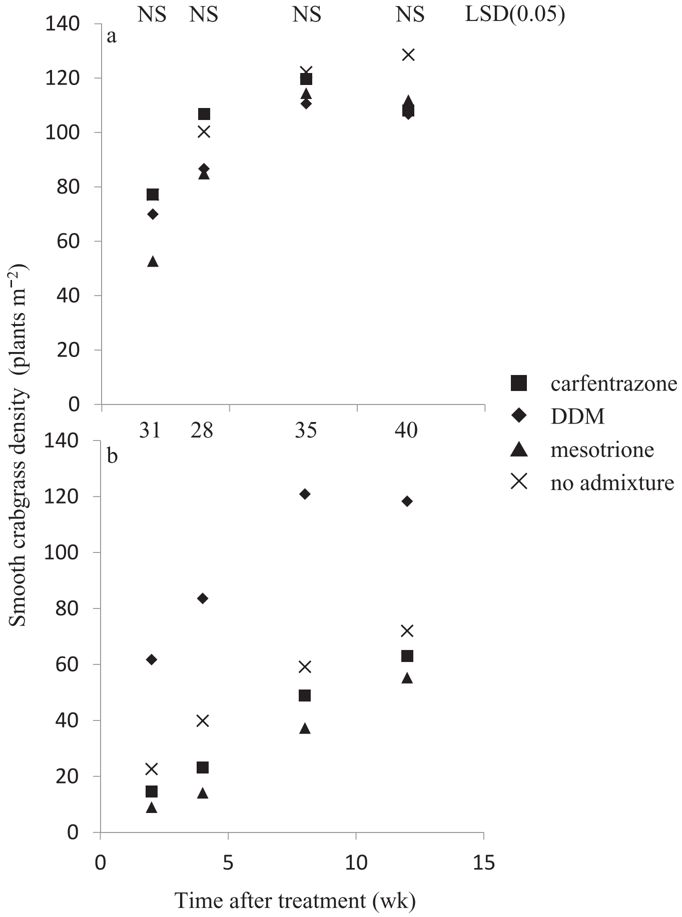

Figure 1. Smooth crabgrass density over time at the Glade Road Research Facility and Prices Fork Road site in 2011 after application of carfentrazone, 2,4-D plus dicamba plus mecoprop (DDM), and mesotrione (a) without and (b) with the addition of metamifop. Least significant difference shown at the top; NS = not significant (P = 0.05).

compared to metamifop alone; however, DDM plus metamifop did not reduce smooth crabgrass density compared to the nontreated check (Figure 1b). These data indicate that DDM antagonizes metamifop when combined as an admixture to control broadleaf and annual grass weeds in one treatment. Similar results were reported by Dernoeden and Fidanza (1994) when a significant decrease in smooth crabgrass control was noted after a broadleaf weed herbicide containing 2,4-D, dicamba, and MCPP was applied less than 14 d before fenoxaprop; however, no antagonism was observed when the broadleaf herbicide was applied after fenoxaprop. Other studies have also indicated that applying broadleaf herbicides 3 d or less before or after an ACCase inhibitor (Culpepper et al. 1998), or applying graminicides 24 h after broadleaf herbicides may result in antagonism (Minton et al. 1989). Cyhalofop efficacy on barnyardgrass was reduced by up to 41% when combined with triclopyr, or when triclopyr was applied 1, 3, or 5 d before cyhalofop (Scherder et al. 2005); however, the addition of triclopyr to metamifop has been shown to increase bermudagrass (*Cynodon* spp.) control and 'Zorro' zoysiagrass [*Zoysia matrella* (L.) Merr.] cover (Doroh et al. 2011). A study evaluating the combination of bromoxynil, a broadleaf weed herbicide that strongly inhibits chloroplast photosystem II (Gentsch 1986), and quizalofop, another AOPP herbicide, also revealed an antagonistic response to controlling yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes] by decreasing absorption of quizalofop (Culpepper et al. 1999). Bentazon, also a photosystem II inhibitor, decreased absorption of the ACCase inhibitor clefoxydim into barnyardgrass and broadleaf signalgrass [*Urochloa platyphylla* (Nash) R. D. Webster] (Brommer et al. 2000).

It is apparent from these data and previous research that metamifop is an effective herbicide for controlling smooth crabgrass in cool-season turfgrasses; however, it appears to behave similarly to other AOPP herbicides when tank-mixed with 2,4-D plus dicamba plus MCPP. Metamifop is effective for smooth crabgrass control with a single treatment, but control may improve when a second treatment is applied 3, 6, or 8 wk later. At seven study sites, three each for Kentucky bluegrass and perennial ryegrass and one for tall fescue, metamifop at greater than 200 g ha^{-1} did not visually injure any turfgrass. We are hesitant, however, to make conclusions about metamifop safety to cool-season turfgrasses. Statistical comparisons of turf injury were not assessed because our study design did not appropriately repeat species within a study or meet the assumptions of ANOVA due to zero-inflated data. Previous studies have alluded to differences in absorption, translocation, metabolism, or enzymatic binding sites as possible mechanisms for increased safety with metamifop in cool-season grasses (Kim et al. 2003a,b). Results from Stoltenberg et al. (1989) led to the hypothesis that an altered binding site may be responsible for varying AOPP herbicide activity within different cool-season turfgrasses. 'Manhattan II' perennial ryegrass and 'Bonsai' tall fescue at the one- to two-leaf stages were injured by fenoxaprop (Cudney et al. 1997), whereas mature stands were not significantly affected (Dernoeden 1987). Fenoxaprop has also been shown to visually injure Kentucky bluegrass (Neal et al. 1990). Metamifop differs from other AOPP herbicides in that the aryl amide, rather than the ester, inhibits ACCase (Matsumoto et al. 1996). This difference in ACCase inhibition may contribute to increased safety of metamifop in cool-season turf compared to other AOPP herbicides such as fenoxaprop. Regardless of the mechanism, metamifop may be safer to cool-season turfgrasses than competitive products already in the marketplace (Flessner and McElroy 2011; Kim et al. 2003a,b; Post and Askew 2010). Future studies should evaluate growth response of cool-season turfgrasses to assess metamifop safety. Future work should also evaluate more broadleaf, sedge, and grass herbicides in conjunction with metamifop to test for possible interactions.

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Literature Cited

Beam JB, Barker WL, Askew SD (2006) Selective creeping bentgrass (*Agrostis stolonifera*) control in cool-season turfgrass. Weed Technol 20:340–344

Brommer CL, Shaw DR, Duke SO, Reddy KN, Willeford, KO (2000) Antagonism of clefoxydim by selected broadleaf herbicides and the role of ethanol. Weed Sci 48:181–187

Buhler DD, Swisher BA, Burnside OC (1985) Behavior of ^{14}C-haloxyfop-methyl in intact plants and cell cultures. Weed Sci 33:291–299

Burke IC, Thomas WE, Spears JF, Wilcut JW (2003) Influence of environmental factors on after-ripened crowfootgrass (*Dactyloctenium aegyptium*) seed germination. Weed Sci 51:342–347

Burton JD, Gronwald JW, Somers DA, Connelly JA, Gengenbach BG, Wyse DL (1987) Inhibition of plant acetyl-coenzyme A carboxylase by the herbicides sethoxydim and haloxyfop. Biochem Biophys Res Commun 148:1039–1044

Chauhan BS, Gill G, Preston C (2006) Influence of environmental factors on seed germination and seedling emergence of rigid ryegrass (*Lolium rigidum*). Weed Sci 54:1004–1012

Chism WJ, Bingham SW (1991) Postemergence control of large crabgrass (*Digitaria sanguinalis*) with herbicides. Weed Sci 39:62–66

Corkern CB, Reynolds DB, Vidrine PR, Griffin JL, Jordan DL (1998) Bromoxynil antagonizes johnsongrass (*Sorghum halepense*) control with graminicides. Weed Technol 12:205–208

Cudney DW, Elmore CL, Gibeault VA, Reints JS (1997) Common bermudagrass (*Cynodon dactylon*) management in cool-season turfgrass. Weed Technol 11:478–483

Culpepper AS, York AC, Jennings KM, Batts RB (1998) Interaction of bromoxynil and postemergence graminicides on large crabgrass (*Digitaria sanguinalis*). Weed Technol 12:554–559

Culpepper AS, York AC, Jordan DL, Corbin FT, Sheldon YS (1999) Basis for antagonism in mixtures of bromoxynil plus quizalofop-P applied to yellow foxtail (*Setaria glauca*). Weed Technol 13:515–519

Dernoeden PH (1987) Tolerance of perennial ryegrass and tall fescue seedlings to fenoxaprop. Agron J 79:1035–1037

Dernoeden PH, Bigelow CA, Kaminski JE, Krouse JM (2003) Smooth crabgrass control in perennial ryegrass and creeping bentgrass tolerance to quinclorac. HortScience 38:607–612

Dernoeden PH, Fidanza MA (1994) Fenoxaprop activity influenced by auxin-like herbicide application timing. HortScience 29:1518–1519

Derr JF, Monaco TJ, Sheets TJ (1985) Response of three annual grasses to fluazifop. Weed Sci 33:693–697

Devine M, Duke SO, Fedtke C (1993) Herbicide effects on lipid synthesis. Pages 225–242 *in* Physiology of Herbicide Action. Englewood Cliffs, NJ: Prentice-Hall

Doroh MC, McElroy JS, van Santen E (2011) Evaluation of new aryloxyphenoxypropionate herbicides for control of bermudagrass in zoysiagrass. Weed Technol 25:97–102

Elmore MT, Brosnan JT, Kopsell DA, Breeden GK (2012) Nitrogen-enhanced efficacy of mesotrione and topramezone for smooth crabgrass (*Digitaria ischaemum*) control. Weed Sci 60:480–485

Flessner ML, McElroy JS (2011) Potential use of metamifop for weed control in turfgrass. Abstract 328-6 *in* Proceedings of the ASA/CSSA/SSSA International Annual Meeting. San Antonio, TX, Madison WI: ASA-CSSA-SSSA

Giese MS, Keese RJ, Christians NE, Gaussoin RE (2005) Mesotrione: a potential selective post-emergence herbicide for turf grass. Turfgrass Soc Res J 10:100–101

Gentsch BJ (1986) Efficacy, Behavior, and Fate of Bromoxynil and Photosynthetic Electron Transport Inhibition by Bromoxynil Following Application in Overhead Irrigation Water. Ph.D dissertation. Raleigh, NC: North Carolina State University. 92 p

Goddard MJR, Willis JB, Askew SD (2010) Application placement and relative humidity affects smooth crabgrass and tall fescue response to mesotrione. Weed Sci 58:67–72

Hart SE, Lycan DW, Murphy JA (2004) Use of quinclorac for large crabgrass (*Digitaria sanguinalis*) control in newly summer-seeded creeping bentgrass (*Agrostis stolonifera*). Weed Technol 18:375–379

Holshouser DH, Coble HD (1990) Compatibility of sethoxydim with five postemergence broadleaf herbicides. Weed Technol 4:128–133

Hoyle JA, Straw C, Henry G, Brosnan J, Breeden G (2012) Efficacy of metamifop for the control of large crabgrass at various growth stages. Abstract 105-8 *in* Proceedings of the

ASA/CSSA/SSSA International Annual Meeting. Cincinnati, OH, Madison WI: ASA-CSSA-SSSA

Jordan DL, Smith MC, McClelland MR, Frans RE (1993) Weed control with bromoxynil applied alone and with graminicides. Weed Technol 7:835–839

Kim TJ, Chang HS, Kim JS, Hwang IT, Hong KS, Kim DW, Cho KY, Myung EJ, Chung BJ (2003a) Metamifop: mechanism of herbicidal activity and selectivity in rice and barnyardgrass. Pages 833–838 *in* Proceedings BCPC–Crop Science and Technology Hampshire UK: British Crop Production Council

Kim TJ, Chang HS, Ryu JW, Ko YK, Kim DW, Cho KY, Park CH, Kwon OY, Chung BJ (2003b) Metamifop: a new post-emergence grass killing herbicide for use in rice. Pages 81–86 *in* Proceedings of The BCPC International Congress: Crop Science and Technology, Volumes 1 and 2. Glasgow, Scotland, UK, Hampshire UK: British Crop Production Council

Konishi T, Sasaki Y (1994) Compartmentalization of two forms of acetyl-CoA carboxylase in plants and the origin of their tolerance toward herbicides. PNAS 91:3598–3601

Konishi T, Shinohara K, Yamada K, Sasaki Y (1996) Acetyl-CoA carboxylase in higher plants: most plants other than Gramineae have both the prokaryotic and the eukaryotic forms of this enzyme. Plant Cell Physiol 37:117–122

Matsumoto K, Ide K, Hayase Y, Takahashi T, Takeda R, Hayashi Y (1996) Selective herbicidal activity of 3, 5-dichloropyridyloxyphenoxypropionamidoxyacetic acid derivatives between wheat and wild oat. J Pestic Sci 21:165–170

McCurdy JD, McElroy JS, Breeden GK (2009) Yellow nutsedge (*Cyperus esculentus*) and large crabgrass (*Digitaria sanguinalis*) response to soil- and foliar-applied mesotrione. Weed Technol 23:62–66

McIntosh MS (1983) Analysis of combined experiments. Agron J 75:153–155

Minton BA, Kurtz ME, Shaw DR (1989) Barnyardgrass (*Echinochloa crus-galli*) control with grass and broadleaf weed herbicide combinations. Weed Sci 37:223–227

Mueller-Warrant GW (1990) Control of roughstalk bluegrass (*Poa trivialis*) with fenoxaprop in perennial ryegrass (*Lolium perenne*) grown for seed. Weed Technol 4:250–257

Neal JC, Bhowmik PC, Senesac AF (1990) Factors influencing fenoxaprop efficacy in cool-season turfgrass. Weed Technol 4:272–278

Post AR, Askew SD (2010) Cool-season turfgrass tolerance and weed control efficacy of metamifop. Korean Soc Pestic Sci 10:50–51

Reicher ZJ, Weisenberger DV, Throssell CS (1999) Turf safety and effectiveness of dithiopyr and quinclorac for large crabgrass (*Digitaria sanguinalis*) control in spring-seeded turf. Weed Technol 13:253–256

Rhodes GN Jr, Coble HD (1984) Influence of bentazon on absorption and translocation of sethoxydim in goosegrass (*Eleusine indica*). Weed Sci 32:595–597

Scherder EF, Talbert RE, Lovelace ML (2005) Antagonism of cyhalofop grass activity by halosulfuron, triclopyr, and propanil. Weed Technol 19:934–941

Senseman SA, ed (2007) Herbicide Handbook. 9th edn. Champaign, IL: Weed Science Society of America. P 37

Stoltenberg DE, Gronwald JW, Wyse DL, Burton JD, Somers DA, Gengenbach BG (1989) Effect of sethoxydim and haloxyfop on acetyl-coenzyme A carboxylase activity in *Festuca* species. Weed Sci 37:512–516

Swisher B, Corbin FT (1982) Behavior of BAS-9052 in soybean (*Glycine max*) and johnsongrass (*Sorghum halepense*) plant and cell cultures. Weed Sci 30:640–650

Turgeon AJ (2005) Turfgrass Management. 7th edn. Upper Saddle River, NJ: Pearson Education, Inc. P 197

Walker KA, Ridley SM, Lewis T, Hardwood JL (1988) Fluazifop, a grass selective herbicide which inhibits acetyl-CoA carboxylase in sensitive plant species. Biochem J 254:307–310

Warren SL, Skroch WA, Monaco TJ, Shribbs JM (1989) Tolerance of five perennial cool-season grasses to fluazifop. Weed Technol 3:385–388

Willis JB, Askew SD, McElroy JS (2007) Improved white clover control with mesotrione by tank-mixing bromoxynil, carfentrazone, and simazine. Weed Technol 21:739–743

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