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MCPA Synergizes Imazamox Control of Feral Rye (*Secale cereale*)

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Field, greenhouse, and laboratory studies were conducted to determine the effect of MCPA ester, fertilizer type, and fertilizer rate on feral rye control with imazamox. In field studies near Sidney, NE, increasing the concentration of liquid ammonium phosphate (10–34–0) from 2.5 to 50% of the spray solution decreased feral rye control with imazamox by as much as 73%. Conversely, adding MCPA ester to imazamox significantly increased feral rye control in field studies by up to 77%. Initial greenhouse studies confirmed the liquid ammonium phosphate antagonism effect, but subsequent greenhouse studies were inconsistent with regard to the interaction between fertilizer and imazamox. At least one source of liquid ammonium phosphate was shown not to be antagonistic, and therefore fertilizer source or contaminants may be responsible for initial field observations. Greenhouse studies confirmed the synergistic interaction between MCPA and imazamox. MCPA ester applied at 560 g ai ha^{-1} decreased the rate of imazamox required to cause 50% reduction in feral rye dry weight (GR_{50}) to 13 g ha^{-1} compared to 35 g ha^{-1} for imazamox alone. Although addition of MCPA ester increased ^{14}C-imazamox absorption by 8% in laboratory studies, less ^{14}C translocated out of the treated leaf; therefore the mechanism of synergism does not appear to be related to imazamox absorption or translocation.

Nomenclature: Imazamox; MCPA; feral rye, *Secale cereale* L.

Key words: Herbicide synergism, winter wheat, imidazolinone-resistant, fertilizer–herbicide interactions.

Se realizaron estudios de campo, invernadero y de laboratorio para determinar el efecto de MCPA éster y tipo y dosis de fertilizante en el control de *Secale cereale* silvestre con imazamox. En los estudios de campo cerca de Sidney, Nebraska, el incremento de la concentración de fosfato de amonio líquido (10-34-0) de 2.5 a 50% de la solución asperjada, disminuyó el control de *S. cereale* con imazamox hasta 73%. Por otra parte, la adición de MCPA éster al imazamox incrementó significativamente el control del *S. cereale* silvestre hasta 77%, en los estudios de campo. Los primeros estudios de invernadero confirmaron un efecto antagónico del fosfato de amonio líquido, pero estudios subsecuentes fueron inconsistentes con respecto a la interacción entre el fertilizante e imazamox. Al menos una fuente de fosfato de amonio líquido no mostró ser antagónica y por lo tanto la fuente del fertilizante o algún contaminante podrían ser los responsables de las primeras observaciones en campo. Los estudios de invernadero confirmaron la interacción de sinergismo a entre MCPA e imazamox. MCPA éster aplicado a 560 g ia ha^{-1} disminuyó la GR50 de imazamox 63%, en comparación con imazamox solo. En estudios de laboratorio, aunque la adición de MCPA éster incrementó la absorción de ^{14}C-imazamox en 8%, menos ^{14}C se translocó fuera de la hoja tratada; por lo tanto, el mecanismo de sinergismo no parece estar relacionado a la absorción o translocación de imazamox.

Feral rye is one of several winter annual grass weeds that can cause serious economic losses in winter wheat due to both direct competition and grain contamination. Economic losses due to feral rye in the western United States have been estimated at $27 million (White et al. 2006). Research conducted across the High Plains region of the United States indicated that the competitiveness of feral rye with winter wheat was heavily influenced by environmental conditions, with economic thresholds ranging from less than 1 to over 40 plants m^{-2} (Pester et al. 2000). In Oklahoma, feral rye causes approximately 10-fold greater economic losses compared to other annual grasses including cheat (*Bromus secalinus* L.), Italian ryegrass [*Lolium perenne* L. subsp. *multiflorum* (Lam.) Husnot], jointed goatgrass (*Aegilops cylindrica* Host), and wild oat (*Avena fatua* L.) when growing at similar densities (Fast et al. 2009).

Historically, selective control of feral rye in winter wheat has been difficult. Prior to the introduction of imidazolinone-resistant (IR) winter wheat, most feral rye management recommendations relied on various cultural practices such as extended crop rotations (Daugovish et al. 1999). Daugovish et al. (1999) demonstrated that inclusion of a summer crop such as proso millet (*Panicum miliaceum* L.) into the winter wheat–fallow rotation could effectively reduce feral rye densities while keeping net economic returns similar to the wheat-fallow rotation. Successful long-term management of feral rye must include preventing seed production, as adult rye plants can produce 600 seeds per plant (Anderson 1998). A small percentage of the seed bank can remain dormant and viable for > 5 yr (Stump and Westra 2000).

The introduction of IR winter wheat provided growers a new tool for management of winter annual grasses in winter wheat; however, feral rye is often the most difficult winter annual grass weed to control in IR winter wheat (Geier et al. 2004; Pester et al. 2001). Imazamox use in IR winter wheat can provide good to excellent feral rye control, but application timing and imazamox rate have a significant effect on control (Geier et al. 2004). Specifically, Geier et al. (2004) found that rye control was reduced by > 20% if the imazamox application was made in November compared to October.

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Imazamox is rapidly absorbed and translocated in winter annual grasses including feral rye (Pester et al. 2001). Feral rye is more difficult to control with imazamox than jointed goatgrass in part because it translocates more of the herbicide to the roots where it can be exuded into the soil, but also because rye can metabolize imazamox at a faster rate (Pester et al. 2001). In addition to feral rye being more tolerant compared to other grassy weeds, significant variability exists within rye populations with respect to imazamox susceptibility (Peeper et al. 2008).

The imazamox herbicide label requires the use of methylated seed oil (MSO), crop oil concentrate, high-surfactant oil concentrate, or a combination of nonionic surfactant (NIS) plus a nitrogen fertilizer source (Anonymous 2010). The adjuvant system used with imazamox has been previously shown to have a significant effect on efficacy. MSO resulted in similar levels of absorption as NIS plus urea ammonium nitrate (UAN) in laboratory studies (Pester et al. 2001). MSO plus UAN caused significantly more injury to several IR wheat cultivars compared to NIS plus UAN (Frihauf et al. 2005). Increasing the amount of UAN in the spray solution also increased feral rye control (Geier and Stahlman 2009). Consistent with the results of Geier and Stahlman (2009), the imazamox label suggests increasing the nitrogen fertilizer rate when targeting feral rye. When used in IR winter wheat, up to 50% of the carrier solution may be liquid fertilizer, with UAN (either 28–0–0 or 32–0–0) or liquid ammonium phosphate (10–34–0) being allowable nitrogen sources (Anonymous 2010).

Geier and Stahlman (2009) have reported on the increased feral rye control from increasing UAN concentration in the spray solution; however, it is unclear if similar effects will result from increasing liquid ammonium phosphate (10–34–0) concentration. It is also not known what effect, if any, increasing fertilizer rate would have on feral rye control in tank mixes of imazamox plus MCPA ester. The initial objective of this research was to evaluate feral rye control with imazamox in IR winter wheat with various combinations of liquid fertilizer and MCPA ester. Based on the results of the field study, subsequent objectives included determining whether MCPA ester synergizes feral rye control with imazamox, and whether imazamox absorption or translocation could explain the interaction between these two herbicides.

Materials and Methods

Field Studies. Field studies were conducted in Nebraska in 2006 to 2007, and in Nebraska and Wyoming in 2008 to 2009 to evaluate the effect of liquid fertilizer rate (2.5, 25, or 50% of the spray solution) on the efficacy of imazamox or imazamox plus MCPA ester herbicides applied in the fall or spring for feral rye control. A field trial was conducted at the High Plains Agricultural Laboratory near Sidney, NE, in 2006 to 2007 and repeated in 2008 to 2009. Feral rye seed was broadcast by hand across the trial area and incorporated with a mulch treader prior to wheat seeding. The wheat cultivar 'Infinity CL' was seeded at a rate of 67 kg ha^{-1} on September 19, 2006, and at a rate of 62 kg ha^{-1} on September 18, 2008. Plots were 3 m wide by 12 m long. Herbicides were applied with an all-terrain-vehicle–mounted sprayer delivering 9.4 L ha^{-1} at 138 kPa. Fall treatments were applied on October 16, 2006, and October 8, 2008, when feral rye was in the one- to four-leaf stage with one tiller. Spring treatments were applied on March 23, 2007, and March 17, 2009, when feral rye had one to four tillers. Soil at Sidney was an Alliance silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls) with 2.1 to 2.6% organic matter and pH of 7.4 to 7.8. The fertilizer used at Sidney was liquid ammonium phosphate (10–34–0). Feral rye control was visually evaluated on June 5, 2007, and June 1, 2009, using a 0 to 100 scale, with 0 indicating no feral rye control, and 100 indicating complete death of all feral rye plants.

A third field trial was conducted at the Sustainable Agriculture Research and Extension Center near Lingle, WY, in 2008 to 2009. The wheat cultivar 'Bond CL' was seeded at a rate of 67 kg ha^{-1} on September 9, 2008, into an area with a natural feral rye infestation. Fall herbicide treatments were applied on October 23, 2008, when feral rye had two to four leaves and one tiller. Spring treatments were applied on April 13, 2009, when feral rye had one to four tillers. All herbicide treatments were applied with a CO_2-pressurized knapsack sprayer delivering 187 L ha^{-1} at 276 kPa. Fertilizer used at Lingle was UAN (32–0–0). Plots at Lingle were 3 m wide by 9 m long. Soil at the site was a Manter (coarse-loamy, mixed, superactive, mesic Aridic Argiustolls) and Anselmo (coarse-loamy, mixed, superactive, mesic Typic Haplustolls) fine sandy loam with 1.7% organic matter and pH of 7.8. Feral rye control was evaluated by counting reproductive tillers in a 9-m^2 area from each plot on May 27, 2009. The number of reproductive tillers in each plot was divided by the mean of the nontreated control to estimate percentage of feral rye control.

Herbicide treatments in all three field studies included a factorial arrangement of fertilizer rates (2.5, 25, or 50% of the spray solution), herbicide treatments (imazamox at 35 g ha^{-1} or imazamox at 35 g ha^{-1} plus MCPA ester at 280 g ha^{-1}), and application timings (fall or spring) plus a nontreated control. The nitrogen fertilizer used in these studies was liquid ammonium phosphate (10–34–0) at Sidney in both years and UAN (32–0–0) at Lingle. All treatments except the nontreated control contained NIS at 0.25% v/v. Experimental design for field studies was a randomized complete block design with four replicates. Feral rye control, wheat yield, and grain contamination data were subject to ANOVA. Trial location, fertilizer rate, herbicide treatment, and application timing were all considered fixed effects in the ANOVA model. Although fertilizer rates were structured, the effect of fertilizer rate was modeled as a factor variable rather than a continuous variable because there was evidence that the response to fertilizer rate was not linear, so inclusion as a linear covariate was not appropriate and the limited number of rates did not allow for a robust nonlinear analysis.

Fertilizer Effect. A greenhouse study was conducted to directly compare the effect of liquid fertilizers on feral rye control with imazamox. The liquid ammonium phosphate source used in the field studies in Nebraska was compared to the UAN source used in the Wyoming field study to determine whether differences between the sites could be related to the fertilizer type. Feral rye seed was planted in cone-shaped containers (3.5 cm diam, 25 cm deep) filled with a mixture of one part sand to two parts commercial potting mix. For all greenhouse studies, plants were grown under supplemental light providing a 16-h photoperiod, at a temperature of 24 C (± 2), and watered and fertilized as needed. Treatments included a factorial arrangement of fertilizer type (either UAN or 10–34–0, using the same fertilizer sources used in the field studies), fertilizer rate (either 2.5, 25, or 50% of the spray solution), and imazamox rate (5, 9, 18, 35, 53, or 70 g ha^{-1}) plus a nontreated control. All herbicide treatments contained NIS at 0.25% v/v. Each treatment had five replications and the experiment was repeated. Experimental design was a randomized complete block with plant growth stage as the blocking criteria. Feral rye growth stage ranged from five-leaf with one tiller in the first block to three-leaf with no tillers in the fifth block. Aboveground biomass was harvested 28 d after treatment (DAT), dried for 48 h at 60 C, and weighed. Dry weight data were subject to ANOVA to test for treatment effects and experiment by treatment interactions, then nonlinear regression was conducted on replicate data to describe the response of feral rye to imazamox at the various fertilizer levels. The R statistical language was used for all analyses, with the drc package being used for nonlinear regression analysis (R Development Core Team 2009; Ritz and Streibig 2005). The four-parameter log-logistic model proposed by Seefeldt et al. (1995) was used (Equation 1).

$$Y = c + (d - c)/1 + \exp[b(\log(X) - \log(e))] \qquad [1]$$

Where c and d are the lower and upper asymptotes, respectively, b is the slope around the inflection point of the curve, and e is the value of X where the inflection point occurs.

A second greenhouse study was conducted to compare additional sources of each fertilizer type to determine whether field studies and the first greenhouse study results were limited to the fertilizer source used. Additional UAN (28–0–0) and liquid ammonium phosphate (10–34–0) were obtained from a local fertilizer dealer and included in the second greenhouse experiment. A total of four fertilizer sources were compared in this study: liquid ammonium phosphate (10–34–0) used in the Nebraska field studies, liquid ammonium phosphate (10–34–0) obtained from a Wyoming dealer, UAN (32–0–0) used in the Wyoming field study, and a second source of UAN (28–0–0). Treatments in this greenhouse experiment included a factorial arrangement of the four fertilizer sources, three fertilizer rates (2.5, 25, or 50% of the spray solution), and two imazamox rates (35 or 70 g ha^{-1}) plus a nontreated control. Aboveground biomass was harvested 28 DAT, dried for 48 h at 60 C, and weighed. The experiment was a randomized complete block design with five replicates; the experiment was repeated. Dry weight data were subject to ANOVA to test for treatment effects and treatment by experiment interactions.

MCPA effect. A greenhouse study was conducted at the conclusion of field studies to confirm whether or not MCPA ester synergizes imazamox for feral rye control. A factorial arrangement of imazamox rates (0, 9, 18, 35, or 70 g ha^{-1}) and MCPA ester rates (0, 70, 140, 280, or 560 g ha^{-1}) were applied to feral rye at the three- to five-leaf growth stage. All treatments included UAN (32–0–0) at 1% v/v plus NIS at 0.25% v/v. Aboveground biomass was harvested 28 DAT, dried for 48 h at 60 C, and weighed. Experimental design was a factorial randomized complete block with five replicates where plant growth stage was used as the blocking criteria. Plants ranged in size at the time of treatment from five-leaf in the first block to three-leaf in the fifth block. The study was repeated. Dry weight data were analyzed using nonlinear regression on replicate data. The four-parameter log-logistic model (Equation 1) was fit to these data using the drc package in the R statistical language (R Development Core Team 2009; Ritz and Streibig 2005; Seefeldt et al. 1995). The GR_{50} imazamox dose was calculated for each MCPA ester rate.

At the conclusion of greenhouse studies, laboratory experiments were conducted to determine if adding MCPA ester to the spray solution increased imazamox absorption or translocation in feral rye. Feral rye seeds were planted in 5-cm-diam by 20-cm-long pots filled with washed sand. Following planting, rye was fertilized with slow-release fertilizer.[1] Plants were grown in the growth chamber at 22/18 C day/night temperature under a 16-h photoperiod (400 $\mu E\ m^{-2}\ s^{-1}$). Plants were allowed to grow for 21 d, and were treated when they had reached the four- to five-leaf stage with one tiller. Plants were sprayed with treatment solutions using an overhead track sprayer in an application volume of 187 L ha^{-1} at 172 kPa. Imazamox treatments were applied at 44 g ha^{-1} and MCPA ester was applied at 350 g ha^{-1}. Treatments included the following: (1) imazamox + 0.25% NIS + 2.5% UAN (32–0–0); (2) imazamox + MCPA ester + 0.25% NIS + 2.5% UAN (32–0–0); (3) imazamox + 2% MSO; (4) imazamox + MCPA ester; and (5) imazamox + MCPA ester + 2% MSO. After spraying, one leaf of each plant was immediately treated with 10 0.5-µl drops of the corresponding treatment solution spiked with ^{14}C-imazamox (4.5 kBq $plant^{-1}$, specific activity 1,850 kBq mg^{-1}).[2] Immediately following treatment, plants were placed in the growth chamber until harvest.

Plants were harvested at 0, 2, 4, 8, and 24 h after treatment (HAT). Treated leaves were excised, placed in 5 ml of a leaf wash solution containing 10% methanol and 0.25% NIS, and shaken for 20 min. After shaking, 10 ml of liquid scintillation cocktail[3] was added to each vial and radioactivity was quantified using liquid scintillation spectroscopy (LSS).[4] Radioactivity quantified in the leaf wash solution was divided by the total applied radioactivity to determine the percentage of the imazamox that was not absorbed. The rest of the plant was harvested and separated into aboveground and root biomass. Treated leaves harvested from all time points were dried at 60 C for 48 h; dry biomass was recorded and oxidized using a biological sample oxidizer.[5] Radioactivity was trapped using 10 ml of ^{14}C trapping cocktail[6] and determined using LSS. Aboveground and root portions for the 24 HAT time point were analyzed in the same manner as the treated leaves to determine translocation out of the treated leaf and into aboveground or root tissue. Experimental design was a randomized complete block with three replicates for each treatment solution by time point combination, and the study was repeated.

Absorption data were analyzed using analysis of covariance to determine whether significant differences existed between treatments over time and whether there was a treatment by experiment interaction. Fisher's LSD was calculated to compare treatment differences within a time point. Nonlinear regression was then conducted on replicate data to describe the absorption pattern for each treatment. An asymptotic regression model of the form

$$absorption = A[1 - \exp(-bt)] \qquad [2]$$

was fit to each treatment solution to describe the absorption of each treatment over time, where absorption is expressed as a percentage of the applied dose; *A* is the upper asymptote, or the theoretical maximum absorption level; *t* is time, expressed in HAT; and *b* is a slope parameter that has a positive relationship to the speed with which absorption reaches the maximum. When appropriate, likelihood ratio tests were used to compare model parameters for differences in maximum absorption (*A*) and speed of absorption (*b*).

Radioactivity quantified in the aboveground or root biomass was divided by the total amount of radioactivity applied, and presented as the percentage of the applied dose that was translocated. Translocation data 24 HAT were analyzed using ANOVA. All statistical analyses were conducted using the R language (R Development Core Team 2009), and nonlinear regression was conducted using the drc package in R (Ritz and Streibig 2005).

Results and Discussion

Field Studies. A significant interaction ($P < 0.05$) between the effects of location, MCPA, fertilizer rate, and application timing were present with respect to feral rye control, and thus simple effects are presented (Table 1). Fall applications generally provided greater feral rye control compared to spring applications in both years at Sidney, but this trend was not observed at Lingle. Increasing the rate of 10–34–0 in the spray solution at Sidney caused a reduction in feral rye control at both application timings in both years. When applied in the fall without MCPA ester at Sidney, the 50% fertilizer concentration reduced feral rye control by 25 to 68% compared to the 2.5% fertilizer rate. Spring applications showed a similar trend at Sidney with control at the 50% fertilizer rate being reduced to 10% or less compared to 50 to 73% control with the lower fertilizer rates. The opposite trend was observed from fall applications at Lingle in 2009, where increasing the fertilizer rate from 2.5% to either 25 or 50% resulted in a 26% increase in feral rye control. There were no differences between spring applications at Lingle, where feral rye was controlled ≥ 98% in all treatments.

The difference between locations with respect to fertilizer rate may be related to the different fertilizers used at the field sites. At Lingle, UAN was used and the increase in control agrees with previous research by Geier and Stahlman (2009) showing that imazamox control of feral rye increased as UAN rate in the spray solution increased. At Sidney in both years, liquid ammonium phosphate (10–34–0) was used as the nitrogen source. The imazamox label specifically allows use of either UAN or 10–34–0 for use with imazamox, and suggests an increase in the fertilizer rate when targeting feral rye. The results from Sidney in both years indicate that increasing the rate of 10–34–0 may actually decrease feral rye control.

Table 1. Feral rye control with imazamox as affected by MCPA ester and nitrogen fertilizer in field studies conducted at three locations.[a]

Location	Application timing	Fertilizer rate[b]	Feral rye control Without MCPA	Feral rye control With MCPA[c]
		%	%	%
Sidney, 2007	Fall	2.5	90	94
		25	83	92
		50	22	93
	Spring	2.5	73	88
		25	8	77
		50	0	77
Sidney, 2009	Fall	2.5	88	97
		25	93	98
		50	63	95
	Spring	2.5	50	75
		25	10	53
		50	10	57
Lingle, 2009	Fall	2.5	70	88
		25	96	95
		50	96	98
	Spring	2.5	98	99
		25	100	97
		50	100	98
LSD (0.05)			10	

[a] Imazamox at 35 g ha^{-1} plus nonionic surfactant at 0.25% v/v was applied with all treatments

[b] Fertilizer consisted of liquid ammonium phosphate (10–34–0) at Sidney, and urea ammonium nitrate (32–0–0) at Lingle.

[c] MCPA ester was applied at 280 g ha^{-1}.

Adding MCPA ester to the spray solution reduced or eliminated the antagonistic effect of increasing fertilizer rate at Sidney (Table 1). In most comparisons within a fertilizer rate and application timing at Sidney, adding MCPA ester resulted in a significant increase in feral rye control. The MCPA effect was most pronounced at the spring application timing when 25 or 50% fertilizer was added (2007), where feral rye control ranged from 0 to 8% without MCPA ester, but was increased to 77% when MCPA ester was included. Based on the Sidney field studies, it was unclear whether MCPA ester was interacting directly with the fertilizer to reduce or eliminate the antagonistic effect, or if the MCPA ester was increasing imazamox efficacy thereby masking the antagonistic fertilizer effect. At Lingle, no fertilizer antagonism was observed, but MCPA ester increased feral rye control 18% when it was added to the 2.5% fertilizer rate in the fall. We therefore hypothesized that MCPA ester was synergizing imazamox for feral rye control. In order to test this hypothesis, separate greenhouse studies were conducted to examine the effect of fertilizer and MCPA ester on control of feral rye with imazamox.

Fertilizer Effect. Greenhouse studies were conducted to determine whether the fertilizer effects observed in the field studies were related to the type of fertilizer used. No

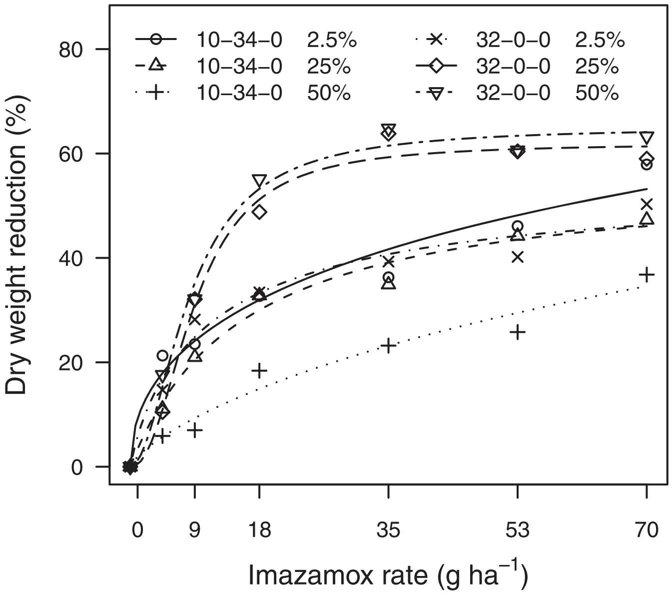

Figure 1. Feral rye dry weight reduction in response to imazamox and various rates of two types of fertilizer. Model equation and parameter estimates are provided in Table 2.

interaction effects with experiment were observed ($P > 0.05$) so data were pooled over experiments for analysis. A significant interaction between fertilizer source and fertilizer rate was observed ($P < 0.0001$), as well as a significant effect of imazamox rate ($P < 0.0001$). When added to the spray solution at 2.5%, liquid ammonium phosphate (10–34–0) and UAN (32–0–0) resulted in similar feral rye dry weight reduction (Figure 1; Table 2). When liquid ammonium phosphate was added at 2.5 or 25% of the spray volume, dry weight reduction caused by 35 g ha^{-1} was predicted to be 41 and 39%, respectively. However, when liquid ammonium phosphate was added at the 50% concentration, dry weight reduction was less than all other treatments. Conversely, when UAN was added at either 25 or 50% of the spray solution, feral rye dry weight was reduced compared to the 2.5% concentration. When applied at 50% of the spray volume with 35 g ha^{-1} imazamox, liquid ammonium phosphate and UAN caused 23 and 61% dry weight reduction, respectively.

Increasing the UAN rates in the Lingle field study provided increased feral rye control at the fall application timing (Table 1). Similar results have been found by other researchers (Geier and Stahlman 2009), thus the recommendation for increased fertilizer on the imazamox product label appears justified; however, the liquid ammonium phosphate that was antagonistic in Sidney field studies (Table 1) was also shown to be antagonistic at the 50% concentration in this greenhouse study (Figure 1; Table 2). These results confirm observations from the field studies that liquid ammonium phosphate at high concentrations can reduce feral rye control with imazamox.

The results of the first greenhouse study and Sidney field studies conflict with label recommendations, and thus a second greenhouse study was conducted to determine whether these results were limited to the specific source of liquid ammonium phosphate used in the field and greenhouse studies, or whether additional sources of liquid ammonium phosphate result in a similar antagonistic effect. No interaction effects with experiment were observed ($P > 0.05$) so data were pooled over experiments for analysis. Results of these subsequent greenhouse fertilizer studies were not consistent with the previous field and greenhouse studies. Effects of fertilizer source and fertilizer rate on feral rye dry weight reduction were not significant in subsequent greenhouse studies ($P < 0.1$; data not shown), indicating that none of the fertilizer sources were antagonistic to imazamox. It is currently unclear whether the antagonism we observed in field and greenhouse studies was caused directly by liquid ammonium phosphate used in the studies, or if that particular source contained contaminants or had been exposed to poor storage conditions that caused the negative effects. Based on the inconsistent results of our greenhouse studies, we feel it will be important to conduct further research under field conditions to conclusively quantify the effect of liquid ammonium phosphate on feral rye control with imazamox.

MCPA Effect. Greenhouse studies were conducted to quantify the synergistic effect of MCPA ester with imazamox on feral rye under controlled conditions. No interaction effects with experiment were observed ($P > 0.05$) so data were pooled over experiments for analysis. In the absence of imazamox, MCPA ester had no significant effect on feral rye dry weight ($P = 0.76$) in the greenhouse study. Feral rye dry

Table 2. Log-logistic model parameters and predicted dry weight reduction for feral rye response to imazamox mixed with two fertilizer types.

		Model parameter (standard error)[a]			Dry weight reduction (standard error)[b]	
Fertilizer type	Fertilizer rate	*b*	*d*	*e*	35 g ha^{-1} imazamox	70 g ha^{-1} imazamox
	%				——%	——
Liquid ammonium phosphate (10–34–0)	2.5	−0.58(0.232)	138(159.7)	200(664)	41(75.0)	53(65.4)
	25	−1.2(1.08)	50(30.7)	17(23.7)	39(866)	46(541)
	50	−1.1(1.22)	72(252)	94(535)	23(3.89)	35(5.75)
Urea ammonium nitrate (32–0–0)	2.5	−0.94(1.32)	51(46.1)	14(32.3)	41(8.94)	46(9.77)
	25	−2.5(1.06)	57(5.18)	9.4(1.89)	59(19.9)	61(33.6)
	50	−2.2(0.91)	60(5.36)	8.7(1.78)	61(3.49)	64(4.32)

[a] Data were fit to the log-logistic equation $y = c + [(d - c)/(1 + (x/e)^b)]$, where y is feral rye dry weight; c and d are the lower and upper asymptotes, respectively, with c fixed at 0; e is the dose required to cause a 50% response in dry weight; b is the slope of the curve around e; and x is the rate of imazamox.

[b] Dry weight reduction and associated standard errors presented are the fitted values from the log-logistic model.

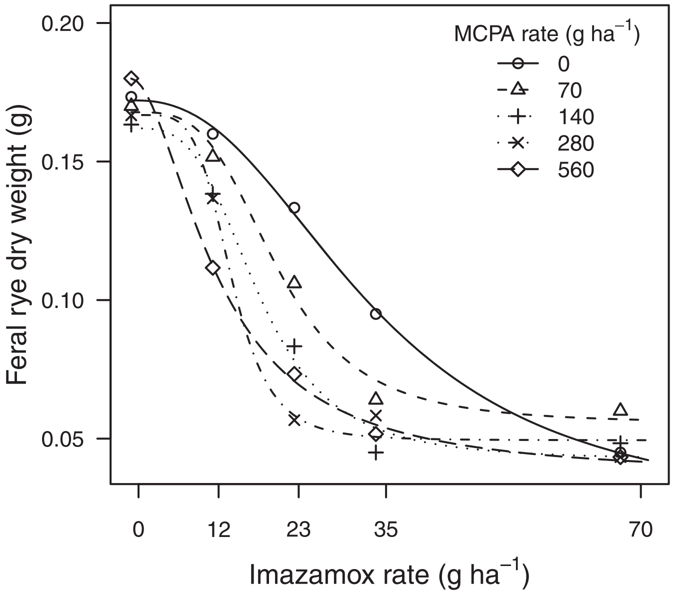

Figure 2. Response of feral rye to imazamox as influenced by MCPA ester. Model equation and parameter estimates are provided in Table 3.

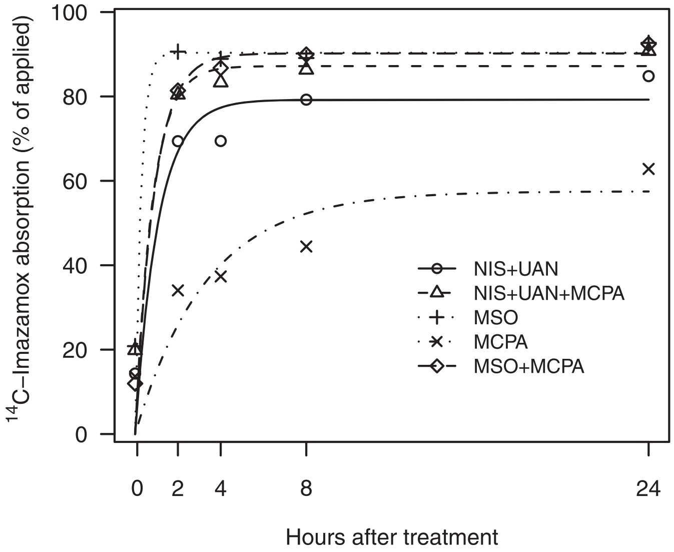

Figure 3. ^{14}C-Imazamox absorption in feral rye as influenced by five different treatment solutions. Data fit to Equation 1: absorption $= A\ [1 - \exp(-\ bt)]$. Parameter estimates (with standard errors): nonionic surfactant (NIS) + urea ammonium nitrate (UAN), $A = 79(3.0)$, $b = 0.93(0.25)$; NIS + UAN + MCPA, $A = 87(2.7)$, $b = 1.2(0.38)$; methylated seed oil (MSO), $A = 90(2.2)$, $b = 3.7(16.5)$; MCPA, $A = 58(4.7)$, $b = 0.30(0.08)$; MSO + MPCA, $A = 90(2.8)$, $b = 1.1(0.29)$.

weight was modeled as a function of imazamox application rate for each level of MCPA ester using the log-logistic model (Figure 2). As the MCPA ester rate increased, the *e* parameter (the rate of imazamox required to cause a 50% feral rye dry weight response) decreased (Table 3). In the absence of MCPA ester, 35 g ha^{-1} imazamox was required to cause a 50% reduction in feral dry weight. MCPA ester at rates of 70 to 560 g ha^{-1} decreased the *e* parameter by 40 to 63%, indicating a substantial synergistic effect of MCPA ester on imazamox. Results of this greenhouse dose response study confirm the field results at Sidney and Lingle demonstrating that MCPA ester improves feral rye control with imazamox.

Laboratory studies were then conducted to determine whether imazamox absorption and translocation were influenced by MCPA ester. No interaction effects were observed ($P > 0.05$) with repeated experiments so data were pooled over experiments for analysis. Maximum ^{14}C-imazamox absorption for MCPA ester plus NIS and UAN reached 87% compared to 79% for the same treatment without MCPA ester ($P = 0.0439$; Figure 3); however, the speed of absorption as characterized by the *b* parameter was similar between the two treatments ($P = 0.4143$). The delivery solution of imazamox plus MCPA ester without any additional adjuvants resulted in only 58% of the applied dose being absorbed, significantly less than any other treatment ($P \leq 0.0026$). This indicates that although MCPA ester increases absorption in the presence of UAN plus NIS, the addition of MCPA ester alone does not provide a similar adjuvant effect as UAN plus NIS or MSO. Both MSO and MSO plus MCPA ester resulted in 90% absorption. If the increase in absorption caused by MCPA ester is responsible for increased imazamox efficacy, similar effects should not be observed if MCPA ester was added to imazamox plus MSO, since MCPA ester did not increase absorption in this treatment.

Table 3. Log-logistic model paramaters for feral rye response to imazamox at five rates of MCPA ester.

MCPA ester rate	Model parameter (standard error)[a]			
	b	*c*	*d*	*e*
g ai ha^{-1}				
0	2.4 (2.2)	0.022 (0.068)	0.17 (0.017)	35 (16)
70	3.7 (2.8)	0.056 (0.018)	0.17 (0.018)	21 (5.1)
140	3.6 (2.0)	0.043 (0.016)	0.16 (0.018)	18 (4.2)
280	5.6 (5.1)	0.050 (0.014)	0.17 (0.017)	14 (3.1)
560	2.0 (1.5)	0.037 (0.027)	0.18 (0.017)	13 (4.0)

[a] Data were fit to the log-logistic equation $y = c + [(d - c)/(1 + (x/e)^b)]$, where y is feral rye dry weight; c and d are the lower and upper asymptotes, respectively; e is the dose required to cause a 50% response in dry weight; b is the slope of the curve around e; and x is the rate of imazamox.

When analyzed 24 h after treatment, the MCPA ester plus NIS and UAN treatment resulted in less radioactivity translocating out of the treated leaf compared to the same treatment without MCPA ester (Figure 4). This trend was especially evident in the amount of radioactivity translocated from the treated leaf to other aboveground plant parts. Given these results, it seems unlikely that the increased absorption observed in response to MCPA ester is enough to explain the differences in efficacy between these treatments. These data suggest that translocation to meristems was actually inhibited by MCPA ester, even though absorption was enhanced by the same treatment.

Although the mechanism remains unclear, this research has shown conclusively in field and greenhouse studies that MCPA ester has a synergistic effect with imazamox for feral rye control. To our knowledge, this is the first report in the peer-reviewed literature of synergism between a synthetic auxin and an imidazolinone herbicide on a grass species. Further research is warranted to determine the mechanism responsible for this synergistic effect. Pester et al. (2001)

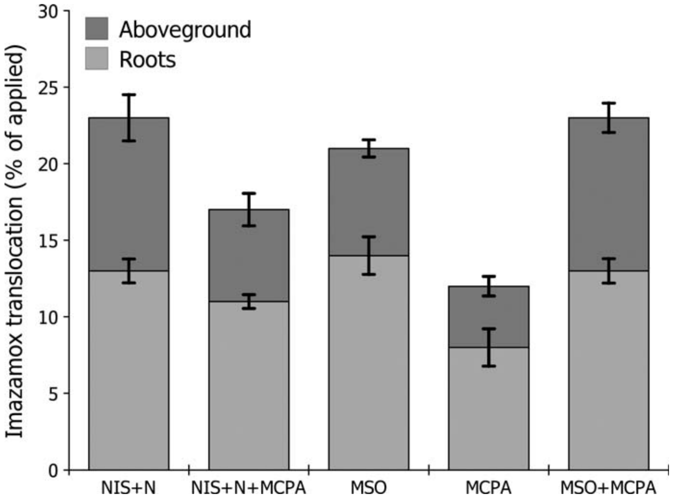

Figure 4. ^{14}C-Imazamox translocation from the treated leaf to aboveground portions and roots in feral rye 24 h after treatment as influenced by five treatment solutions. Bars represent standard errors of the mean.

demonstrated that feral rye metabolizes imazamox rapidly and to a greater extent compared to other winter annual grasses, which may explain differences in relative efficacy of the herbicide on these species. Imazamox metabolism in grass species has not been thoroughly described in the literature. Pester et al. (2001) separated two major imazamox metabolites in feral rye, but no attempt was made to identify these metabolites. Imidazolinone metabolism typically follows a two- or three-phase process, but the reactions involved can differ depending on the specific imidazolinone (Tecle et al. 1993). Imazamox metabolism in soybean involves hydroxylation of the methyl group followed by a glucose conjugation (Shaner 2003), and it is likely that a similar process occurs in feral rye and other grasses.

The addition of MCPA ester might inhibit imazamox metabolism (although we provide no direct evidence for or against this potential mechanism) and therefore it would be of interest to study the effect of MCPA ester on imazamox metabolism. High levels of plant auxin or auxin-mimic herbicides are known to interfere with a variety of plant processes. Although typically used for selective control of broadleaf weeds, recent research has documented significant physiological effects of auxin-mimic herbicides on grass species when applied POST (Rinella et al. 2010) or PRE (Kniss and Lyon 2011). It is possible that MCPA ester is inhibiting either the phase I reaction (hydroxylation), or phase II reaction (glucose conjugation) metabolism of imazamox in feral rye. It is also of interest to know whether similar herbicides (such as 2,4-D ester), or other formulations of MCPA (such as MCPA amine) would result in a similar synergistic effect.

Sources of Materials

[1] Osmocote 14-14-14, Scotts-Sierra Horticultural Products Co., Marysville, OH 43041.

[2] Imazamox, BASF, Florham Park, NJ 07932.

[3] Ultima Gold LLT (6013371), Perkin Elmer Life and Analytical Sciences, Inc., Waltham, MA 02451.

[4] Packard Tri-Carb, model 2500 TR, Packard Instrument Co., Meriden, CT 06450.

[5] OX-500, R.J. Harvey Instrument Co., Tappan, NY 10983.

[6] OX-161, R.J. Harvey Instrument Co., Tappan, NY 10983.

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