Weed Technology

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Weed control in corn with tolpyralate and atrazine plus grass herbicides

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Research Article

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Nomenclature:
Acetochlor; atrazine, dimethenamid-p; flufenacet; pendimethalin; pyroxasulfone; *S*-metolachlor; tolpyralate; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv.; common lambsquarters, *Chenopodium album* L.; common ragweed, *Ambrosia artemisiifolia* L.; giant foxtail, *Setaria faberii* Herrm.; green foxtail, *Setaria viridis* (L.) Beauv.; yellow foxtail, *Setaria glauca* (L.) Beauv.; redroot pigweed, *Amaranthus retroflexus* L.; nightshades, velvetleaf, *Abutilon theophrasti* Medik.; corn, *Zea mays* L.

Keywords:
Corn injury; efficacy; grasses; herbicide interaction; herbicide mixtures; weed control; yield

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Abstract

Six field experiments were established in southwestern Ontario in 2021 and 2022 to evaluate whether the addition of a grass herbicide (acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor) to tolpyralate + atrazine improves late-season weed control in corn. Tolpyralate + atrazine caused 12% and 5% corn injury at 1 and 4 wk after herbicide application (WAA); corn injury was not increased with the addition of a grass herbicide. Weed interference reduced corn yield 60%. The addition of a grass herbicide to tolpyralate + atrazine did not enhance velvetleaf control. The addition of acetochlor or dimethenamid-p to tolpyralate + atrazine enhanced pigweed species control 4% 4 WAA; the addition of other grass herbicides tested did not increase pigweed species control. The addition of acetochlor enhanced common ragweed control 5% at 4 WAA, and the addition of acetochlor or dimethenamid-p enhanced common ragweed control 8% at 8 WAA; the addition of other grass herbicides did not improve common ragweed control. The addition of acetochlor to tolpyralate + atrazine enhanced common lambsquarters control up to 4%; there was no enhancement in common lambsquarters control with the addition of the other grass herbicides. Tolpyralate + atrazine controlled barnyardgrass 90% and 78% at 4 and 8 WAA, respectively; the addition of a grass herbicide enhanced barnyardgrass control 9% to 10% and 21% at 4 and 8 WAA, respectively. Tolpyralate + atrazine controlled green or giant foxtail 80% and 69% at 4 and 8 WAA, respectively; the addition of a grass herbicide enhanced foxtail species control 15% to 19% and 24% to 29% at 4 and 8 WAA, respectively. This research shows that adding a grass herbicide to tolpyralate + atrazine mixture can improve weed control efficacy, especially increased annual grass control in corn production.

Introduction

Tolpyralate is a pyrazole (Group 27) herbicide registered for the control of some annual grass and broadleaf weeds in corn (Anonymous 2021). Tolpyralate is applied postemergence and inhibits the 4-hydroxyphenyl-pyruvate dioxygenase (HPPD) enzyme in sensitive plants (Anonymous 2021). Tolpyralate is often co-applied with atrazine, a photosystem II–inhibiting herbicide from the triazines (Group 5) chemical family for improved control of velvetleaf (*Abutilon theophrasti* Medic.), common lambsquarters (*Chenopdium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], Palmer amaranth (*Amaranthus palmeri* S. Watson), common ragweed (*Ambrosia artemisiifolia* L.), kochia [*Bassia scopfaria* (L.) A.J. Scott], barnyardgrass (*Echinochloa crus-galli*), green foxtail (*Setaria viridis* L.), and giant foxtail (*Setaria faberi* L.) (Metzger et al. 2018a, b; Tonks et al. 2015). Earlier studies have shown inadequate control of annual grasses with tolpyralate + atrazine (Fluttert et al. 2022; Metzger et al. 2018a; Osipitan et al. 2018). The mixture of tolpyralate + atrazine with a residual grass herbicide may improve late-season weed control in corn, especially control of annual grasses. Additionally, utilizing other modes of action in a mixture with tolpyralate + atrazine may slow down the evolution of additional herbicide-resistant weeds in corn (Lamichhane et al. 2017; Osipitan and Dille 2017; Owen 2016). Grass herbicides that can potentially be co-applied with tolpyralate + atrazine to improve residual weed control efficacy include acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor.

Group 15 herbicides, acetochlor, dimethenamid-p, flufenacet, pyroxasulfone, and *S*-metolachlor belong to the chloroacetanilide, chloroacetamide, oxyacetamide, isoxazoline, and chloroacetanilide chemical families, respectively. The Group 15 herbicides are taken up by both roots and shoots of sensitive weed seedlings and inhibit the biosynthesis of very-long-chain fatty acid elongases (Fogleman 2018; Grichar et al. 2005; Hopkins et al. 1998; Shaner 2014). Acetochlor, dimethenamid-p, flufenacet, pyroxasulfone, and *S*-metolachlor control some small-seeded annual grass including barnyardgrass, *Digitaria* spp., fall panicum (*Panicum dichotomiflorum* Michx.), *Setaria* spp., and witchgrass (*Panicum capillare* L.) and broadleaved weeds including pigweeds, common ragweed, common lambsquarters, *Polygonum* spp., *Solanum* spp., and wild mustard (*Sinapis arvensis* L.) (Fogleman 2018; Hopkins et al. 1998; Shaner 2014; Steckel et al. 2003).

Pendimethalin is an herbicide from the dinitroaniline chemical family (Group 3) used preemergence or postemergence in corn to control annual grasses such as barnyardgrass, fall panicum, giant foxtail, green foxtail, yellow foxtail (*Setaria pumila* L.), smooth crabgrass [*Digitaria ischaemum* (Schreb.) Muhl.], and large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and broadleaf weeds such as common lambsquarters and redroot pigweed (Hopkins et al. 1998; Shaner 2014). Pendimethalin is absorbed by roots and shoots and is a microtubule polymerization inhibitor that inhibits mitosis and cell wall formation in sensitive plants (Shaner 2014).

Little research has been published on improved residual weed control with the co-application of residual grass herbicides with tolpyralate + atrazine for late-season weed control in corn. The aim of this study was to determine if the addition of a grass herbicide to tolpyralate + atrazine would improve late-season weed control in corn.

Materials and Methods

In 2021 and 2022, three field experiments were carried out at the University of Guelph Ridgetown Campus, Ridgetown, ON, Canada (42.45° N, 81.88° W), and three field experiments were completed at the Huron Research Station near Exeter, ON, Canada (43.32° N, 81.50° W). The experiments were designed as randomized complete block designs with four replicates. The experimental plots were 3 m wide and 8 m long at Ridgetown and 10 m long at Exeter. Glyphosate/glufosinate-resistant corn hybrids 'DKC39-97 RIB'/'DKC 42-04RIB' were seeded to a depth of 4–5 cm at 80,000 seeds ha^{-1} in rows that were 0.75 m apart (four rows in each plot).

Treatments consisted of a weedy control, weed-free control, and tolpyralate + atrazine (30 + 560 g ai ha^{-1}) applied as a mixture and co-applied with acetochlor (1225 g ai ha^{-1}), dimethenamid-p (544 g ai ha^{-1}), flufenacet (360 g ai ha^{-1}), pendimethalin (1680 g ai ha^{-1}), pyroxasulfone (125 g ai ha^{-1}), or *S*-metolachlor (1140 g ai ha^{-1}). All tolpyralate + atrazine mixtures included methylated seed oil (MSO Concentrate®) at 1% v/v (Tables 1–7).

Herbicide treatments were applied postemergence when the naturally occurring weed population reached an average canopy height of 10 cm with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} aqueous solution at 240 kPa. The boom was 1.5 m long with four Hypro ULD120-02 nozzle tips (Pentair, New Brighton, MN) spaced 50 cm apart, producing a spray width of 2.0 m. The weed-free control plots were sprayed with *S*-metolachlor/atrazine/mesotrione/bicyclopyrone (Acuron, 2230 g ai ha^{-1}, Syngenta Canada Inc, Guelph, ON, Canada) applied preemergence followed by glyphosate (Roundup WeatherMAX®, 540 g ae L^{-1}; Bayer CropScience Canada Inc., Calgary, AB, Canada).

Visible injury in corn was evaluated 1 and 4 wk after herbicide application (WAA), and weed control was evaluated 4 and 8 WAA on a scale of 0% to 100% (0% = no corn injury/no weed control and 100% = complete plant necrosis) relative to the weed-free/nontreated control. Weed density was determined by counting each weed species present in two randomly selected quadrats (0.25 m^2 each) within each plot at 8 WAA. Shoot dry weight (biomass) was measured by removing each weed at the soil level within each quadrat, separating them by species, placing them in a paper bag, drying them (60 C) to constant moisture, and then weighing them. The two middle rows of corn in each plot were combined at harvest maturity with a small-plot combine; weight and seed moisture were recorded. Yields were adjusted to 15.5% moisture prior to statistical analysis.

Statistical Analysis

Data were analyzed with PROC GLIMMIX. The generalized linear mixed model fixed effect was herbicide treatment and random effects were environment (year–location combinations), environment-by-treatment interaction, and replicate within environment. The normal probability plot from PROC UNIVARIATE and the Shapiro-Wilk statistic was used to assess normality. Deviations from the assumption of homogeneity of variance were checked using studentized residual plots generated in PROC GLIMMIX. Visible percent weed control evaluations were arcsine-square root transformed prior to using a Gaussian distribution. Weed density and shoot dry biomass were analyzed using a log-normal distribution. Corn yield was analyzed using a Gaussian distribution. Least square means for all variables except yield were back-transformed to the data scale for presentation, with treatment differences reflecting the results of the analysis performed on the model scale. Treatment differences were determined using the Tukey-Kramer multiple-range test at a significance level of $P < 0.05$. When a treatment had zero variance due to assigned values (nontreated and weed-free controls), it was excluded from the analysis; comparisons between each treatment and the value zero were possible using the P value generated for each mean in the LSMEANS output.

Results and Discussion

Corn Injury and Corn Yield

Tolpyralate + atrazine applied as a mixture and in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor caused 11% to 16% corn injury at 1 WAA; there was no difference among the herbicide mixtures assessed (Table 1). Tolpyralate + atrazine applied as a mixture and in combination with grass herbicides assessed caused 4% to 8% injury in corn at 4 WAA; tolpyralate + atrazine + dimethenamid-p resulted in higher corn injury than tolpyralate + atrazine + pendimethalin.

Weed interference reduced corn yield 60%. Decreased weed interference with tolpyralate + atrazine and when mixed with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor resulted in corn yield that was comparable to the weed-free control.

Similar corn yields were reported in other studies conducted with tolpyralate + atrazine at comparable rates in corn (Metzger et al. 2018a, b; Osipitan et al., 2018; Tonks et al., 2015). Osipitan et al. (2018) found that decreased weed interference with tolpyralate and tolpyralate + atrazine caused higher corn yields by 52% and 61%, respectively in comparison to the weedy control. Metzger et al. (2019) found a significant yield enhancement in corn (10,400 kg ha^{-1} vs 4,300 kg ha^{-1}) due to reduced weed interference with tolpyralate + atrazine in comparison to the weedy control. Other research has shown that reduced weed interference provided by the residual activity of pyroxasulfone or dimethenamid-p can result in corn yields that are similar to the weed-free control (Soltani et al. 2019; Stephenson et al. 2017). However, weed interference with *S*-metolachlor applied alone caused a 33% corn yield reduction in comparison to the weed-free control (Soltani et al. 2019).

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Table 1. Visible percent corn injury 1 wk after herbicide application (WAA) ($n = 5$), 4 WAA ($n = 3$), and corn yield ($n = 6$) for herbicide treatments consisting of tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Exeter and Ridgetown, ON, in 2021 and 2022.[a]

Herbicide treatment[b]	Rate	Corn injury 1 WAA	Corn injury 4 WAA	Corn yield
	g ai ha^{-1}	%	%	kg ha^{-1}
Weed-free control		0	0	12,100 a
Nontreated control		0	0	4,800 b
Tolpyralate + atrazine[b]	30 + 560	12 a	5 bc	10,300 a
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	11 a	6 bc	11,400 a
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	16 a	8 c	11,400 a
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	13 a	7 bc	11,400 a
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	11 a	4 ab	11,500 a
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	11 a	5 bc	11,700 a
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	16 a	6 bc	11,200 a

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

Table 2. Visible percent control 4 and 8 wk after herbicide application (WAA), density and dry biomass 8 WAA for velvetleaf (ABUTH) treated with tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Exeter and Ridgetown, ON in 2021 and 2022 ($n = 4$).[a]

Herbicide treatment[b]	Rate	ABUTH control[a] 4 WAA	ABUTH control[a] 8 WAA	ABUTH density	ABUTH dry biomass
	g ai ha^{-1}	%	%	No. plants m^{-2}	g m^{-2}
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0	0	10.8 b	36.3 c
Tolpyralate + atrazine[b]	30 + 560	82 a	74 a	2.5 a	2.8 b
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	94 a	92 a	2.1 a	1.5 b
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	93 a	92 a	1.7 a	1.0 ab
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	89 a	82 a	2.2 a	1.7 b
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	95 a	94 a	2.1 a	0.7 ab
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	94 a	93 a	1.9 a	1.4 b
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	87 a	74 a	3.6 ab	6.3 b

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

Weed Control

Velvetleaf

Tolpyralate + atrazine controlled velvetleaf 82% and 74% at 4 and 8 WAA, respectively; there was no enhancement of velvetleaf control when acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor were added to the mixture of tolpyralate + atrazine (Table 2). Tolpyralate + atrazine decreased velvetleaf density and shoot dry biomass 77% and 92%, respectively; there was no further reduction in velvetleaf density and shoot dry biomass with the addition of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone or *S*-metolachlor to tolpyralate + atrazine. In other studies, tolpyralate + atrazine controlled velvetleaf 92% to 96% in corn (Fluttert et al. 2022). Metzger et al. (2019) observed 72% to 81% control of velvetleaf with tolpyralate + atrazine in corn. Tonks et al. (2015) reported >90% velvetleaf control with tolpyralate + atrazine 30 d after application in corn.

Pigweed Species (Green and Redroot Pigweeds)

Tolpyralate + atrazine applied as a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor controlled pigweed species 96% to 100% at 4 WAA (Table 3). The inclusion of acetochlor or dimethenamid-p with tolpyralate + atrazine enhanced pigweed species control 4% at 4 WAA; the inclusion of flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine provided no significant enhancement of pigweed species control. Tolpyralate + atrazine applied as a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor controlled pigweed species 95% to 100% at 8 WAA; pigweed species control was similar with all mixtures tested. Tolpyralate + atrazine decreased pigweed species density 88% and shoot dry biomass 96%. The inclusion of acetochlor with tolpyralate + atrazine decreased pigweed species density and shoot dry biomass 100%; the inclusion of dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine did not cause a further reduction in pigweed species density and shoot dry biomass relative to tolpyralate + atrazine. In other studies, tolpyralate + atrazine controlled pigweed species >90% in corn (Fluttert et al. 2022; Langdon et al. 2020; Metzger et al. 2019). Metzger et al. (2018b) observed excellent control (96% to 98%) of pigweed species with tolpyralate + atrazine in corn. In another study, Metzger et al. (2019) found 88% to 92% control of pigweeds with tolpyralate + atrazine in corn. In other studies, dimethenamid-p, pyroxasulfone, and *S*-metolachlor applied alone provided 99%, 99%, and 98% redroot pigweed control (Soltani et al. 2019). Additionally, the density of redroot pigweed was reduced 98%, 93%, and 92%; and shoot biomass was reduced 99%, 93%, and 91% with dimethenamid-p, pyroxasulfone, and *S*-metolachlor, respectively (Soltani et al. 2019).

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Table 3. Visible percent control 4 and 8 wk after herbicide application (WAA), density and dry biomass 8 WAA for green and redroot pigweed species (AMASS) treated with tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Exeter and Ridgetown, ON in 2021 and 2022 ($n = 5$).[a]

Herbicide treatment[b]	Rate	AMASS control[a]		AMASS density	AMASS dry biomass
		4 WAA	8 WAA		
	g ai ha^{-1}	———%———		No. plants m^{-2}	g m^{-2}
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0	0	12.6 c	31.8 c
Tolpyralate + atrazine[b]	30 + 560	96 b	95 a	1.5 b	1.4 b
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	100 a	100 a	0.0 a	0.0 a
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	100 a	100 a	0.1 ab	0.1 ab
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	97 ab	96 a	1.3 b	0.8 ab
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	96 ab	95 a	1.6 b	0.9 ab
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	98 ab	98 a	0.8 ab	0.9 ab
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	99 ab	99 a	0.6 ab	0.3 ab

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

Table 4. Visible percent control 4 and 8 wk after herbicide application (WAA), density and dry biomass 8 WAA for common ragweed (AMBEL) treated with tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Exeter and Ridgetown, ON in 2021 and 2022 ($n = 5$).[a]

Herbicide treatment[b]	Rate	AMBEL control[a]		AMBEL density	AMBEL dry biomass
		4 WAA	8 WAA		
	g ai ha^{-1}	———%———		No. plants m^{-2}	g m^{-2}
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0	0	20.9 c	78.6 c
Tolpyralate + atrazine[b]	30 + 560	94 b	91 b	2.4 b	1.8 b
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	99 a	99 a	0.2 ab	0.0 a
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	98 ab	98 a	1.1 b	0.6 ab
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	96 b	95 ab	2.4 b	3.7 b
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	95 b	95 ab	1.8 b	1.0 b
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	97 ab	95 ab	1.0 b	0.9 ab
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	97 ab	95 ab	1.9 b	0.6 ab

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

Common Ragweed

Tolpyralate + atrazine applied as a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor controlled common ragweed 94% to 99% and 91% to 99% at 4 and 8 WAA, respectively (Table 4). The addition of acetochlor enhanced common ragweed control 5% at 4 WAA, and the addition of acetochlor and dimethenamid-p enhanced common ragweed control 7% to 8% at 8 WAA; the inclusion of other grass herbicides did not enhance common ragweed control (Table 4). Tolpyralate + atrazine decreased common ragweed density 88%; the inclusion of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor did not enhance the reduction in common ragweed density. Tolpyralate + atrazine decreased common ragweed shoot dry biomass 98%. The inclusion of acetochlor with tolpyralate + atrazine reduced common ragweed shoot dry biomass 100%; the inclusion of dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine did not cause a further decrease in common ragweed shoot dry biomass relative to tolpyralate + atrazine. In other research, tolpyralate + atrazine controlled common ragweed >90% in corn (Fluttert et al. 2022; Langdon et al., 2020; Metzger et al., 2018a). Metzger et al. (2018b) observed 93% to 100% control of common ragweed with tolpyralate + atrazine in corn. Tonks et al. (2015) observed common ragweed control of 89% with tolpyralate and 95% with tolpyralate + atrazine. Metzger et al. (2019) observed excellent (up to 99%) common ragweed control with tolpyralate + atrazine in corn. In other studies, solo application of dimethenamid-p, pyroxasulfone, and *S*-metolachlor provided only 56%, 77%, and 42% control of common ragweed in corn, respectively (Soltani et al. 2019). Additionally, the density of redroot pigweed was reduced by only 52% with dimethenamid-p and 63% with pyroxasulfone (Soltani et al. 2019). Inadequate common ragweed control (7% to 28%) was also observed in other studies with preemergence application of dimethenamid-p, pyroxasulfone, and *S*-metolachlor in corn (Steele et al. 2005).

Common Lambsquarters

Tolpyralate + atrazine as a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor controlled common lambsquarters 97% to 100% at 4 WAA and 96% to 100% at 8 WAA (Table 5). The inclusion of acetochlor with tolpyralate + atrazine enhanced common lambsquarters control 3% at 4 WAA and 4% at 8 WAA; in contrast, the inclusion of the other grass herbicides with tolpyralate + atrazine did not enhance control of common lambsquarters (Table 5). Tolpyralate + atrazine alone or in a mixture with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor decreased common lambsquarters density 96% to 99% and shoot dry biomass 99% to 100%. Tolpyralate + atrazine + acetochlor and tolpyralate + atrazine + dimethenamid-p decreased the density of common lambsquarters to the extent that it was comparable to the weed-free control. All of the mixtures tested except tolpyralate + atrazine +

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Table 5. Visible percent control 4 and 8 wk after herbicide application (WAA), density and dry biomass 8 WAA for common lambsquarters (CHEAL) treated with tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Exeter and Ridgetown, ON in 2021 and 2022 ($n = 6$).[a]

Herbicide treatment[b]	Rate	CHEAL control[a]		CHEAL density	CHEAL dry biomass
		4 WAA	8 WAA		
	g ai ha^{-1}	——%——		No. plants m^{-2}	g m^{-2}
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0	0	54.8 d	84.2 c
Tolpyralate + atrazine[b]	30 + 560	97 b	96 b	2.0 c	0.5 ab
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	100 a	100 a	0.3 ab	0.1 ab
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	99 ab	99 ab	0.5 abc	0.2 ab
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	98 b	97 b	1.4 bc	0.8 b
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	99 ab	99 ab	0.8 bc	0.2 ab
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	99 ab	99 ab	1.2 bc	0.5 ab
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	98 b	98 b	0.9 bc	0.5 ab

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

Table 6. Visible percent control 4 and 8 wk after herbicide application (WAA), density and dry biomass 8 WAA for barnyardgrass (ECHCG) treated with tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Ridgetown, ON in 2021 and 2022 ($n = 4$).[a]

Herbicide treatment[b]	Rate	ECHCG control		ECHCG density	ECHCG dry biomass
		4 WAA	8 WAA		
	g ai ha^{-1}	——%——		No. plants m^{-2}	g m^{-2}
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0	0	10.2 bc	11.0 b
Tolpyralate + atrazine[b]	30 + 560	90 b	78 b	19.6 c	3.4 b
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	100 a	99 a	0.8 ab	0.1 a
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	100 a	99 a	1.1 ab	0.2 a
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	99 a	99 a	2.5 bc	0.3 a
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	99 a	99 a	1.5 abc	0.1 a
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	99 a	99 a	1.6 abc	0.3 a
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	99 a	99 a	1.8 abc	0.2 a

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

flufenacet reduced common lambsquarters shoot dry biomass so that it was comparable to the weed-free control (Table 5). In other research, tolpyralate + atrazine controlled common lambsquarters >90% in corn (Fluttert et al. 2022; Langdon et al. 2020). Metzger et al. (2018b) observed excellent (93% to 100%) control of common lambsquarters with tolpyralate + atrazine at 2, 4, and 8 WAA in corn. In another study, Metzger et al. (2019) found up to 99% control of common lambsquarters with tolpyralate + atrazine in corn. In other studies, dimethenamid-p, pyroxasulfone, and *S*-metolachlor applied preemergence controlled common lambsquarters 68%, 84%, and 60%, respectively (Soltani et al. 2019). Additionally, common lambsquarters density was reduced 98%, 93%, and 92%; and common lambsquarters shoot dry biomass was reduced 74%, 92%, and 66% with dimethenamid-p, pyroxasulfone, and *S*-metolachlor, respectively (Soltani et al. 2019). Jha et al. (2015) observed 12% to 65%, 15% to 66%, and 33% to 77% control of common lambsquarters with acetochlor, pyroxasulfone, and dimethenamid-p in corn, respectively.

Barnyardgrass

Tolpyralate + atrazine in a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor controlled barnyardgrass 90% to 100% at 4 WAA and 78% to 99% at 8 WAA, respectively (Table 6). The co-application of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine increased the control of barnyardgrass 9% to 10% at 4 WAA and 21% at 8 WAA (Table 6). Tolpyralate + atrazine did not decrease barnyardgrass density and shoot dry biomass in comparison to the weedy control (Table 6). The mixture of tolpyralate + atrazine with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor reduced barnyardgrass density 75% to 92% and shoot dry biomass 97% to 99%; there was no variation between the grass herbicides tested (Table 6). In other studies, Fluttert et al. (2022) reported only 64% to 72% barnyardgrass control with tolpyralate + atrazine. However, Tonks et al. (2015) observed 90% control of barnyardgrass with tolpyralate + atrazine 30 d after application. Metzger et al. (2018b) observed 86% to 97% barnyardgrass control with tolpyralate + atrazine. In another study, Metzger et al. (2019) reported 71% to 97% barnyardgrass control with tolpyralate + atrazine sprayed at various application timings in corn. In other studies, preemergence applications of dimethenamid-p, pyroxasulfone, and *S*-metolachlor caused 80%, 56%, and 61% barnyardgrass control in corn (Soltani et al. 2019). Stephenson et al. (2017) found 93% to 96% barnyardgrass control with pyroxasulfone applied preemergence in corn. Similarly, Yamaji et al. (2014) showed 100% barnyardgrass control with pyroxasulfone applied preemergence in corn.

Foxtail Species (Giant and Green Foxtails)

Tolpyralate + atrazine in a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor controlled foxtail species 80% to 99% at

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Table 7. Visible percent control 4 and 8 wk after herbicide application (WAA), density and dry biomass 8 WAA for green or giant foxtail (SETSS) treated with tolpyralate + atrazine alone and in combination with various grass herbicides applied postemergence at Exeter and Ridgetown, ON in 2021 and 2022 ($n = 5$).[a]

Herbicide treatment[b]	Rate	SETSS control[a] 4 WAA	SETSS control[a] 8 WAA	SETSS density	SETSS dry biomass
	g ai ha^{-1}	%	%	No. plants m^{-2}	g m^{-2}
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0	0	86.9 c	169.0 d
Tolpyralate + atrazine[b]	30 + 560	80 b	69 b	39.9 c	15.3 c
Tolpyralate + atrazine + acetochlor	30 + 560 + 1,225	99 a	98 a	6.6 b	0.8 ab
Tolpyralate + atrazine + dimethenamid-p	30 + 560 + 544	98 a	97 a	11.6 b	1.6 b
Tolpyralate + atrazine + flufenacet	30 + 560 + 360	95 a	93 a	15.2 b	3.3 b
Tolpyralate + atrazine + pendimethalin	30 + 560 + 1,680	96 a	95 a	9.0 b	1.7 b
Tolpyralate + atrazine + pyroxasulfone	30 + 560 + 125	96 a	94 a	15.8 b	2.8 b
Tolpyralate + atrazine + *S*-metolachlor	30 + 560 + 1,140	97 a	95 a	9.0 b	1.4 b

[a]Means within a column followed by the same letter do not differ significantly according to a Tukey-Kramer multiple-range test at $P < 0.05$.
[b]All tolpyralate + atrazine treatments included methylated seed oil (MSO Concentrate®) at 1% v/v.

4 WAA and 69% to 98% at 8 WAA (Table 7). The inclusion of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine increased foxtail species control 15% to 19% at 4 WAA and 24% to 29% at 8 WAA; there was no variation in foxtail species control between the grass herbicides when co-applied with tolpyralate + atrazine. Tolpyralate + atrazine did not decrease foxtail species density in comparison to the weedy control. The co-application of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine decreased foxtail species density 83% to 92%; there was no variation between the grass herbicides tested. Tolpyralate + atrazine reduced foxtail species shoot dry biomass 91%. The co-application of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine decreased foxtail species shoot dry biomass 98% to 100%; there was no variation between grass herbicides tested. In other studies, Fluttert et al. (2022) reported 72% to 75% control of foxtails with tolpyralate + atrazine. Metzger et al. (2019) observed 68% to 72% control of foxtails with tolpyralate + atrazine. In other studies, preemergence applications of dimethenamid-p, pyroxasulfone, and *S*-metolachlor provided 96% green foxtail control in corn (Soltani et al. 2019). Additionally, the density of green foxtail was reduced 99%, 95%, and 95%; and shoot biomass was reduced 99%, 93%, and 97% with dimethenamid-p, pyroxasulfone, and *S*-metolachlor, respectively (Soltani et al. 2019). Geier et al. (2006) observed 95% green foxtail control with the preemergence application of pyroxasulfone, but the control was 88% with the preemergence application of *S*-metolachlor.

Tolpyralate + atrazine in a mixture or in combination with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor caused up to 16% and 8% injury at 1 and 4 WAA in corn, respectively. Weed interference reduced corn yield by 60%; reduced weed interference with tolpyralate + atrazine mixture with the grass herbicides tested provided corn yield that was comparable to the weed-free control. The inclusion of the grass herbicides tested with tolpyralate + atrazine did not enhance velvetleaf control. However, the co-application of the grass herbicides tested with tolpyralate + atrazine generally enhanced control of the other weed species evaluated, especially barnyardgrass and foxtail species in corn. The mixture of acetochlor with tolpyralate + atrazine generally provided the most consistent weed control. The co-application of the grass herbicides tested with tolpyralate + atrazine improves the range of weed species controlled and may help reduce the evolution of new herbicide-resistant weed biotypes in corn. Future research is needed to determine if the addition of a grass herbicide to tolpyralate + atrazine would improve the control of other late-emerging weed species in corn.

Practical Implications

There is limited information available on the benefit of adding acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor to tolpyralate + atrazine for weed management in corn. Results show that the co-application of the aforementioned grass herbicides with tolpyralate + atrazine did not increase injury in corn. Weed interference decreased corn yield 60% in this study; however, tolpyralate + atrazine alone or in a mixture with acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor provided corn yield that was comparable to the weed-free plots. The inclusion of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine did not enhance velvetleaf control. The co-application of acetochlor or dimethenamid-p with tolpyralate + atrazine enhanced pigweed species control 5% and common ragweed control 7% to 8% at 8 WAA, but the inclusion of flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine does not enhance pigweed species or common ragweed control. The inclusion of acetochlor with tolpyralate + atrazine improved common lambsquarters control 4% at 8 WAA, but the co-application with the other grass herbicides with tolpyralate + atrazine gave no additional benefits. The inclusion of acetochlor, dimethenamid-p, flufenacet, pendimethalin, pyroxasulfone, or *S*-metolachlor with tolpyralate + atrazine increased barnyardgrass control 21% and green foxtail control 24% to 29% 8 at WAA. The application of tolpyralate + atrazine plus a grass herbicide provided species-specific improvement in weed control in corn except for velvetleaf.

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