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Nomenclature: Atrazine; tolpyralate; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv. ECHCG; common lambsquarters, *Chenopodium album* L. CHEAL; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; green foxtail, *Setaria viridis* (L.) P. Beauv. SETVI; ladysthumb, *Persicaria maculosa* Gray POLPE; Powell amaranth, *Amaranthus powelli* S. Watson AMAPO; redroot pigweed, *Amaranthus retroflexus* L. AMARE; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; wild mustard, *Sinapis arvensis* L. SINAR; corn, *Zea mays* L.

Key words: Dose response; hydroxyphenyl-pyruvate dioxygenase (HPPD); HPPD-inhibiting herbicides; photosystem II-inhibiting herbicides

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Tolpyralate Efficacy: Part 1. Biologically Effective Dose of Tolpyralate for Control of Annual Grass and Broadleaf Weeds in Corn

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Abstract

Tolpyralate is a new 4-hydroxyphenyl-pyruvate dioxygenase (HPPD)-inhibiting herbicide for POST weed management in corn; however, there is limited information regarding its efficacy. Six field studies were conducted in Ontario, Canada, over 3 yr (2015 to 2017) to determine the biologically effective dose of tolpyralate for the control of eight annual weed species. Tolpyralate was applied POST at six doses from 3.75 to 120 g ai ha^{-1} and tank mixed at a 1:33.3 ratio with atrazine at six doses from 125 to 4,000 g ha^{-1}. Regression analysis was performed to determine the effective dose (ED) of tolpyralate, and tolpyralate + atrazine, required to achieve 50%, 80%, or 90% control of eight weed species at 1, 2, 4, and 8 wk after application (WAA). The ED of tolpyralate for 90% control (ED_{90}) of velvetleaf, common lambsquarters, common ragweed, redroot pigweed or Powell amaranth, and green foxtail at 8 WAA was ≤15.5 g ha^{-1}; however, tolpyralate alone did not provide 90% control of wild mustard, barnyardgrass, or ladysthumb at 8 WAA at any dose evaluated in this study. In contrast, the ED_{90} for all species in this study with tolpyralate + atrazine was ≤13.1 + 436 g ha^{-1}, indicating that tolpyralate + atrazine can be highly efficacious at low field doses.

Introduction

Competition from weeds represents one of the principal factors affecting corn grain yield. Herbicides are regarded as an effective and economical form of weed management and are applied to more than 95% of corn hectares in North America (Gianessi and Reigner 2007). Development of the critical weed-free period (CWFP) in corn has determined that corn yield loss due to weed interference is most probable during early growth stages, before V8 (Hall et al. 1992). Introduction of selective herbicides and glyphosate-resistant (GR) corn hybrids facilitated timely control of weeds during the CWFP with POST herbicide applications; however, diversity of chemical weed management programs has generally declined (Duke and Powles 2009). Evolving weed management challenges, including those associated with managing GR weed biotypes, have spurred renewed interest in the development of new herbicide active ingredients to broaden the number of available herbicides.

Herbicides that inhibit the 4-hydroxyphenyl-pyruvate dioxygenase (HPPD) enzyme in susceptible plants impede the biosynthesis of plastoquinone (PQ) and α-tocopherols, thereby inhibiting biosynthesis of carotenoid pigments (Hawkes 2012; Matsumoto et al. 2002; Shulz et al. 1993). Carotenoids act as both accessory light-harvesting pigments and quenchers of high-energy triplet chlorophyll (Hawkes 2012). Carotenoid depletion by way of HPPD inhibition leaves chlorophyll susceptible to oxidative degradation by reactive oxygen species (ROS), resulting in white bleaching of plant tissues, protein and lipid destruction, and subsequent plant death (Ahrens et al. 2013; Hawkes 2012). The HPPD inhibitors include triketones, isoxazoles, and pyrazolones, and are currently used for weed management in corn, rice (*Oryza sativa* L.), and cereals (Hawkes 2012).

Photosystem II (PSII)-inhibiting herbicides, including atrazine, are commonly tank mixed with HPPD inhibitors because of their complementary mechanisms of action (Armel et al. 2005; Hess 2000). The HPPD inhibitors are presumed to increase efficiency of atrazine binding on the D1 protein of PSII via depletion of PQ, while concurrently intensifying cell membrane destruction by subsequently produced ROS, due to their inhibition of antioxidant biosynthesis

(Armel et al. 2005; Kim et al. 1999). The addition of atrazine to mesotrione or tembotrione has been documented to induce herbicide synergy in some instances (Abendroth et al. 2006; Armel et al. 2007; Kohrt and Sprague 2017); however, additive effects are more widely reported with topramezone plus atrazine, which suggests that the benefit of atrazine addition is specific to the HPPD inhibitor and weed species (Kohrt and Sprague 2017).

Tolpyralate is a new pyrazolone-type HPPD-inhibiting herbicide that has recently been registered in the United States and Canada for use in corn (US Environmental Protection Agency 2018; Health Canada 2018). Tolpyralate has relatively low water solubility (26.5 mg L^{-1}) and low potential for volatilization and has not been found to pose significant risk to humans or the environment (Health Canada 2017). POST applications of tolpyralate at 30 to 40 g ha^{-1} alone or in combination with atrazine at 560 to 1,000 g ha^{-1} have been reported to control a range of annual grass and broadleaf weed species and exhibit selectivity in all types of corn (Kikugawa et al. 2015). Currently, there is limited information in the published literature on the use of tolpyralate in North America and globally. Therefore, the objective of this research was to determine the efficacy of tolpyralate in corn for the control of several weed species across environments. The results of this research are presented in two companion articles in this journal.

The purpose of this manuscript, which is the first of a pair of companion articles, was to develop weed species–specific dose–response curves for tolpyralate alone or tank mixed with atrazine to ascertain a biologically effective dose (BED) of tolpyralate and tolpyralate plus atrazine for several weed species. The subsequent companion manuscript (1) examines tolpyralate efficacy applied alone or in combination with atrazine to determine the benefit of atrazine addition and (2) compares the efficacy and selectivity of tolpyralate with existing HPPD-inhibiting herbicides (Metzger et al. 2018).

Materials and Methods

Experimental Methods

Six field experiments were conducted over a 3-yr period (2015 to 2017) near Ridgetown and Exeter, Ontario, Canada, on field research sites managed under corn–soybean [*Glycine max* (L.) Merr.]–winter wheat (*Triticum aestivum* L.) rotations. Seedbed preparation consisted of fall moldboard plowing, followed by two passes with a field cultivator with rolling basket harrows in the spring. Sites were fertilized in accordance with soil test results and crop requirements each year before planting. No herbicides aside from treatments described herein were applied to the trial sites during the years of study.

Each field experiment was organized as a randomized complete block with four replications. Plots were 3-m wide (4 rows of corn spaced 0.76 m apart) and 8- or 10-m long at Ridgetown and Exeter, respectively. GR corn was seeded to a depth of 4 to 5 cm at 78,000 to 82,000 seeds ha^{-1}. Hybrids were selected for each site based on geographic suitability and were DKC42-42RIB and DKC53-56 (Monsanto, St Louis, MO) at Exeter and Ridgetown, respectively. Information pertaining to soil characteristics, planting/harvest dates, and spray application dates are presented in further detail in Table 1.

Herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1} at 240 kPa through four ULD 12002 nozzles (Pentair, New Brighton, MN, USA) spaced 50 cm apart. Applications were made POST when native weed populations in the nontreated check plots reached an average of 10 cm in height. Crop stage at time of application ranged from V4 to V6. Weed-free control plots were maintained free of weeds for the entirety of the trial period with *S*-metolachlor (1,600 g ai ha^{-1}) plus atrazine (1,280 g ai ha^{-1}) plus mesotrione (140 g ai ha^{-1}) (Lumax® EZ Herbicide; Syngenta Canada Inc., Guelph, ON, Canada) applied PRE, followed by glyphosate (900 g ae ha^{-1}) applied POST and subsequent hand weeding as needed.

Treatments consisted of tolpyralate at 3.75, 7.5, 15, 30, 60, and 120 g ha^{-1} and a tank mixture of tolpyralate + atrazine at a 1:33.3 ratio at doses of 3.75 + 125, 7.5 + 250, 15 + 500, 30 + 1,000, 60 + 2,000, and 120 + 4,000 g ha^{-1}, respectively. Adjuvants were included in accordance with herbicide manufacturer recommendations. All tolpyralate applications included methylated seed oil (MSO Concentrate®; Loveland Products Inc., Loveland, CO, USA) at 0.50% vol/vol and 28% N urea ammonium nitrate (2.50% v/v).

Crop injury was evaluated at 1, 2, and 4 wk after application (WAA) on a scale of 0 to 100, with 0 representing no injury and 100 representing complete plant death. Visible weed control was assessed at 1, 2, 4, and 8 WAA, with control of each species evaluated relative to the nontreated control plot and assigned a value from 0, indicating no control, to 100, indicating complete control. Following the final weed control assessment at 8 WAA, density and dry weight of each weed species was determined by counting the number of weeds within two randomly placed 0.5-m^2 quadrats per plot. The weeds were cut at the soil surface, separated by species into paper bags, and dried at 60 C to constant moisture, and the dry weight was recorded.

Table 1. Soil characteristics, planting, spraying, and harvest dates for trials near Ridgetown and Exeter, Ontario, Canada, in 2015, 2016, and 2017.

		Soil characteristics					
Location	Year	Type	OM (%)	pH	Planting date	Spray date	Harvest date
Ridgetown	2015	Brady sandy clay loam	4.2	7.3	May 14	June 17	November 5
	2016	Brady sandy clay loam	3.2	7.1	May 6	June 9	October 18
	2017	Brady sandy clay loam	3.9	7.2	May 15	June 21	October 31
Exeter	2015	Perth clay loam	3.6	7.7	May 6	June 9	n/a[a]
	2016	Perth clay loam	3.2	7.7	May 6	June 10	October 7
	2017	Perth clay loam	4.5	7.8	May 19	June 13	October 19

[a] Not harvested in 2015.

Table 2. Nonlinear regression parameters (± SE) and predicted tolpyralate or tolpyralate + atrazine dose required for 50%, 80%, and 90% control of velvetleaf (ABUTH), pigweed species (AMASS), common ragweed (AMBEL), common lambsquarters (CHEAL), barnyardgrass (ECHCG), ladysthumb (POLPE), green foxtail (SETVI) and wild mustard (SINAR) at 2 wk after application in field studies conducted in Ontario, Canada in 2015, 2016 and 2017.

	Parameters			Predicted tolpyralate dose[a]		
Equation 1	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				———————g ai ha^{-1}———————		
ABUTH	86.77 (1.93)	0.57 (0.07)	86.74 (4.53)	1.5	4.5	—
AMASS	86.46 (1.72)	0.56 (0.06)	86.45 (3.97)	1.5	4.5	—
AMBEL	85.45 (1.31)	0.77 (0.02)	85.2 (2.78)	3.4	10.6	—
CHEAL	89.76 (1.19)	0.6 (0.03)	89.67 (2.78)	1.6	4.4	—
ECHCG	77.36 (2.89)	0.7 (0.06)	77.1 (6.44)	3	—	—
POLPE	70.69 (2.64)	0.73 (0.05)	70.37 (5.78)	3.8	—	—
SETVI	78.51 (1.92)	0.7 (0.04)	78.15 (4.27)	2.9	—	—
SINAR	64.25 (3.08)	0.92 (0.01)	65.01 (4.7)	18.6	—	—

	Parameters			Predicted tolpyralate + atrazine dose[a]		
Equation 2	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				———————g ai ha^{-1}———————		
ABUTH	98.36 (0.59)	98.35 (1.41)	0.02 (0.001)	1.1 + 35.7	2.5 + 84.4	3.7 + 124
AMASS	97.62 (1.19)	97.46 (2.73)	0.01 (0.001)	1.6 + 52.7	3.8 + 125.8	5.6 + 187.4
AMBEL	98.3 (0.77)	98.15 (1.73)	0.01 (0.001)	1.8 + 59.3	4.2 + 140.6	6.2 + 206.7
CHEAL	99.29 (0.44)	99.29 (1.03)	0.02 (0.001)	1.1 + 35.8	2.5 + 83.7	3.6 + 121
ECHCG	94.57 (2.04)	94.05 (4.55)	0.01 (0.001)	2.1 + 71.1	5.3 + 177.5	8.6 + 287.9
POLPE	94.01 (1.7)	92.83 (3.58)	0.01 (0.001)	2.9 + 98.1	7.5 + 248.5	12.4 + 412.9
SETVI	95.53 (1.3)	95.05 (2.8)	0.01 (0.001)	2.6 + 87.5	6.5 + 214.9	10 + 334.7
SINAR	97.59 (1.64)	96.5 (3.53)	0.01 (0.001)	2.6 + 85.2	6.2 + 205.1	9.2 + 306.3

[a] ED_{50}, ED_{80}, and ED_{90} denote the predicted effective dose of tolpyralate or tolpyralate + atrazine for 50%, 80%, and 90% control, respectively. Where a predicted dose could not be computed by the regression equation, values are represented by a dash (—).

At maturity, the center two rows of each plot were harvested with a small plot combine. Moisture content and grain weight were recorded, and grain yields were calculated and adjusted to 15% moisture for analysis.

Statistical Analysis—Nonlinear Regression

Visual percent control of each weed species at 1, 2, 4, and 8 WAA was regressed against the dose of tolpyralate alone and the combined dose of tolpyralate + atrazine using NLIN procedures in SAS v. 9.4 (SAS Institute, Cary, NC) with one of two exponential to a maximum equations. Where tolpyralate was applied alone, Equation 1 was fit to the data. Where tolpyralate + atrazine were applied, Equation 2 was used due to a better fit, as determined by pseudo-R^2 values and standard errors associated with parameter estimates of each model. Yield data were expressed as a percentage of the yield of weed-free control plots within each replication and regressed against tolpyralate dose (using Equation 1) and tolpyralate + atrazine dose (using Equation 2). Weed density (plants m^{-2}) and dry biomass (g dry matter m^{-2}) were regressed against tolpyralate and tolpyralate + atrazine dose using an inverse exponential equation (Equation 3). Predicted values generated from regression analyses were used to compute the effective dose (ED) of tolpyralate and tolpyralate + atrazine required to provide 50%, 80%, and 90% control of each weed species at each assessment timing and a 50%, 80%, or 90% reduction in weed density/dry weight. Where the predicted value could not be computed or was beyond the dosage range used in this study, it is expressed as a dash (—) in tables. The following equations were used for nonlinear regression analysis.

Exponential to a maximum equation:

$$y = a - b\left(\mathrm{e}^{-c*\mathrm{dose}}\right) \qquad [1]$$

where
y = response parameter
a = upper asymptote
b = magnitude
c = slope

Exponential to a maximum alternate equation:

$$y = a - c\left(b^{\mathrm{dose}}\right) \qquad [2]$$

where
y = response parameter
a = upper asymptote

Table 3. Nonlinear regression parameters (± SE) and predicted tolpyralate or tolpyralate + atrazine dose required for 50%, 80%, and 90% control of velvetleaf (ABUTH), pigweed species (AMASS), common ragweed (AMBEL), common lambsquarters (CHEAL), barnyardgrass (ECHCG), ladysthumb (POLPE), green foxtail (SETVI), and wild mustard (SINAR) at 4 wk after application in field studies conducted in Ontario, Canada in 2015, 2016, and 2017.

	Parameters			Predicted tolpyralate dose[a]		
Equation 1	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				————g ai ha^{-1}————		
ABUTH	96.15 (0.58)	0.48 (0.03)	96.15 (1.38)	1	2.4	3.8
AMASS	92.66 (1.39)	0.6 (0.04)	92.58 (3.16)	1.5	3.9	6.9
AMBEL	95.99 (1)	0.72 (0.01)	95.83 (2.2)	2.2	5.4	8.4
CHEAL	96.41 (0.63)	0.45 (0.04)	96.41 (1.52)	0.9	2.2	3.4
ECHCG	82.21 (2.53)	0.74 (0.04)	81.96 (5.53)	3	11.8	—
POLPE	72.47 (2.83)	0.8 (0.03)	70.72 (5.82)	5.2	—	—
SETVI	90.05 (1.63)	0.78 (0.02)	89.29 (3.44)	3.2	8.7	29.6
SINAR	73.53 (4.26)	0.96 (0.009)	71.78 (5.11)	24.5	—	—
	Parameters			Predicted tolpyralate + atrazine dose[a]		
Equation 2	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				————g ai ha^{-1}————		
ABUTH	98.56 (0.44)	98.55 (1.06)	0.02 (0.001)	1 + 34.4	2.4 + 81.1	3.6 + 118.6
AMASS	97.68 (1.55)	97.52 (3.5)	0.01 (0.001)	1.8 + 60.9	4.4 + 145.4	6.5 + 216.5
AMBEL	98.55 (0.79)	98.46 (1.8)	0.01 (0.001)	1.6 + 52	3.7 + 122.8	5.4 + 179.7
CHEAL	99.2 (0.33)	99.2 (0.79)	0.02 (0.001)	0.9 + 30.3	2.1 + 70.9	3.1 + 102.6
ECHCG	94.29 (2.14)	93.82 (4.78)	0.01 (0.001)	2.1 + 69.4	5.2 + 174	8.6 + 285.2
POLPE	93.61 (1.79)	92.47 (3.78)	0.01 (0.001)	3 + 101.2	7.7 + 258	13.1 + 436.7
SETVI	96.27 (1.14)	95.8 (2.46)	0.01 (0.001)	2.6 + 85	6.2 + 207.1	9.6 + 318.6
SINAR	98.92 (1.31)	98.34 (2.73)	0.01 (0.0004)	3 + 101.2	7.2 + 238.8	10.4 + 347.8

[a] ED_{50}, ED_{80}, and ED_{90} denote the predicted effective dose of tolpyralate or tolpyralate + atrazine for 50%, 80%, and 90% control, respectively. Where a predicted dose could not be computed by the regression equation, values are represented by a dash (—).

b = slope
c = magnitude

Inverse exponential equation:

$$y = a + be^{(-c*\text{dose})} \qquad [3]$$

where
y = response parameter
a = lower asymptote
b = reduction in y from intercept to asymptote
c = slope

Results and Discussion

Weed Control

The eight weed species analyzed in this study were naturally occurring at each trial site and reflect typical native weed populations encountered in corn production systems in southwestern Ontario, Canada. Four of these species were ranked among the top 10 most troublesome weed species by Ontario farmers in a 2016 opinion poll conducted by Bilyea (2016). Broadleaf weed species included common lambsquarters (average density 14 plants m^{-2}), velvetleaf (average density 5 plants m^{-2}), common ragweed (average density 50 plants m^{-2}), ladysthumb (average density 7 plants m^{-2}), wild mustard (average density 20 plants m^{-2}), and pigweed species [AMASS] (average density 14 plants m^{-2}). Pigweed species were grouped, because sites comprised a heterogeneous population of Powell amaranth and redroot pigweed, which have similar morphology and exhibit the potential to hybridize with one another (Weaver 2009). Grass weed species included green foxtail (average density 17 plants m^{-2}) and barnyardgrass (average density 38 plants m^{-2}).

There was interspecific variation in sensitivity to tolpyralate at each assessment timing as indicated by predicted ED values; however, control generally improved with increasing herbicide dose. Based on regression analysis, tolpyralate alone at the tested doses did not provide ≥80% control of any species in this study at 1 WAA (unpublished data). Weed injury symptoms at 1 WAA consisted of bleaching, stunting, and slight leaf necrosis. At 1 WAA, 50% control of common lambsquarters, velvetleaf, pigweed species, common ragweed, green foxtail, barnyardgrass, and ladysthumb was recorded with tolpyralate rates of 2.8 to 6.4 g ha^{-1};

Table 4. Nonlinear regression parameters (± SE) and predicted tolpyralate or tolpyralate + atrazine dose required for 50%, 80%, and 90% control of velvetleaf (ABUTH), pigweed species (AMASS), common ragweed (AMBEL), common lambsquarters (CHEAL), barnyardgrass (ECHCG), ladysthumb (POLPE), green foxtail (SETVI), and wild mustard (SINAR) at 8 wk after application in field studies conducted in Ontario, Canada in 2015, 2016, and 2017.

	Parameters			Predicted tolpyralate dose[a]		
Equation 1	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				———g ai ha^{-1}———		
ABUTH	97.61 (0.37)	0.45 (0.02)	97.6 (0.89)	0.9	2.2	3.2
AMASS	92.93 (1.74)	0.67 (0.03)	92.77 (3.96)	1.9	4.9	8.5
AMBEL	95.7 (0.86)	0.68 (0.02)	95.55 (1.94)	1.9	4.7	7.3
CHEAL	93.37 (1.25)	0.55 (0.04)	93.35 (2.96)	1.3	3.3	5.6
ECHCG	87.21 (1.78)	0.78 (0.02)	86.57 (3.73)	3.4	10.1	—
POLPE	71.27 (3.2)	0.87 (0.03)	68 (5.89)	8.2	—	—
SETVI	92.41 (1.76)	0.79 (0.02)	91.6 (3.66)	3.3	8.5	15.5
SINAR	73.6 (4.58)	0.95 (0.01)	68.2 (5.89)	19.8	—	—

	Parameters			Predicted tolpyralate + atrazine dose[a]		
Equation 2	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				———g ai ha^{-1}———		
ABUTH	98.9 (0.24)	98.9 (0.57)	0.03 (0.002)	0.7 + 23.6	1.7 + 55.4	2.4 + 80.6
AMASS	97.13 (1.12)	96.99 (2.56)	0.01 (0.001)	1.6 + 54.7	4 + 131.5	5.9 + 198
AMBEL	98.8 (0.66)	98.7 (1.5)	0.01 (0.001)	1.7 + 56.5	4 + 133	5.8 + 193.9
CHEAL	98.3 (0.54)	98.28 (1.3)	0.02 (0.001)	1 + 34.5	2.5 + 81.6	3.6 + 120
ECHCG	93.83 (1.46)	93.28 (3.2)	0.01 (0.001)	2.5 + 81.7	6.2 + 206.4	10.4 + 345.2
POLPE	94.69 (1.78)	92.88 (3.69)	0.01 (0.001)	3.2 + 106.8	8.1 + 269.3	13.1 + 436
SETVI	94.66 (1.4)	94.27 (2.98)	0.01 (0.001)	2.8 + 93.7	7 + 233.5	11.3 + 377.3
SINAR	99.12 (1.5)	98.9 (3.13)	0.01 (0.001)	3 + 100.1	7.1 + 235	10.2 + 340.8

[a] ED_{50}, ED_{80}, and ED_{90} denote the predicted effective dose of tolpyralate or tolpyralate + atrazine for 50%, 80%, and 90% control, respectively. Where a predicted dose could not be computed by the regression equation, values are represented by a dash (—).

however, wild mustard was less sensitive and required 25.5 g ha^{-1} to achieve equivalent control. Tolpyralate efficacy at 1 WAA has not been previously reported; however, these results are consistent with experiments using other HPPD inhibitors. Woodyard et al. (2009) reported 52% to 68% control of common lambsquarters and 53% to 75% control of waterhemp (*Amaranthus tuberculatus* Moq. J.D. Sauer) with mesotrione (105 g ha^{-1}) at 10 d after application.

At 1 WAA, the addition of atrazine to tolpyralate improved control of all species (unpublished data). These results are similar to those of Woodyard et al. (2009), who found that the addition of atrazine to mesotrione increased control of common lambsquarters and waterhemp at 10 d after application relative to mesotrione applied alone. Similarly, Abendroth et al. (2006) found greater leaf necrosis in Palmer amaranth (*Amaranthus palmeri* S. Watson) and velvetleaf with mesotrione + atrazine compared with mesotrione alone. At 1 WAA, all eight weed species were controlled 80% with tolpyralate + atrazine at doses of 10.4 + 345.9 g ha^{-1} or less; with velvetleaf, pigweed species, common lambsquarters, barnyardgrass, and common ragweed showing greater sensitivity to tolpyralate + atrazine compared with ladysthumb, green foxtail, and wild mustard. At 1 WAA, the ED_{90} of tolpyralate + atrazine for common lambsquarters, velvetleaf, pigweed species, and common ragweed was 10.4 + 347.8 g ha^{-1} or less.

At 2 WAA, common lambsquarters, velvetleaf, pigweed species, common ragweed, green foxtail, barnyardgrass, and ladysthumb were more sensitive to tolpyralate alone compared with wild mustard (Equation 1; Table 2). Regression analysis indicated that common lambsquarters, velvetleaf, and pigweed species were controlled 80% with tolpyralate alone at 4.4, 4.5, and 4.5 g ha^{-1}, respectively, while common ragweed required 10.6 g ha^{-1}. At 2 WAA, regression analysis could not estimate the tolpyralate dose required for 80% control of four species (green foxtail, barnyardgrass, ladysthumb, and wild mustard), and no dose provided ≥90% control. At 2 WAA, when atrazine was added to tolpyralate, 90% control of all species was achieved with doses of 3.6 + 121 to 12.4 + 412.9 g ha^{-1} of tolpyralate + atrazine. Ladysthumb, green foxtail, wild mustard, and barnyardgrass required comparatively higher doses of tolpyralate + atrazine to achieve 90% control compared with other species; common lambsquarters and velvetleaf had lowest ED values for the same level of control.

Table 5. Nonlinear regression parameters (± SE) and predicted tolpyralate or tolpyralate + atrazine dose required for 50%, 80%, and 90% reduction in velvetleaf (ABUTH), pigweed species (AMASS), common ragweed (AMBEL), common lambsquarters (CHEAL), barnyardgrass (ECHCG), ladysthumb (POLPE), green foxtail (SETVI), and wild mustard (SINAR) density relative to nontreated check plots within blocks at 8 wk after application in field studies conducted in Ontario, Canada in 2015, 2016, and 2017.

	Parameters			Predicted tolpyralate dose[a]		
Equation 3	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				g ai ha^{-1}		
ABUTH	1.05 (0.24)	2.44 (0.6)	0.48 (0.38)	2.6	—	—
AMASS	8.99 (2.06)	14.4 (5.23)	0.81 (1.89)	2.1	—	—
AMBEL	1.46 (3.53)	47.81 (6.47)	0.13 (0.04)	5.7	13.7	20.6
CHEAL	7.42 (1.44)	17 (3.36)	0.54 (0.39)	2.4	—	—
ECHCG	6.1 (3.81)	20.69 (5.7)	0.06 (0.04)	17.6	—	—
POLPE	4.79 (4.5)	8.84 (4.3)	0.02 (0.03)	62.2	—	—
SETVI	8.81 (3.87)	36.34 (5.76)	0.08 (0.03)	12.7	66.7	-
SINAR	0 (0)	44.31 (7.83)	0.004 (0.005)	—	—	—
	Parameters			Predicted tolpyralate + atrazine dose[a]		
Equation 3	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				g ai ha^{-1}		
ABUTH	0.54 (0.2)	2.92 (0.49)	0.01 (0.005)	2.2 + 73.8	7.3 + 242.9	—
AMASS	2.95 (1.83)	20.31 (4.39)	0.01 (0.01)	2 + 67.1	5.9 + 195.7	—
AMBEL	0.23 (2.22)	49.25 (5.1)	0.01 (0.002)	2.2 + 72.5	5.1 + 169.3	7.3 + 243.8
CHEAL	1.21 (0.9)	23.18 (2.1)	0.01 (0.005)	1.5 + 49	3.6 + 120.9	5.8 + 192.6
ECHCG	0.28 (1.61)	24.08 (2.75)	0.002 (0.001)	9.6 + 321.3	22.7 + 755.5	33 + 1100
POLPE	0 (0)	11.06 (1.37)	0.001 (0.0004)	19.2 + 640.9	44.7 + 1488.2	63.9 + 2129.1
SETVI	0.75 (4.16)	46.35 (5.77)	0.01 (0.001)	2.6 + 87.6	6.2 + 207.1	9.1 + 303.9
SINAR	0 (0)	28.97 (3.43)	0.003 (0.001)	6.8 + 225.1	15.7 + 522.6	22.4 + 747.7

[a] ED_{50}, ED_{80}, and ED_{90} denote the predicted effective dose of tolpyralate or tolpyralate + atrazine for a 50%, 80%, and 90% reduction in weed density relative to the nontreated control plot within blocks, respectively. Where a predicted dose could not be computed by the regression equation, values are represented by a dash (—).

Weed control with tolpyralate applied alone improved considerably from 2 to 4 WAA. At 4 WAA, 90% control of common lambsquarters, velvetleaf, pigweed species, and common ragweed was achieved with 3.4, 3.8, 6.9, and 8.4 g ha^{-1} tolpyralate, respectively (Table 3). Previous research by Kohrt and Sprague (2017) and Tonks et al. (2015) investigated tolpyralate efficacy 3 to 4 WAA at 30 to 40 g ha^{-1}. Kohrt and Sprague (2017) reported 96% control of atrazine-resistant Palmer amaranth with tolpyralate (40 g ha^{-1}) 3 WAA. In contrast to the results from this study, Tonks et al. (2015) reported that on average, tolpyralate (30 g ha^{-1}) controlled velvetleaf, common ragweed, *Amaranthus* spp., and common lambsquarters <90% at 30 d after application. At 4 WAA, green foxtail was also controlled 90% in this study; however, a comparatively higher dose of tolpyralate (29.6 g ha^{-1}) was required for equivalent control of this species compared with common lambsquarters, velvetleaf, pigweed species, and common ragweed. Consistent with these results, Tonks et al. (2015) reported 91% control of green foxtail at 30 d after application with tolpyralate at 30 g ha^{-1}. Tolpyralate alone provided <90% control of barnyardgrass, and <80% control of ladysthumb and wild mustard at 4 WAA. However, tolpyralate + atrazine at doses of 13.1 + 436.7 g ha^{-1} or less provided 90% control of all the weed species evaluated in this study at this timing. At 4 WAA, differences in the tolpyralate and tolpyralate + atrazine ED_{90} for common lambsquarters, velvetleaf, and pigweed species were less than 0.4 g ha^{-1}; however, the ED_{90} for green foxtail was reduced from 29.6 to 9.6 g ha^{-1} when atrazine was included. The significance of this relationship is presented in further detail in the companion manuscript (Metzger et al. 2018).

At 8 WAA, control of wild mustard and ladysthumb with tolpyralate alone at the doses evaluated in this study was less than 80%. Wild mustard and ladysthumb were not adequately controlled with tolpyralate alone, and they recovered from injury and resumed growth. Previous research has not investigated tolpyralate efficacy on either of these species; however Pannacci and Covarelli (2009) found that mesotrione applied alone did not provide >90% control of ladysthumb based on regression analysis. Control of green foxtail improved from 4 to 8 WAA. At 8 WAA, tolpyralate controlled common lambsquarters, velvetleaf, pigweed species, common ragweed, and green foxtail 90% at predicted doses of 15.5 g ha^{-1} or less (Table 4). Tolpyralate + atrazine at doses of 13.1 + 436 g ha^{-1} or less, gave 90% control for

Table 6. Nonlinear regression parameters (± SE) and predicted tolpyralate or tolpyralate + atrazine dose required for 50%, 80%, and 90% reduction in velvetleaf (ABUTH), pigweed species (AMASS), common ragweed (AMBEL), common lambsquarters (CHEAL), barnyardgrass (ECHCG), ladysthumb (POLPE), green foxtail (SETVI), and wild mustard (SINAR) dry biomass relative to nontreated check plots within blocks at 8 wk after application in field studies conducted in Ontario, Canada in 2015, 2016, and 2017.

	Parameters[a]			Predicted tolpyralate dose[a]		
Equation 3	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				——————————g ai ha^{-1}——————————		
ABUTH	0.23 (0.21)	4.69 (0.53)	0.81 (0.64)	0.9	2.3	3.5
AMASS	6.67 (4.32)	44.07 (10.68)	0.53 (0.44)	1.6	4.8	—
AMBEL	2.62 (9.1)	221.3 (22.36)	0.64 (0.29)	1.1	2.6	3.8
CHEAL	3.09 (2.94)	86.6 (7.13)	0.98 (0.88)	0.7	1.8	2.7
ECHCG	1.84 (1.85)	32.72 (5)	0.22 (0.06)	3.4	8.5	13.7
POLPE	2.21 (3.34)	16.21 (4.15)	0.05 (0.03)	17.4	49.6	—
SETVI	2.78 (1.58)	35.45 (3.5)	0.34 (0.09)	2.3	5.8	10.3
SINAR	28.56 (34.2)	231.9 (40.21)	0.04 (0.02)	19.1	53	—
	Parameters			Predicted tolpyralate + atrazine dose[a]		
Equation 3	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				——————————g ai ha^{-1}——————————		
ABUTH	0.07 (0.2)	4.84 (0.52)	0.02 (0.01)	1.1 + 36.6	2.6 + 86.4	3.8 + 126.5
AMASS	1.7 (3.59)	48.93 (8.82)	0.015 (0.01)	1.4 + 47.8	3.5 + 115.4	5.3 + 175.6
AMBEL	0.5 (8.99)	223.5 (22.17)	0.02 (0.01)	1.1 + 35.5	2.5 + 82.7	3.6 + 118.7
CHEAL	0.36 (2.89)	89.32 (7)	0.03 (0.02)	0.8 + 26.7	1.9 + 62.2	2.7 + 89.4
ECHCG	1.31 (0.8)	31.91 (2.43)	0.01 (0.002)	1.8 + 59.5	4.3 + 144.7	6.7 + 223.5
POLPE	6.73 (4.17)	9.44 (9.33)	0.008 (0.02)	6.8 + 225.2	—	—
SETVI	1.93 (1.69)	36.05 (3.47)	0.01 (0.002)	3.4 + 111.6	8.3 + 276	13.3 + 441.6
SINAR	0.46 (8.92)	254.2 (19.67)	0.01 (0.002)	2.1 + 71	5 + 165.2	7.11 + 237

[a] ED_{50}, ED_{80}, and ED_{90} denote the predicted effective dose of tolpyralate or tolpyralate + atrazine for a 50%, 80%, and 90% reduction in weed dry biomass relative to the nontreated control plot within blocks, respectively. Where a predicted dose could not be computed by the regression equation, values are represented by a dash (—).

all of the weed species evaluated in this study. Topramezone + atrazine (12.5 + 500 g ha^{-1}) provides control of wild mustard and ladysthumb (Anonymous 2016), indicating either a difference in topramezone and tolpyralate activity or that control of these species in this study is relative to the dose of atrazine. Consistent with results from previous assessment timings, common lambsquarters, velvetleaf, pigweed species, and common ragweed could be controlled 90% with lower predicted tolpyralate doses than could green foxtail, barnyardgrass, wild mustard, and ladysthumb. In all species, the predicted tolpyralate dose for 50%, 80%, or 90% control was lower when applied with atrazine compared with tolpyralate applied alone. Similar results were reported with mesotrione by Hugie et al. (2008), who found that a lower dose of mesotrione was required for control of redroot pigweed when applied with atrazine compared with mesotrione applied alone.

There was variation in density of each weed species within trial sites, which was reflective of natural species composition and interspecific competition within plots; however, density and biomass data generally reflected control assessments at 8 WAA. Regression analyses provided a better fit to the data when conducted on species with higher natural densities (>20 m^{-2}) within trial sites or replications compared to those with lower natural densities (<5 m^{-2}). Common ragweed, common lambsquarters, pigweed species, wild mustard, and green foxtail were generally more numerous within trial areas compared with velvetleaf and ladysthumb. Tolpyralate applied alone at doses of 17.6 g ha^{-1} or less provided a 50% reduction in density of all species, except ladysthumb and wild mustard (Table 5). Common ragweed and green foxtail were the only species for which density could be reduced by 80% with tolpyralate applied alone, while a 90% reduction in common ragweed density was achieved with tolpyralate at 20.6 g ha^{-1}. Conversely, biomass of all species could be reduced at least 80% with tolpyralate alone (Table 6). Tolpyralate at predicted doses of 2.7, 3.5, 3.8, 10.3, and 13.7 g ha^{-1} could reduce biomass by 90% for common lambsquarters, velvetleaf, common ragweed, green foxtail, and barnyardgrass, respectively. In many cases in which tolpyralate was applied alone, weeds became severely necrotic by 8 WAA but were still present in plots and therefore recorded, thus contributing to inconsistencies reflected in density and biomass data within species.

Table 7. Nonlinear regression parameters (± SE) and predicted tolpyralate or tolpyralate + atrazine dose required to obtain 50%, 80%, and 90% grain yield of weed-free check plots within blocks in field studies conducted in Ontario, Canada in 2015, 2016, and 2017.

	Parameters			Predicted tolpyralate dose[a]		
Equation 1	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				———g ai ha^{-1}———		
Grain yield	87.95 (1.79)	0.7 (0.06)	42 (4)	0.3	4.7	—
	Parameters			Predicted tolpyralate + atrazine dose[a]		
Equation 2	*a*	*b*	*c*	ED_{50}	ED_{80}	ED_{90}
				———g ai ha^{-1}———		
Grain yield	95.55 (1.33)	50.8 (3.03)	0.01 (0.002)	0.3 +8.2	2.7 + 89.7	5 + 167.8

[a] ED_{50}, ED_{80}, and ED_{90} denote the predicted effective dose of tolpyralate or tolpyralate + atrazine to achieve 50%, 80%, and 90% of the yield obtained in weed-free plots within blocks, respectively. Where a predicted dose could not be computed by the regression equation, the value is represented by a dash (—).

Consistent with control assessments, tolpyralate applied in combination with atrazine provided a higher level of weed control and therefore more consistent reduction in density and dry biomass than tolpyralate applied alone. Density of all species could be reduced 80% with tolpyralate + atrazine at doses of 44.7 + 1,488.2 g ha^{-1} or less (Table 5). Tolpyralate + atrazine at doses of 5.8 + 192.6 to 33 + 1,100 g ha^{-1} provided a 90% reduction in density of common lambsquarters, common ragweed, green foxtail, barnyardgrass, and wild mustard; however ED_{90} values for reduction in velvetleaf and pigweed density could not be computed. Biomass of all species with the exception of ladysthumb could be reduced 90% with tolpyralate + atrazine at doses of 13.3 + 441.6 g ha^{-1} or less.

Yield and Phytotoxicity

Crop injury with all treatments evaluated in this study was <10% and therefore considered commercially acceptable (unpublished data). Where phytotoxicity did occur, injury symptoms consisted of minor leaf speckling, slight chlorosis, or marginal necrosis of leaves exposed at the time of application. Symptoms were only observed in plots where tolpyralate + atrazine were applied at rates of 60 + 1,000 g ha^{-1} or higher (unpublished data).

Corn grain yields varied by year and location, but were reflective of overall weed control, and ranged from 0.92 t ha^{-1} in nontreated plots to 15.3 t ha^{-1} in weed-free control plots (unpublished data). Tolpyralate applied alone at doses of 0.3 and 4.7 g ha^{-1} could maintain 50% and 80% of the yield obtained in the weed-free control plots, respectively. However, weed control was not sufficient to avoid 10% yield loss with any of the doses of tolpyralate alone based on regression analyses (Table 7). This yield loss can likely be attributed to inadequate control of wild mustard with tolpyralate applied alone. Conversely, tolpyralate + atrazine at 5 + 167.8 g ha^{-1} was sufficient to maintain 90% of the yield obtained in the weed-free controls. Corn is particularly susceptible to yield loss due to weed interference during emergence and early vegetative growth stages (Hall et al. 1992; Page et al. 2009). Therefore, despite complete weed control with POST applications of tolpyralate + atrazine in these studies, some level of yield loss may have occurred as a result of early-season weed interference before herbicide application. Future research could investigate the benefits of POST tolpyralate applications following application of a PRE herbicide to mitigate this risk.

Conclusions

This research indicates that there are species-specific differences in weed sensitivity to tolpyralate. Based on predicted values calculated from regression analyses, common lambsquarters, velvetleaf, pigweed species, and common ragweed were controlled at least 90% with tolpyralate alone at doses below the current label rate range of 30 to 40 g ha^{-1}. Conversely, the BED of tolpyralate for 90% control of ladysthumb and wild mustard was beyond those used in this study when tolpyralate was applied alone. Therefore, the addition of atrazine to tolpyralate applications may broaden the spectrum of weed control and improve speed of control in some species. Further insights in this regard are provided in the subsequent companion manuscript (Metzger et al. 2018).

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