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Does Timing Influence the Utility of Reduced Atrazine Rates for Proactive Resistance Management?

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Atrazine is an important herbicide for broadleaf weed control in corn. Use rates have declined in many corn production systems due to environmental concerns and the availability of other effective herbicides, especially glyphosate in glyphosate-resistant hybrids. However, using multiple effective herbicide modes of action is ever more important because occurrence of herbicide-resistant weeds is increasing. An experiment to compare application timings of reduced rates of atrazine to benefit resistance management in broadleaf weeds while protecting corn yield was conducted in Wisconsin across four site-years in 2012 and 2013. Herbicide treatments consisted of five atrazine rate and timing combinations and three POST base herbicides: glyphosate, glufosinate, and tembotrione. Metolachlor was applied PRE at 2.1 kg ai ha^{-1} for grass control in all treatments. A linear regression model estimated that atrazine rates $\geq$ 1.0 kg ai ha^{-1} applied PRE would prevent exposure of common lambsquarters plants to POST herbicides, but giant ragweed and velvetleaf exposure was not influenced by timing. Corn yield was also not influenced by atrazine rate and timing combinations at the $\alpha = 0.05$ level; however, at $P = 0.06$, corn yield was greater for atrazine applied PRE at 1.1 kg ha^{-1} than for atrazine applied PRE at 0.5 kg ha^{-1}, POST at 1.1 kg ha^{-1}, or not at all. In summary, higher rates of atrazine applied PRE may improve yield, as reported by others, but this study concludes reduced rates of atrazine (i.e., $\leq$ 1.1 kg ha^{-1}) applied to corn in a POST tank mixture combination provided more consistent control of giant ragweed, velvetleaf, and common lambsquarters compared with atrazine applied PRE. This information should help direct atrazine application timing applied POST when applied at low rates to improve proactive herbicide resistance management.

Nomenclature: Atrazine; glufosinate; glyphosate; metolachlor; tembotrione; common lambsquarters, *Chenopodium album* L. CHEAL; giant ragweed, *Ambrosia trifida* L. AMBTR; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; corn, *Zea mays* L.

Key words: Application timing, corn, glufosinate resistance, glyphosate resistance, herbicide resistance, transgenic crops.

Atrazine es un herbicida importante para el control de malezas de hoja ancha en maíz. Las dosis han sido reducidas en muchos sistemas de producción de maíz debido a preocupaciones sobre su impacto en el ambiente y la disponibilidad de otros herbicidas efectivos, especialmente glyphosate en híbridos de maíz con resistencia a glyphosate. Sin embargo, el uso de herbicidas efectivos con múltiples modos de acción es aún más importante debido al incremento en la aparición de malezas resistentes a herbicidas. En 2012 y 2013, se realizó un experimento en Wisconsin a lo largo de cuatro sitios-años para comparar momentos de aplicación de atrazine a dosis reducidas para beneficiar el manejo de resistencia en malezas de hoja ancha y a la vez proteger el rendimiento del maíz. Los tratamientos de herbicidas consistieron en cinco combinaciones de dosis de atrazine y de momentos de aplicación y tres herbicidas POST: glyphosate, glufosinate, y tembotrione. Metolachlor fue aplicado PRE a 2.1 kg ai ha^{-1} para el control de gramíneas en todos los tratamientos. Un modelo de regresión lineal estimó que dosis de atrazine $\geq$ 1.0 kg ai ha^{-1} aplicadas PRE prevendrían la exposición de *Chenopodium album* a los herbicidas POST, pero *Ambrosia trifida* y *Abutilon theophrasti* no fueron influenciadas por el momento de aplicación. El rendimiento del maíz no fue influenciado por las combinaciones de dosis de atrazine y momentos de aplicación al nivel $\alpha = 0.05$. Sin embargo, a un nivel de $P = 0.06$, el rendimiento del maíz fue mayor para atrazine PRE a 1.1 kg ha^{-1} que para atrazine PRE a 0.5 kg ha^{-1}, POST a 1.1 kg ha^{-1}, o sin atrazine del todo. En resumen, las dosis más altas de atrazine aplicado PRE podrían mejorar el rendimiento, como otros han reportado, pero este estudio concluye que las dosis reducidas de atrazine (i.e., $\leq$ 1.1. kg ha^{-1}) aplicadas a maíz en una combinación de mezcla en tanque POST brinda un control más consistente de *A. trifida, A. theophrasti*, y *C. álbum*, al compararse con atrazine aplicado PRE. Esta información debería ayudar a dirigir el momento de aplicación de atrazine aplicado POST cuando se usan dosis bajas para mejorar el manejo proactivo de resistencia a herbicidas.

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Glyphosate use in glyphosate-resistant crops has dominated weed management strategies in recent years (Fernandez-Cornejo et al. 2014; Owen 2010; Sankula 2006). Glyphosate applied POST has been relied upon as a sole weed management tactic in soybean [*Glycine max* (L.) Merr.] for many years, which has led to glyphosate resistance evolution in many weed species (Young 2006). Moreover, POST glyphosate use became increasingly common in corn production, and in 2007, glyphosate passed atrazine as the herbicide applied to the most U.S. corn hectares (Mitchell 2013). One option for corn growers to reduce the risk and spread of glyphosate-resistant weeds is to use an alternative POST herbicide, such as glufosinate or HPPD (4-hydroxyphenylpyruvate dioxygenase) inhibiting herbicides. Despite what POST herbicide program is used, a best management practice (BMP) to control and reduce the risk of herbicide-resistant weed populations is to use herbicide combinations with multiple effective modes of action to reduce herbicide selection pressure (Norsworthy et al. 2012).

Atrazine is a herbicide that can be used to accomplish this BMP approach in corn because it can be applied PRE or POST to control many broadleaf and some grass weed species and, as a photosynthesis inhibitor, has a different mode of action than glyphosate, glufosinate, and HPPD inhibiting herbicides (Bridges 2008). Atrazine applied PRE has the potential to reduce the number of weeds exposed to other herbicides applied POST, which is an effective way to decrease the selection pressure of herbicides applied POST and therefore decrease the risk of herbicide resistance. A three-state study showed that atrazine applied PRE at 1.1 kg ha^{-1} reduced the density of common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer var. *rudis* (Sauer) Costea and Tardif] and common lambsquarters from 33 to 13 plants m^{-2} and 23 to 5 plants m^{-2}, respectively, at the POST glyphosate application timing, compared with no atrazine applied PRE, but did not reduce the density of giant ragweed or velvetleaf (Loux et al. 2011). The study did not evaluate atrazine applied at rates < 1.1 kg ha^{-1}, and atrazine can have a synergistic interaction and improve POST weed control when used with HPPD inhibiting herbicides below that rate (Abendroth et al. 2006; Bollman et al. 2006; Hugie et al. 2008; Sutton et al. 2002; Woodyard et al. 2009). In light of this synergistic potential, HPPD inhibitors do not reduce the need for atrazine in a corn herbicide program; rather, they further increase the need and utility of atrazine to be used in tank mixture combinations. Weed control and synergism by the combination of atrazine and HPPD inhibitors can be dependent on atrazine rate, application timing, rainfall, and the target weed species (Armel et al. 2003; Bollman et al. 2006; Hugie et al. 2008; Woodyard et al. 2009). Even with the synergistic effects expected from atrazine and HPPD inhibiting herbicides, it would not be advisable to rely only on these two herbicides applied at a PRE timing. Effective POST-applied herbicides are still advisable to reduce the chances of weed survival leading to metabolic resistance to these PRE-applied herbicides, which is why elimination of late-season weeds contributing seeds to the weed seedbank is critical for herbicide resistance management.

Although atrazine is an effective broadleaf herbicide, it also has been implied to have environmental concerns, such as surface and groundwater contamination (Gilliom et al. 2006; Postle et al. 1997; Solomon et al. 1996). One integrated strategy to reduce unwanted environmental concerns would be to utilize reduced rates, which would decrease environmental exposure and herbicide input costs. In the case of groundwater contamination, previous research suggests that reduced application rates of atrazine are asscociated with reduced movement of atrazine and its metabolites through the root zone of Plano Silt loam soil (Hanson et al. 1997). However, atrazine applied at rates lower than a level required to provide adequate weed control would not accomplish the goal of reducing the risk of herbicide resistance. If reduced rates are utilized, they should be applied at the optimal timing to improve weed control and reduce the selection pressure of herbicides applied POST, such as glyphosate. Atrazine applied PRE can potentially reduce the selection pressure of herbicides applied POST by reducing the number of weeds exposed to herbicides applied POST, whereas atrazine applied POST can provide an additional herbicide mode of action in a POST herbicide program. The timing of an atrazine application at reduced rates can also influence whether atrazine use successfully protects corn yield potential. Therefore, research examining the ability of atrazine applied PRE and POST at reduced rates to compliment glyphosate as well as other glyphosate alternatives such as glufosinate and certain HPPD

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Table 1. Sources of materials.

Common name	Rate (ai or ae ha^{-1})	Trade name	Manufacturer	Address	Website
Atrazine	0.6-1.1	AAtrex®4L	Syngenta Crop Protection, LLC.	Greensboro, NC	http://www.syngentacropprotection.com
Glufosinate	0.5	Liberty® 280 SL	Bayer CropScience LP	Research Triangle Park, NC	http://www.cropscience.bayer.com
Glyphosate	0.9	Roundup WeatherMax®	Monsanto Co.	St. Louis, MO	http://www.monsanto.com
Metolachlor	2.1	Dual II Magnum®	Syngenta Crop Protection, LLC.	Greensboro, NC	http://www.syngentacropprotection.com
Tembotrione	0.1	Laudis®	Bayer CropScience LP	Research Triangle Park, NC	http://www.cropscience.bayer.com

inhibitors is important for understanding the utility of atrazine in current weed management strategies.

Previous research has shown inconsistent results for the optimal timing of atrazine applied at reduced rates to compliment other nonselective POST herbicide treatments for a herbicide management strategy. Jones et al. (2001) found that atrazine applied PRE (1.1 kg ha^{-1}) followed by glufosinate POST provided more consistant weed control than when these herbicides were tank-mixed and applied POST. Tharp and Kells (2002) found no differences in weed control between atrazine (1.1 kg ha^{-1}) applied sequentially or tank-mixed with glyphosate or glufosinate, except for velvetleaf control, which was improved by tank-mixing atrazine with glyphosate compared with the sequential application in 2 of 4 yr. Bradley et al. (2000) and Johnson et al. (2000) reported that atrazine applied POST (1.1 kg ha^{-1}) with glufosinate or glyphosate, respectively, improved the weed control of many species compared with glufosinate or glyphosate applied POST alone. These studies did not evaluate weed control of atrazine at use rates $<$ 1.1 kg ha^{-1} applied sequentially vs. tank-mixed with glyphosate or glufosinate. Additionally, results did not include weed population densities at POST application timing to quantify whether reduced rates of atrazine applied PRE reduced the selection pressure of glyphosate or glufosinate. Further research on atrazine use rates of $<$ 1.1 kg ha^{-1} at PRE and POST timings in the context of herbicide resistance management could direct BMPs in areas where lower rates are needed because of regulations, environmental concerns, or both. The objective of this research was to determine the optimal application timing of atrazine applied at reduced rates to reduce the risk of evolving herbicide-resistant broadleaf weeds and to protect corn yield potential. The hypothesis was that atrazine applied POST would improve late-season weed control and herbicide resistance management strategies compared with atrazine applied PRE, but with a tradeoff of reduced corn yield.

Materials and Methods

Field experiments were conducted during 2012 and 2013 near Janesville, WI (43.72°N, 89.02°W), and Sauk City, WI (43.32°N, 89.68°W). At the Janesville site, the research area was chisel-plowed in the preceding fall and field-cultivated twice before planting to prepare a weed-free seedbed. The Sauk City site was managed as a no-tillage site for many years, and glyphosate (Table 1) was applied at 0.9 kg ae ha^{-1} over the entire research area before planting to prepare a weed-free seedbed. Metolachlor was also applied at 2.1 kg ha^{-1} over the entire research area at the time of planting at each site to provide residual grass control. The soil type at the Janesville site was Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls). At the Sauk City site, soil type was primarily Plano silt loam with small pockets of St. Charles silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). Corn was planted at all locations in 76-cm rows at a population between 81,000 and 89,000 seeds ha^{-1} and with adequate soil moisture in the soil profile, in which the surface was dry but moist at seed depth. No supplemental weed seeds were sown, nor supplemental irrigation used, at any location.

The experiment was designed as a randomized complete block with four replications. The treat-

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ment structure was a five by three factorial, with five levels of atrazine rate and timing combinations and three POST base herbicides (glyphosate, glufosinate, or tembotrione). Atrazine was applied at rates (kg ha^{-1}) of 0, 0.6 PRE, 0.6 POST, 1.1 PRE, or 1.1 POST in combination with glyphosate, glufosinate, or tembotrione at POST at rates of 0.9 kg ha^{-1}, 0.5 kg ai ha^{-1}, and 0.1 kg ai ha^{-1}, respectively. The full labeled rate of atrazine per application in most states is 2.2 kg ha^{-1} on soils that are not highly erodible (Anonymous 2013); thus, the rates of atrazine applied in this study were considered "reduced." Adjuvants were used with herbicides applied POST as recommended by the respective product labels. Each year by site combination was considered a unique environment, resulting in a total of four site-years.

Plots were 3 m wide and 7.6 m long consisting of four corn rows spaced 76 cm apart. PRE treatments were applied as soon as possible after planting, and POST treatments were applied when the corn was approximately 25 cm tall (V3 to V4 across sites). Herbicide treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} of total spray solution, and water was used as a carrier. Corn was visually assessed for phytotoxic effects at 14 and 10 d after PRE and POST herbicide application timings, respectively. Weed control was evaluated by counting weeds before the POST application, and control was estimated visually at 10, 21, and 35 d after POST treatment (DAPT) on a scale ranging from 0 (no control) to 100 (complete plant death), and weeds were again counted before harvest. Weed population densities were counted before the POST application timing and at corn harvest. Total weed shoot biomass was collected from a 1-m^2 area before corn harvest, dried at 54 C for 1 wk, and weighed. The center two rows of each plot were harvested with a plot combine, and the final corn grain yield was determined by standardizing to 15.5% moisture.

Weed population density and shoot dry biomass data were transformed as indicated by Box-Cox analysis (Box and Cox 1964). Giant ragweed and common lambsquarters population density data at the POST timing were analyzed as natural log transformations, whereas velvetleaf population density data were analyzed as a square root transformation. Total weed shoot dry weight data were analyzed as a natural log transformation. Weed control data from visual assessment were analyzed as arcsine square-root transformations. Least square means from the untransformed data are presented. Weed population densities before the POST application timing were regressed over atrazine rate. ANOVA was used to determine whether a quadratic regression model was significantly improved ($\alpha = 0.05$) from a linear model. Weed control data collected after the POST application timing were subjected to ANOVA, and factorial structured treatment means were separated using Fisher's protected LSD test ($P \leq 0.05$). Site-year and replications within a site-year were analyzed as random effects to account for site-year variability and improve the predictive power of results presented. Best-fit models were selected using the smallest Akaike information criterion and Bayesian information criterion values (Schwarz 1978). A single degree of freedom preplanned contrast was also used to compare treatment means of atrazine applied PRE with atrazine applied POST regardless of rate and POST base herbicide for dependent variables assessed after the POST application timing.

Results and Discussion

Weather and Weed Populations. Rainfall was low in 2012, totaling only 63 and 44 mm of rain from planting until canopy closure at Janesville and Sauk City sites, respectively (Table 2). Rainfall was adequate in the early growing season in 2013 and abundant soon after the POST application timing. In a 7-d span shortly after the POST application timing, 194 mm of rain fell at the Sauk City site. The field flooded and water stood in many plots for days; therefore, data were not collected at the Sauk City site in 2013 after this rainfall event. Giant ragweed was present across all four site-years, but density was low in some replications. Therefore, giant ragweed control data were limited to three replications at both locations in 2012 and two replications at Janesville in 2013. Total weed shoot biomass and corn grain yield data were also limited to three replications at the Sauk City site in 2012 because of negligible weed pressure. Velvetleaf and common lambsquarters were abundant at the Janesville site in 2012 and 2013, but not at the Sauk City site in either year.

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Table 2. Rainfall during the corn growing season at Janesville and Sauk City, WI, sites in 2012 and 2013.

Days after planting	Janesville[a]		Sauk City[b]	
	2012	2013	2012	2013
	mm of rainfall			
1–14	40	10	3	66
15–28	19	26	34	44
29–42	4	162	8	204
43–56	0	24	0	28
57–70	74	40	41	23
71–84	23	46	57	13
85–98	54	5	40	6
99–112	4	14	15	31
113–126	39	29	18	69
127–140	15	18	6	10
141–154	42	43	1	20
155–168	0	0	83	22

[a] Average monthly rainfall from 1981 to 2010 near Janesville, WI, is 85, 118, 97, 109, and 92 mm for months May to September, respectively.

[b] Average monthly rainfall from 1981 to 2010 near Sauk City, WI, is 92, 116, 103, 109, and 84 mm for months May to September, respectively.

Weed Exposure to Herbicides applied POST. Across locations, giant ragweed was 5 to 8 cm tall and ranged in density from 2 to 13 plants m^{-2} (Table 3). In Janesville across years, lambsquarters was 1 to 3 cm tall at 4 to 129 plants m^{-2}, and velvetleaf was 2 to 3 cm tall at 12 to 13 plants m^{-2} (Table 3). The quadratic term was not significant for any of the models regressing weed population density at the POST application timing over atrazine rate; therefore, the linear model was used for all three weed species. The slope estimate did not differ from zero for giant ragweed density ($P = 0.4302$), but velvetleaf and common lambsquarters density slope estimates were 1.2 ($P = 0.0050$) and 74.1 ($P < 0.0001$) plants m^{-2} less, respectively, for 1.0 kg ha^{-1} atrazine applied PRE compared with no atrazine applied PRE (Table 4). Although the slope estimate was significant for velvetleaf density, the density data were highly variable, and the standard error of the slope was high. Therefore, > 0.7 kg ha^{-1} of atrazine applied PRE was needed to be confident (at $P \leq 0.05$) that velvetleaf population densities would be decreased compared with no atrazine applied PRE. Conversely, atrazine applied PRE was effective in reducing the number of common lambsquarters plants exposed to herbicides applied POST (Table 5). The linear model indicates that no common lambsquarters plants were exposed to POST herbicides after atrazine applied PRE at rates ≥ 1 kg ha^{-1}. Moreover, common lambsquarters densities at the POST application

Table 4. Linear regression parameter estimates of weed population density response to atrazine rate[a,b] at the POST application timing. Data are pooled over site-years.

Weed species[c]	Intercept	Slope	Slope SE	R^2
	plants m^{-2}			
AMBTR	6.2***	NS[d]	NS	0.002
ABUTH	3.5***	−1.2**	0.42	0.038
CHEAL	72.0*	−74.1***	14.2	0.301

[a] Significance and coefficient of determination are based on transformed data. Parameter estimates and standard error (SE) of slope are from untransformed data.

[b] Estimate of the number of plants per square meter decreased by the addition of 1.0 kg ai ha^{-1} of atrazine PRE to 2.1 kg ai ha^{-1} of metolachlor compared with 2.1 kg ai ha^{-1} of metolachlor with no atrazine.

[c] ABUTH, *Abutilon theophrasti;* AMBTR, *Ambrosia trifida*; CHEAL, *Chenopodium album.*

[d] NS, not significant at $P \leq 0.05$.

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$

Table 3. Average weed height and population densities at POST application timings at Janesville and Sauk City, WI, sites in 2012 and 2013 in the absence of atrazine applied PRE.[a]

Site	Weed species[b]	2012 Weed height cm	2012 Weed density plants m^{-2}	2013 Weed height cm	2013 Weed density plants m^{-2}
Janesville	AMBTR	5 (0.68)	2 (0.54)	7 (0.37)	4 (1.11)
	ABUTH	2 (0.05)	12 (0.99)	3 (0.05)	13 (1.47)
	CHEAL	3 (0.16)	4 (0.81)	1 (0.04)	129 (14.03)
Sauk City	AMBTR	8 (0.37)	13 (1.59)	8 (0.39)	2 (0.39)

[a] Standard error is shown in parentheses.

[b] ABUTH, *Abutilon theophrasti;* AMBTR, *Ambrosia trifida*; CHEAL, *Chenopodium album.*

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Table 5. The effect of atrazine timing and rate of application on late-season weed control, total weed shoot dry weight, and corn yield. Data are pooled over all three POST base herbicide treatments (glyphosate, glufosinate, or tembotrione) and site-years.

Atrazine treatment		Control[a]				
Timing	Rate	AMBTR	ABUTH	CHEAL	Total weed dry weight[b]	Corn yield
	kg ai ha^{-1}	———	%	———	g m^{-2}	kg ha^{-1}
—	0.0	96	98	97	12.3 b	12,540
PRE	0.6	96	97	97	6.3 b	12,690
PRE	1.1	96	98	98	4.6 b	13,170
POST	0.6	97	98	99	4.2 ab	12,920
POST	1.1	97	99	99	1.1 a	12,720
$P > F$[c]		NS	NS	0.0564	0.0299	0.0601
Preplanned contrast						
PRE vs. POST[d]		−0.7	−1.2	−1.6	2.8	110
P value		NS	NS	0.0185	0.0106	NS

[a] ABUTH, *Abutilon theophrasti;* AMBTR, *Ambrosia trifida*; CHEAL, *Chenopodium album.*

[b] Means in the same column with the same letter are not significantly different according Fisher's protected LSD test ($P \leq 0.05$).

[c] P values corresponding to *F* tests with the null hypothesis that the least square means of atrazine rate/timings are equal. NS, not significant.

[d] Difference between the PRE minus POST atrazine treatments pooled across atrazine rates and POST treatment bases.

timing were reduced after atrazine applied PRE at $\geq$ 0.4 kg ha^{-1} relative to no atrazine applied. These results were similar to findings of Loux et al. (2011), who reported that 1.1 kg ha^{-1} of atrazine applied PRE reduced population densities at POST timing of common lambsquarters, but not giant ragweed or velvetleaf. Additionally, these findings suggest that atrazine rates could be reduced to as low as 0.4 kg ha^{-1} and still reduce the number of common lambsquarters plants exposed to herbicides applied POST.

Midseason Weed Control. There were no significant interactions ($P \leq 0.05$) between atrazine rate and timing combinations and POST base herbicides (glyphosate, glufosinate, or tembotrione) for weed control at 10, 21, or 35 DAPT (data not shown). Furthermore, weed control ratings at 10, 21, or 35 DAPT did not differ among POST base herbicides. Giant ragweed control at 10, 21, and 35 DAPT was not influenced by atrazine rate and timing combinations and ranged from 92 to 97% (data not shown). Velvetleaf control at 10 DAPT was improved by atrazine applied POST at either rate or PRE at 1.1 kg ha^{-1} compared with PRE at 0.6 kg ha^{-1}. However, velvetleaf control ranged from 95 to 99% (data not shown) for the atrazine rate and timing combinations at 10, 21, and 35 DAPT, indicating they would likely satisfy most growers' expectations for midseason weed control and yield protection. Common lambsquarters control at 10 DAPT was slightly improved by any rate and timing combination of atrazine compared with herbicide treatments that did not include atrazine. The contrast of atrazine applied PRE vs. POST pooled over rates and base POST treatment herbicides also indicates common lambsquarters control was improved at 35 DAPT by atrazine applied POST compared with PRE, likely because of the extended residual control of atrazine when applied later in the growing season.

Late-Season Weed Control and Corn Grain Yield. Analogous to midseason weed control, there were no interactions between atrazine rate and timing combinations and POST base herbicides for weed control before corn harvest or corn grain yield. Furthermore, there were no differences between POST base herbicides for these ratings. Corn yield data were not transformed.

Visual weed control estimates before corn harvest did not differ among atrazine rate and timing treatment combinations. Yet, the contrast of atrazine applied PRE vs. POST pooled over rates and POST treatment bases indicates improved control of common lambsquarters before corn harvest by atrazine applied POST compared with PRE (Table 5). The contrast estimated a reduction of 2.8 g m^{-2} of total dry weed biomass before corn harvest when atrazine was applied POST compared with PRE.

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Table 6. Average weed height and population densities[a] of all treatments before corn harvest at research sites near Janesville, WI, in 2012 and 2013 and Sauk City, WI, in 2012.

Site	Weed species[b]	2012 Weed height	2012 Weed density	2013 Weed height	2013 Weed density
		cm	plants m^{-2}	cm	plants m^{-2}
Janesville	AMBTR	107 (10.76)	0 (0.09)	90 (22.21)	0 (0.03)
	ABUTH	47 (5.94)	0 (0.06)	13 (1.23)	0 (0.05)
	CHEAL	80 (13.5)	0 (0.05)	6 (0.95)	2 (0.35)
Sauk City	AMBTR	88 (4.05)	2 (0.19)	—[c]	—

[a] Standard error is shown in parentheses

[b] ABUTH, *Abutilon theophrasti;* AMBTR, *Ambrosia trifida*; CHEAL, *Chenopodium album.*

[c] —, No weed height or density data were recorded at Sauk City location in 2013 after the flood event.

The primary drivers for this difference were giant ragweed at the Sauk City site in 2012 and common lambsquarters at the Janesville site in 2013, as other weeds were at low frequencies (Table 6).

Corn injury from herbicides application was negligible after treatments (data not shown). Corn yield was not influenced by atrazine rate and timing combinations ($P \leq 0.05$, Table 5). However, at $P = 0.06$, corn yield was greater for atrazine applied PRE at 1.1 kg ha^{-1} than atrazine applied PRE at 0.5 kg ha^{-1}, POST at 1.1 kg ha^{-1}, or no atrazine. These results are similar to those of Bradley et al. (2000) and Johnson et al. (2000), who concluded that atrazine applied POST improved weed control 5 wk after POST treatment but reduced corn yield from less efficacious PRE herbicide programs, which resulted in longer periods of early-season weed interference.

In conclusion, atrazine applied PRE at rates as low as 0.4 kg ha^{-1} decreased the number of common lambsquarters plants exposed to herbicides applied POST. Atrazine applied PRE at rates > 0.7 kg ha^{-1} were needed to reduce velvetleaf exposure. Giant ragweed densities were not reduced at the POST application timing when atrazine was applied PRE at rates as high as 1.1 kg ha^{-1} compared with no atrazine applied PRE. When atrazine was applied POST in combination with glyphosate, glufosinate, or tembotrione, atrazine provided an additional mode of action for each of these broadleaf weed species and subsequently reduced the selection pressure and the risk of herbicide resistance to both atrazine and its tank mixture partner. In this research, the weeds present at the POST application timing were susceptible to and adequately controlled by POST base herbicides alone, but an additional short-term benefit of atrazine applied at reduced rates POST was residual control of late-season common lambsquarters flushes. Because most fields have both large- and small-seeded broadleaf weeds that need to be controlled, it is likely that atrazine applied POST at rates ≤ 1.1 kg ha^{-1} tank mixed with other effective herbicides will contribute more to proactive herbicide resistance management than atrazine applied PRE at rates ≤ 1.1 kg ha^{-1} followed by POST herbicides such as glyphosate, glufosinate, or tembotrione. The importance of scouting and properly identifying the target weed species is reemphasized with these results because in a situation in which a small-seeded broadleaf weed, such as common lambsquarters, is the target species that needs to be controlled, 0.4 to 1.1 kg ha^{-1} of atrazine applied PRE also proved to be a viable option to reduce the risk of herbicide resistance for that species. Moreover, the PRE application timing should provide the best protection of corn yield by reducing early-season weed interference.

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