Tolerance of corn to PRE- and POST-applied photosystem II–inhibiting herbicides

Authors: Richburg, Jacob T., Norsworthy, Jason K., Barber, Tom, Roberts, Trent L., and Gbur, Edward E.

Source: Weed Technology, 34(2) : 277-283

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wet.2019.119

Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Richburg JT, Norsworthy JK, Barber T, Roberts TL, Gbur EE (2020) Tolerance of corn to PRE- and POST-applied photosystem II–inhibiting herbicides. Weed Technol. **34**: 277–283. doi: 10.1017/wet.2019.119

Received: 24 June 2019
Revised: 28 October 2019
Accepted: 4 November 2019
First published online: 14 November 2019

Associate Editor:
Lawrence E. Steckel, University of Tennessee

Nomenclature:
Ametryn; atrazine; diuron; fluometuron; linuron; metribuzin; prometryn; propazine; simazine; barnyardgrass; *Echinochloa crus-galli* (L.) P. Beauv.; Palmer amaranth, *Amaranthus palmeri* (S.) Watson; corn, *Zea mays* L.

Keywords:
Photosystem II–inhibiting herbicides; corn tolerance

Author for correspondence:
Jacob T. Richburg, 1366 W. Altheimer Dr., Fayetteville, AR 72704. Email: jrichburg95@gmail.com

Tolerance of corn to PRE- and POST-applied photosystem II–inhibiting herbicides

Jacob T. Richburg[1], Jason K. Norsworthy[2], Tom Barber[3], Trent L. Roberts[4] and Edward E. Gbur[5]

[1]Former Graduate Student, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [2]Professor and Elms Farming Chair of Weed Science, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA; [3]Professor, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Lonoke, AR, USA; [4]Associate Professor, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA and [5]Professor, Agricultural Statistics Laboratory, University of Arkansas, Fayetteville, AR, USA

Abstract

Weed control in corn traditionally has relied on atrazine as a foundational tool to control problematic weeds. However, the recent discovery of atrazine in aquifers and other water sources increases the likelihood of more strict restrictions on its use. Field-based research trials to find atrazine alternatives were conducted in 2017 and 2018 in Fayetteville, AR, by testing the tolerance of corn to PRE and POST applications of different photosystem II (PSII) inhibitors alone or in combination with mesotrione or *S*-metolachlor. All experiments were designed as a two-factor factorial, randomized complete block, with the two factors being (1) PSII-inhibiting herbicide and (2) the herbicide added to create the mixture. The PSII-inhibiting herbicides were prometryn, ametryn, simazine, fluometuron, metribuzin, linuron, diuron, atrazine, and propazine. The second factor consisted of either no additional herbicide, *S*-metolachlor, or mesotrione. Treatments were applied immediately after planting in the PRE experiments and to 30-cm–tall corn for the POST experiments. For the PRE study, low levels of injury (<15%) were observed at 14 and 28 d after application and corn height was negatively affected by the PSII-inhibiting herbicide applied. PRE-applied fluometuron- and ametryn-containing treatments consistently caused injury to corn, often exceeding 5%. Because of low injury levels caused by all treatments, crop density and yield did not differ from that of the nontreated plants. For the POST study, crop injury, relative height, and relative yield were affected by PSII-inhibiting herbicide and the herbicide added. Ametryn-, diuron-, linuron-, propazine-, and prometryn-containing treatments caused at least 25% injury to corn in at least 1 site-year. All PSII-inhibiting herbicides, except metribuzin and simazine when applied alone, caused yield loss in corn when compared with atrazine alone. Diuron-, linuron-, metribuzin-, and simazine-containing treatments applied PRE and metribuzin- and simazine-containing treatments applied POST should be investigated further as atrazine replacements.

Introduction

Weed control is a necessity for corn producers because poor weed control can negatively affect yields. Smith and Scott (2017) demonstrated that one Palmer amaranth plant that goes uncontrolled in corn for 4 wk after emergence can potentially reduce yields by 4%. Therefore, weed competition should be eliminated to allow for maximum yield potential. Weeds can also impede harvest; Bensch et al. (2003) showed Palmer amaranth can grow up to 2 m tall in less than 40 d, meaning that late-season infestations could result in less than optimal harvest conditions. Whether it is early in the growing season or late, weed control is vital to ensure profitable yields in corn. Troublesome weeds for corn in the southern United States include morningglories (*Ipomoea* spp.), Texas millet [*Panicum texana* (Buckley) R. Webster], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R. D. Webster], johnsongrass [*Sorghum halepense* (L.) Pers.], sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby], nutsedge (*Cyperus* spp.), and Palmer amaranth (Webster and Nichols 2012).

In 2016, more than 25 million kg of atrazine were applied in the United States (NASS 2018). Atrazine, a photosystem II (PSII)-inhibiting herbicide, has been the foundation for weed control in corn for over 70 y since its discovery in 1958 (Kramer and Schirmer 2007). PSII-inhibiting herbicides make up Weed Science Society of America herbicide site of action Groups 5, 6, and 7, with the largest portion of PSII-inhibiting herbicides being contained in Group 5. PSII-inhibiting herbicides create oxidative stress to the D1 protein by halting electron flow within the photosynthetic electron transport chain (Aro et al. 1993).

PSII inhibitors act on one of two mechanisms: inactivation and protein damage on the acceptor side or inactivation and damage on the donor side of P680 (Aro et al. 1993). After these mechanisms begin to work, the D1 protein is triggered to begin degradation and is digested by the proteinase of the PSII pathway (Aro et al. 1993). Though each PSII-inhibiting herbicide works by binding with the D1 protein, each group binds somewhat differently.

Atrazine controls an assortment of broadleaf weeds, including common cocklebur (*Xanthium strumarium* L.), common ragweed (*Ambrosia artemisiifolia* L.), morningglories, and Palmer amaranth, as well as numerous monocot species (Culpepper and York 1999; Greir and Stahlman 1999; Krausz and Kapusta 1998; Sprague et al. 1999; Webster et al. 1998). Although atrazine can be applied alone, best management practices for slowing resistance evolution suggest using multiple sites of action and residual herbicides (Norsworthy et al. 2012). A common addition to atrazine in the Midsouth is mesotrione, which works by inhibiting 4-hydroxyphenylpyruvate dioxygenase, the enzyme that breaks down the amino acid tyrosine, thus hindering weed growth and development (Moran 2005). Research has shown that atrazine and mesotrione have synergistic effects when applied together, allowing for broader spectrum weed control (Abendroth et al. 2006; Sutton et al. 2002).

Another herbicide commonly added to atrazine applications is *S*-metolachlor. This very long chain fatty acid–inhibitor has no POST activity but offers widespread residual control of annual grasses and small-seeded broadleaf weeds (Grichar et al. 2004). Although there is no documented synergy between *S*-metolachlor and atrazine, the combination of these two herbicides applied PRE at 1,820 g ha^{-1} and 1,408 g ha^{-1}, respectively, provided greater than 90% control of giant foxtail (*Setaria faberi* Herrm.), redroot pigweed (*Amaranthus retroflexus* L.), and giant ragweed (*Ambrosia trifida* L.) (Taylor-Lovell and Wax 2001). Combinations of atrazine, mesotrione, and *S*-metolachlor increase the longevity of use of each of these herbicides by decreasing the risk for target-site resistance evolution.

As discussed previously, atrazine alone and in combination with other herbicides provides corn growers with an unmatched tool for weed control. However, this tool does face potential issues. Numerous reviews have been written supporting the use of atrazine in agriculture as well as addressing its environmental impact (Fan and Song 2014; Mudhoo and Garg 2011; Neuberger 1996; Odukkathil and Vasudevan 2013; Solomon et al. 1996; Singh et al. 2018). Survey results from Barbash et al. (2006) indicated that atrazine is routinely found in drinking water aquifers and shallow groundwater under agricultural areas, although not at levels considered harmful to humans. Studies have also shown that contamination of groundwater by endocrine disrupters such as atrazine may pose health concerns for the public (Lasserre et al. 2009).

Other PSII-inhibiting herbicides, although not as broad spectrum, include ametryn, diuron, fluometuron, linuron, metribuzin, prometryn, propazine, and simazine, among others. Several of these PSII-inhibiting herbicides, including diuron, linuron, metribuzin, and propazine, are generally applied to crops for residual weed control at lower rates than used for atrazine (Shaner 2014). One way to decrease the prevalence of atrazine in groundwater is by reducing the amount used in agriculture, and specifically atrazine use related to corn production. Hence, we tested the tolerance of corn to the aforementioned PSII-inhibiting herbicides alone and in combination with mesotrione and *S*-metolachlor to determine their potential as replacements for atrazine.

Materials and Methods

Corn Trial Common Methodology

Field experiments were conducted in 2017 and 2018 to test the tolerance of corn to PRE- and POST-applied PSII-inhibiting herbicides. Corn experiments used variety 1197YHR (Pioneer, Johnston, IA 50131), a 111-d maturing, glyphosate- and glufosinate-tolerant hybrid, planted at 79,000 seeds ha^{-1} into conventionally tilled and raised beds at a 5-cm depth. Plot sizes were 3.7 m wide by 6.1 m long and rows were spaced 91 cm apart. Plots were maintained weed-free with POST applications of glufosinate and glyphosate on an as-needed basis. All corn trials received 56, 73, and 56 kg ha^{-1} of N, P_2O_5, and K_2O, respectively, before planting and 168 kg ha^{-1} N when the corn was at V6 (Richie et al. 1986). Urea (46-0-0), triple superphosphate (0-45-0), and potash (0-0-60) were the fertilizer sources used. Irrigation in the amount of 2.5 cm was provided via furrow irrigation when 7 d without rainfall in excess of 2.5 cm occurred. Trials were otherwise managed according to the Arkansas *Corn Production Handbook* (Espinoza and Ross 2015).

Experimental Sites

Field experiments were conducted on a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults) at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, in 2017 and 2018. The soil at Fayetteville consisted of 34% sand, 53% silt, and 13% clay, with an organic matter content of 1.5% and a pH of 6.8.

PRE Tolerance Study Design and Data Collection

Experiments were designed as a two-factor factorial, randomized complete block, with the factors being (1) PSII-inhibiting herbicide and (2) the herbicide added to create the mixture. The PSII-inhibiting herbicides included ametryn, atrazine, diuron, fluometuron, linuron, metribuzin, prometryn, propazine, and simazine. The second factor consisted of either no herbicide, *S*-metolachlor, or mesotrione. PSII-inhibiting herbicides were applied at the same rate as they would be applied at in a labeled crop. Herbicide rates and manufacturers are listed in Table 1. All treatments were applied at 140 L ha^{-1} after corn planting (Table 2). The experimental treatments were replicated four times. Visible crop injury was rated at 14 and 28 d after application (DAA) on a scale of 0% to 100%, with 0% representing no injury and 100% representing crop death (Frans and Talbert 1977). Crop height measurements of three random plants in each plot were measured to the crop canopy, recorded at 28 DAA, and then averaged. Crop density was counted as plants m^{-1} row 14 DAA. Grain was harvested from the middle two rows of each plot using a small-plot combine, and weights were adjusted to 15.5% moisture and expressed as corn grain yield in kg ha^{-1}.

POST Tolerance Study Setup and Data Collection

Experiments followed the same treatments and design as the previously discussed PRE trial. However, for the POST experiments, treatments were applied when corn was 30-cm tall (V3 to V4). Visible crop injury was rated at 14 and 28 DAA. Crop height and yield were determined as outlined in the PRE tolerance section.

Table 1. Herbicides, rates, and manufacturers for PRE and POST corn trials in 2017 and 2018 at Fayetteville, AR.

Herbicide			
Common name	Trade name	Rate	Manufacturer
		g ai ha^{-1}	
Ametryn	Evik	2,200	Syngenta Crop Protection, LLC
Atrazine	Aatrex 4L	1,100	Syngenta Crop Protection, LLC
Diuron	Direx	450	ADAMA
Fluometuron	Cotoran	1,100	ADAMA
Linuron	Linex	840	Tessenderlo Kerley, Inc.
Mesotrione	Callisto	210[a]	Syngenta Crop Protection, LLC
Metribuzin	Tricor 4F	280	United Phosphorous Limited
Prometryn	Caparol	2,200	Syngenta Crop Protection, LLC
Propazine	Milo-Pro	540	Albaugh, LLC
Simazine	Princep 4L	2,200	Syngenta Crop Protection, LLC
S-metolachlor	Dual II Magnum	1,400	Syngenta Crop Protection, LLC

[a]Applied POST at 105 g ai ha^{-1}.

Table 2. Planting, herbicide application, and harvest dates for PRE- and POST-corn trials in Fayetteville, AR in 2017 and 2018.

		Dates of significance		
Trial	Year	Planting	Herbicide application	Harvest
PRE	2017	May 26	May 26	October 26
	2018	April 20	April 22	October 8
POST	2017	April 12	May 18	September 21
	2018	April 20	May 20	October 8

Statistical Analysis

Data from the trials were analyzed separately by year, given the different planting dates from year to year. All visible estimates of crop injury for the nontreated plots in these studies were zero; thus, the nontreated plots were excluded from the analysis for injury at 14 and 28 DAA. Crop height, crop density, and yield values were converted to be relative to those of the nontreated plots. This was done by dividing the observations for each response variable by the average of the nontreated observations for each respective response variable. Data were then subjected to an analysis of variance using the GLIMMIX procedure in SAS, version 9.4, statistical software (SAS Institute Inc, Cary, NC), assuming a beta distribution for injury assessments and a gamma distribution for all other assessments, to see if the main PSII-inhibiting herbicide, the additive herbicide, or the interaction had an effect (Gbur et al. 2012). Means were compared for injury, relative crop height, relative crop density, and relative yield using Fisher protected LSD ($P = 0.05$).

Results and Discussion

PRE Study

Rainfall

The amount and timing of rainfall relative to the PRE applications differed between years (Figure 1). The performance of soil-applied herbicides is affected by numerous factors, including, but not limited to, soil texture, organic matter, and soil moisture (Curran 2001; Hartzler 2002). Given that both experiments were conducted on the same soil texture, with similar organic matter and pH, it is likely that any differences in herbicide performance depended on rainfall timing and rate after herbicide application. Because herbicides applied PRE are taken up through the roots of young, germinating seedlings, 1 to 2 cm of rainfall is required for activation (Rao 2000). In 2017, PRE herbicides were applied immediately after planting and received an activating rainfall of 3.5 cm 2 d later (Figure 1). In 2018, PRE herbicides were applied 2 d after planting and received 1.6 cm of rainfall the evening immediately after the application (Figure 1).

Injury

In both years, corn injury 14 DAA was influenced by an interaction of the PSII-inhibiting herbicide and the additive herbicide ($P = 0.0305$ for 2017; $P = 0.0292$ for 2018) (Table 3). Injury was in the form of leaf-tip chlorosis with some bleaching of new leaves on plants that received mesotrione-containing treatments. In 2017, applications of ametryn alone, ametryn plus mesotrione, and ametryn plus *S*-metolachlor caused 9%, 5%, and 7% injury, respectively (Table 4). However, in 2018, ametryn and ametryn plus mesotrione caused no observable injury. Fluometuron-containing treatments caused injury in both years, with fluometuron plus mesotrione causing 10% injury in both years. In 2017, this was the highest injury rate observed for any treatment, but it did not differ from fluometuron alone or ametryn alone. In 2018, fluometuron plus mesotrione injury was higher than that occurring with all other treatments.

Corn injury in 2018 was temporary, and by 28 DAA, no differences were detected among treatments. No treatment displayed injury greater than 3% (data not shown). However, corn injury 28 DAA in 2017 was not temporary and was influenced by an interaction of PSII-inhibiting herbicide and the herbicide added ($P < 0.0001$) (Table 3). In 2017, some plots with injury of 5% or higher 14 DAA did not recover by 28 DAA (Table 4). For example, fluometuron alone, fluometuron plus mesotrione, and fluometuron plus *S*-metolachlor exhibited 9%, 10%, and 5% injury, respectively, 14 DAA, and then 9%, 16%, and 9% injury, respectively, 28 DAA. However, treatments containing ametryn plus mesotrione, diuron plus mesotrione, prometryn plus mesotrione, and simazine plus *S*-metolachlor were exceptions to this lack of recovery. Each of these treatments exhibited 5% injury 14 DAA and then exhibited no injury 28 DAA. Overall, injury in both years and at both ratings was less than 20%. Excluding ametryn- and fluometuron-containing treatments, injury was less than 10% at 14 and 28 DAA.

Relative Stand

There was no significant effect for the main effects of PSII-inhibiting herbicide and herbicide added and the interaction (Table 3). Densities in nontreated plots were 8.1 and 7.7 plants m^{-1} row in 2017 and 2018, respectively (data not shown).

Relative Height

In 2017, corn height was not affected by any factor. Although visible injury symptoms of interveinal chlorosis were not present by 28 DAA in 2018, height was influenced by the PSII-inhibiting herbicides ($P < 0.0001$) (Table 3). Consistent with injury at 14 DAA, fluometuron-containing treatments, which caused the highest visible injury, also caused the greatest reduction in height (77% of the nontreated plots; Tables 4 and 5). Generally, any PSII-inhibiting herbicide that caused injury 14 DAA reduced height compared with the nontreated plots, except metribuzin- and simazine-containing treatments, which did not reduce height compared with nontreated plots in 2018.

Table 3. Significance of P values for interactions and main factors of PSII-inhibiting herbicide and herbicide added on various factors by year for PRE corn trials.

Year	Factor	Injury 14 DAA[a]	Injury 28 DAA	Relative stand 14 DAA	Relative height 28 DAA	Relative yield
		P value[b]				
2017	PSII herbicide	<0.0001	<0.0001	0.4403	0.0667	0.1341
	Herbicide added	0.0359	0.1969	0.6312	0.1849	0.2123
	PSII herbicide by herbicide added	0.0305	<0.0001	0.2601	0.0633	0.8833
2018	PSII herbicide	0.0038	0.1331	0.8979	<0.0001	0.1304
	Herbicide added	0.9924	0.5905	0.6933	0.5604	0.0952
	PSII herbicide by herbicide added	0.0292	0.1846	0.7074	0.4607	0.0904

[a]Abbreviation: DAA, days after application.
[b]P < 0.05 was considered statistically significant.

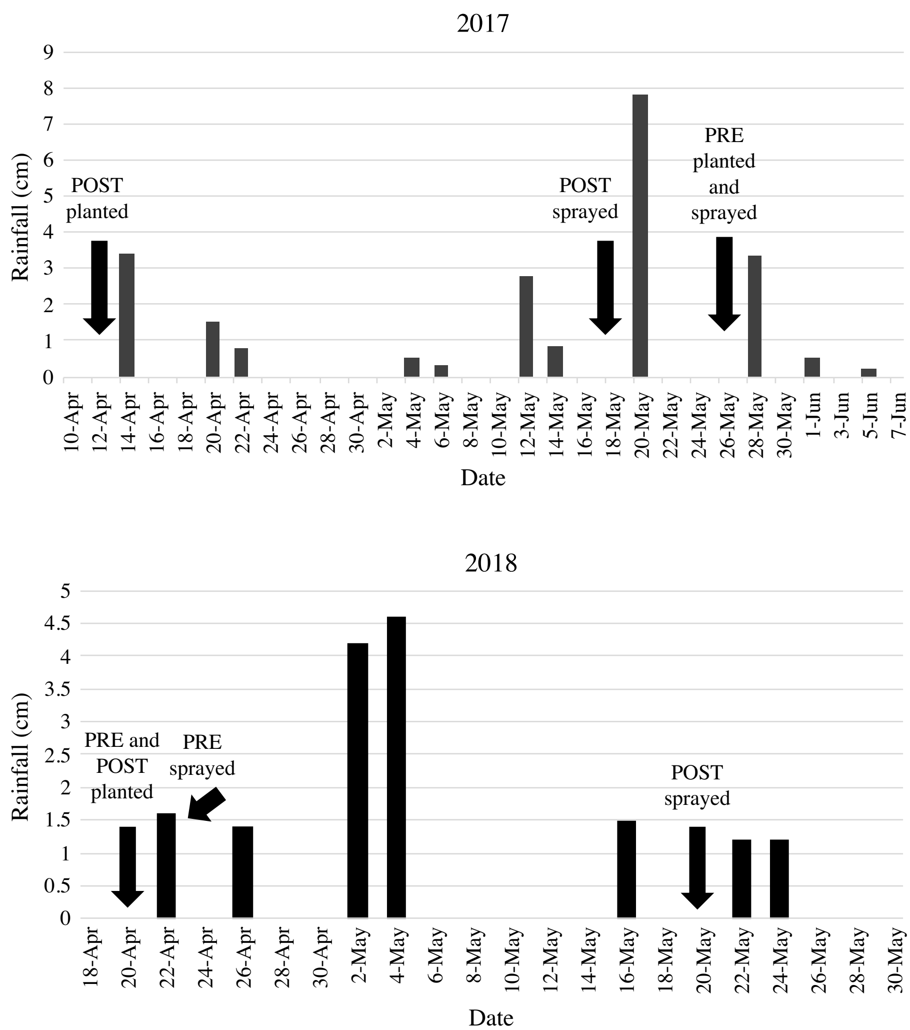

Figure 1. Rainfall amounts by day along with corn planting and herbicide application dates at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, in 2017 and 2018.

Relative Yield

Although various treatments may have caused visible injury and height reduction in 2017 and 2018, relative yield was not significantly influenced by the main effects of PSII-inhibiting herbicide, herbicide added, or the interaction (Table 3). On average, corn in the nontreated plots yielded 11,000 and 12,510 kg ha^{-1} for 2017 and 2018, respectively. Corn is a fairly vigorous crop with the ability to recover from early-season injury caused by herbicides. Corn yield components develop at different stages, giving corn the ability to compensate for adverse effects throughout the growing season (Milander 2015). Yield components such as kernels row^{-1}, rows ear^{-1}, and kernel weight are each primary yield components that are determined at different times after the V4 growth stage (Fageria et al. 2006). However, ears m^{-1} is typically correlated with crop density (i.e., plant stands). Because injury in 2017 and 2018 was minimal and, in most treatments, temporary, and because density

Table 4. Average visible estimates of corn injury as influenced by interactions between PSII-inhibiting herbicide and herbicide added applied PRE in Fayetteville, AR, in 2017 and 2018.

		Injury		
		14 DAA[a,b]		28 DAA
PSII herbicide	Herbicide added	2017	2018	2017
		%		
Ametryn	None	9 ab	0 d	11 b
	Mesotrione	5 c	0 d	0 d
	S-metolachlor	7 bc	6 bc	10 b
Atrazine	None	0 d	0 d	0 d
	Mesotrione	0 d	0 d	0 d
	S-metolachlor	0 d	0 d	0 d
Diuron	None	0 d	0 d	0 d
	Mesotrione	5 c	0 d	0 d
	S-metolachlor	0 d	0 d	0 d
Fluometuron	None	9 ab	7 b	9 bc
	Mesotrione	10 a	10 a	16 a
	S-metolachlor	5 c	5 bc	9 bc
Linuron	None	0 d	0 d	0 d
	Mesotrione	0 d	0 d	0 d
	S-metolachlor	0 d	0 d	0 d
Metribuzin	None	0 d	0 c	0 d
	Mesotrione	4 cd	0 c	0 d
	S-metolachlor	5 c	5 bc	6 c
Prometryn	None	7 bc	3 c	0 d
	Mesotrione	5 c	3 c	0 d
	S-metolachlor	5 c	5 bc	6 c
Propazine	None	0 d	3 c	0 d
	Mesotrione	0 d	3 c	0 d
	S-metolachlor	4 cd	3 c	0 d
Simazine	None	0 d	5 bc	0 d
	Mesotrione	5 c	0 d	6 c
	S-metolachlor	0 d	5 bc	8 bc

[a]Abbreviation: DAA, days after application.
[b]Means within a column followed by the same letter are not significantly different according to Fisher protected LSD (P = 0.05).

Table 5. Relative corn height as influenced by PSII-inhibiting herbicide applied PRE in Fayetteville, AR, in 2018.

PSII herbicide	Relative corn height[a,b]
	% of nontreated
Ametryn	86 c
Atrazine	96 ab
Diuron	100 a
Fluometuron	77 d
Linuron	98 ab
Metribuzin	96 ab
Prometryn	89 c
Propazine	91 bc
Simazine	98 ab

[a]Height of corn in the nontreated plots averaged 36 cm.
[b]Means followed by the same letter are not significantly different according to Fisher protected LSD (P = 0.05).

was not affected, the corn likely was able to compensate for any yield component affected by the herbicides later in the growing season. Curran et al. (1991) found that corn treated PRE with clomazone, chlorimuron, imazaquin, and imazethapyr, although exhibiting injury up to 20%, did not suffer any yield loss. This reinforces that corn treated with PRE herbicides can compensate for early-season injury and still produce optimal yields.

Table 6. Significance of P values for interactions and main effects of PSII-inhibiting herbicide and herbicide added on various factors by year for POST herbicide study conducted at Fayetteville, Arkansas in 2017 and 2018.

		Injury[a,b]		Relative height	
Year	Factor	14 DAA	28 DAA	14 DAA	Relative yield
		P-value			
2017	PSII herbicide	<0.0001	<0.0001	0.0030	<0.0001
	Herbicide added	0.0001	0.0143	0.0030	0.0001
	PSII herbicide* Herbicide added	0.0072	0.0009	0.0051	0.0006
2018	PSII herbicide	<0.0001	0.8141	<0.0001	<0.0001
	Herbicide added	<0.0001	0.8262	<0.0001	<0.0001
	PSII herbicide* Herbicide added	<0.0001	0.6551	0.0003	<0.0001

[a]Abbreviation: DAA, days after application.
[b]Statistical significance set at $P < 0.05$.

POST Study

Rainfall

Given that corn was already 30-cm tall at application, the herbicides did not need to be activated to provide ideal performance. However, any herbicide that did reach the soil surface would have to be activated before providing residual activity. In 2017, 7.8 and 3.5 cm of rainfall were received 2 and 10 DAA, respectively (Figure 1). In 2018, rainfall events each totaling 1.5 cm were received 2 and 4 DAA (Figure 1).

Injury

In 2017 and 2018, corn injury 14 DAA was influenced by the interaction of PSII-inhibiting herbicide and herbicide added ($P = 0.0072$ for 2017; $P < 0.0001$ for 2018) (Table 6). Injury was in the form of leaf-tip chlorosis and necrosis with some bleaching of contacted leaves as well as new growth on plants to which mesotrione-containing treatments were applied. In 2017, linuron plus *S*-metolachlor caused the highest injury (45%) (Table 7). In general, linuron-containing treatments, along with diuron plus *S*-metolachlor and prometryn plus *S*-metolachlor, caused greater injury compared with most other treatments. The Linex (linuron) label (Tessenderlo Kerley, Inc., Phoenix, AZ) does not allow for over-the-top use of the herbicide in corn, because of injury concerns (Anonymous 2017). In 2018, prometryn alone and in combination with *S*-metolachlor caused 45% and 49% injury, respectively (Table 7). Ametryn plus *S*-metolachlor, linuron plus *S*-metolachlor, and prometryn plus mesotrione caused 38%, 38%, and 35% injury, respectively, all of which were comparable. Atrazine-, fluometuron-, metribuzin-, and simazine-containing treatments each caused no more than 15% injury in both years (Table 7).

Injury 28 DAA in 2017 was influenced by an interaction between PSII-inhibiting herbicide and herbicide added ($P = 0.0009$) (Table 6). Linuron plus *S*-metolachlor caused 29% injury in 2017 and was the most injurious treatment (Table 7). Diuron plus *S*-metolachlor, linuron plus mesotrione, and prometryn plus *S*-metolachlor were comparable and caused 17%, 18%, and 18% injury, respectively. No other treatment caused greater than 10% injury in 2017. In 2018, injury 28 DAA was less than 10% (data not shown) and was not affected by PSII-inhibiting herbicide, herbicide added, or the interaction (Table 6). Overall, injury

Table 7. Average visible estimates of corn injury and yield as influenced by interactions between PSII-inhibiting herbicide and herbicide added applied POST in Fayetteville, AR in 2017 and 2018.

PSII herbicide	Herbicide added	Injury[a,b] 14 DAA 2017	Injury 14 DAA 2018	Injury 28 DAA 2017	Relative yield[c] 2017	Relative yield 2018
		—%—			—% of nontreated—	
Ametryn	None	0 h	13 fg	6 cde	85 abcdef	83 defg
	mesotrione	4 gh	16 f	6 cde	81 bcdefg	78 fgh
	S-metolachlor	0 h	38 bc	5 cde	71 hij	81 efgh
Atrazine	none	4 d	4 i	6 cde	94 a	96 abc
	mesotrione	4 d	4 i	6 cde	89 abc	96 abc
	S-metolachlor	4 d	8 hi	6 cde	91 ab	99 ab
Diuron	None	10 def	4 i	9 cd	82 bcdefg	56 j
	Mesotrione	4 gh	14 fg	5 cde	84 abcdef	67 i
	S-metolachlor	22 b	29 de	17 b	73 ghij	66 i
Fluometuron	None	5 fg	15 f	3 e	66 j	56 j
	Mesotrione	8 efg	7 hij	9 cd	69 ij	93 abcd
	S-metolachlor	6 efgh	7 hij	8 cd	57 k	87 cdef
Linuron	None	21 bc	6 hij	9 cd	78 defghi	68 i
	Mesotrione	26 b	6 hij	18 b	80 cdefgh	73 hi
	S-metolachlor	45 a	38 bc	29 a	69 ij	82 defgh
Metribuzin	None	0 h	4 i	6 cde	89 abc	90 abcde
	Mesotrione	4 gh	6 hij	6 cde	77 fghi	96 abc
	S-metolachlor	8 efg	9 gh	5 cde	80 cdefgh	88 cdef
Prometryn	None	15 cd	45 ab	10 c	66 j	74 ghi
	Mesotrione	11 de	35 cd	7 cd	76 fghi	100 a
	S-metolachlor	29 bc	49 a	18 b	71 hij	95 abc
Propazine	None	0 h	14 fg	6 cde	87 abcde	58 j
	Mesotrione	0 h	5 hij	6 cde	67 j	72 hi
	S-metolachlor	0 h	25 e	6 cde	71 hij	43 k
Simazine	None	0 h	4 i	7 cd	87 abcde	88 cdef
	Mesotrione	0 h	4 i	4 de	77 efghi	89 abcdef
	S-metolachlor	0 h	7 hij	4 de	88 abcd	38 k

[a]Abbreviation: DAA, days after application.
[b]Means within a column followed by the same letter are not significantly different according to Fisher protected LSD (P = 0.05).
[c]Corn yield in 2017 and 2018 averaged 11,000 and 12,500 kg ha^{-1} in nontreated plots, respectively.

Table 8. Relative corn height as influenced by PSII-inhibiting herbicide applied POST in Fayetteville, AR in 2017 and 2018.

PSII herbicide	Herbicide added	Relative corn height[a,b,c] 14 DAA 2017	Relative corn height 14 DAA 2018
		—% of nontreated—	
Ametryn	None	92 abc	86 def
	Mesotrione	92 abc	86 def
	S-metolachlor	90 abcd	83 efg
Atrazine	None	96 ab	99 ab
	Mesotrione	96 ab	99 ab
	S-metolachlor	96 ab	98 abc
Diuron	None	93 abc	91 bcde
	Mesotrione	97 a	93 abcde
	S-metolachlor	77 gh	82 efg
Fluometuron	None	95 abcd	89 cdef
	Mesotrione	91 abcd	89 cdef
	S-metolachlor	90 abcd	96 abcd
Linuron	None	87 cdef	89 cdef
	Mesotrione	83 defg	88 def
	S-metolachlor	74 h	73 g
Metribuzin	None	89 abcde	100 a
	Mesotrione	90 abcd	97 abcde
	S-metolachlor	90 abcd	93 abcde
Prometryn	None	88 bcdef	79 fg
	Mesotrione	81 efg	83 efg
	S-metolachlor	80 fgh	73 g
Propazine	None	95 abc	93 abcde
	Mesotrione	93 abc	90 cdef
	S-metolachlor	94 abc	62 h
Simazine	None	90 abcd	90 cdef
	Mesotrione	92 abcd	83 ef
	S-metolachlor	95 abcd	92 abcde

[a]Abbreviation: DAA, days after application.
[b]Means within a column followed by the same letter are not significantly different according to Fisher protected LSD (P = 0.05).
[c]Height of corn in 2017 and 2018 in the nontreated plots averaged 52 and 46 cm, respectively.

was moderate among treatments in both years, excluding fluometuron-, metribuzin-, and simazine-containing treatments, which caused less than 15% injury (Table 7).

Relative Height

In 2017 and 2018, height 14 DAA was influenced by an interaction between PSII-inhibiting herbicide and herbicide added (P = 0.0051 for 2017; P = 0.0003 for 2018) (Table 6). Generally, height followed the trend of injury. For example, in 2017, linuron plus *S*-metolachlor resulted in the highest injury rate (45%), and corn height after this treatment was only 77% of that of nontreated plots (Tables 7 and 8). In 2017, plots with greater than 10% injury also had plant heights that were reduced compared with plants in nontreated plots. In 2018, the same was true, excluding plots treated with diuron plus mesotrione and plots treated with propazine alone (Tables 7 and 8). Overall, height 14 DAA generally followed the same trends as injury 14 DAA for a given year.

Relative Yield

In 2017 and 2018, relative yield was influenced by an interaction between PSII-inhibiting herbicide and herbicide added (P = 0.0006 for 2017; P < 0.0001 for 2018) (Table 6). Corn in plots treated with ametryn alone, ametryn plus mesotrione, diuron alone, diuron plus mesotrione, metribuzin alone, metribuzin plus *S*-metolachlor, propazine alone, simazine alone, and simazine plus *S*-metolachlor had yields comparable to atrazine-containing treatments in 2017 (Table 7). In 2018, corn in plots treated with fluometuron plus mesotrione and *S*-metolachlor, metribuzin alone, metribuzin plus mesotrione or *S*-metolachlor, prometryn plus mesotrione, prometryn plus *S*-metolachlor, and simazine plus mesotrione had yields comparable to corn that receiving atrazine-containing treatments.

These applications were made while the corn was 30-cm tall or at the V3 to V4 growth stage. During this time and subsequent weeks after application, yield components such as kernels row^{-1} and rows ear^{-1} were developing (Fageria et al. 2006; Uribelarrea et al. 2002). Corn hybrid 1197YHR contains a semiflex ear trait, meaning that it has the potential to set a small range of rows ear^{-1}. It is possible the chlorosis and stunting caused by certain herbicides affected the development of these yield components and, therefore, hindered yield in some treatments.

Practical Implications

Determining which herbicides should be tested further to potentially replace atrazine should be based on a combination of visible injury, crop height, and yield. Efforts should be made to avoid herbicides that injure corn beyond a reasonable level, even if yield is not affected, because injury may translate into delayed maturity or increased potential for disease and pest pressure. Therefore, even though yield was not affected for any PRE-applied herbicide, certain ametryn- and fluometuron-containing treatments caused greater than 10% injury and, therefore, no longer should be considered as an atrazine replacement in corn, because safer options were identified.

Although not directly measured, it is possible that herbicides that injured corn or reduced height could delay canopy closure. Any delay in canopy closure would negatively affect weed control (Anderson 2008). Given the negative effects of reduced crop height, prometryn- and propazine-containing treatments should also be eliminated from additional testing. Corn tolerance to diuron-, linuron-, metribuzin-, and simazine-containing treatments applied PRE should be further tested to validate the tolerance observed in this study. Furthermore, weed control trials should also be conducted for these herbicides and herbicide combinations to ensure adequate replacement of atrazine.

The same factors should be considered for POST application of these herbicides. On the basis of crop injury, relative crop height, and relative yield in 2017 and 2018, only metribuzin- and simazine-containing treatments should be further assessed for crop tolerance and weed control when applied POST. Efforts should be made to evaluate these herbicides over as many diverse environments as possible.

Acknowledgements. The authors would like to thank the Arkansas Corn and Grain Sorghum Board for funding this study, and the University of Arkansas System Division of Agriculture for their support. No conflicts of interest have been declared.

References

Abendroth JA, Martin AR, Roeth FW (2006) Plant response to combinations of mesotrione and photosystem II inhibitors. Weed Technol 20:267–274

Anderson, RL (2008) Weed seedling emergence and survival as affected by crop canopy. Weed Technol 22:736–740

Anonymous (2017) Linex 4L herbicide product label. EPA Reg. No. 61842-21. Phoenix, AZ: Tessenderlo Kerley, Inc. 14 p

Aro E-M, Virgin I, Andersson B (1993) Photoinhibition of photosystem II. Inactivation, protein damage and turnover. Biochim Biophys Acta 1143: 113–134

Barbash JE, Thelin GP, Kolpin DW, Gilliom RJ (2006) Major herbicides in groundwater: results from the national water-quality assessment. J Environ Qual 30:831–845

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Culpepper AS, York AC (1999) Weed management in glufosinate-resistant corn (*Zea mays*). Weed Technol 13:324–333

Curran WS (2001) Persistence of herbicides in soil. Penn State Extension. https://extension.psu.edu/persistence-of-herbicides-in-soil. Accessed: December 19, 2019

Curran WS, Knake EL, Liebl RA (1991) Corn (*Zea mays*) injury following use of clomazone, chlorimuron, imazaquin, and imazethapyr. Weed Technol 5:539–544

Espinoza L, Ross J, eds. (2015) Corn production handbook. Handbook MP 437. Little Rock, AR: University of Arkansas Cooperative Extension Service. 97 p

Fageria N, Baligar V, Clark R (2006) Physiology of crop production. 1st edn. Boca Raton, FL: CRC Press. 356 p

Fan X, Song F (2014) Bioremediation of atrazine: recent advances and promises. J Soil Sediment 14:1727–1737

Frans RE, Talbert RE (1977) Design of field experiments and the measurement and analysis of plant responses. Pages 15–23 *in* Truelove B, ed. Research Methods in Weed Science. Auburn, TX: Southern Weed Science Society

Gbur EE, Stroup WW, McCarter KS, Durham S, Young LJ, Christman M, West M, Kramer M (2012) Analysis of Generalized Linear Mixed Models in the Agricultural and Natural Resources Sciences. Madison, WI: American Society of Agronomy, Soil Science Society of America, Crop Science Society of America. 298 p

Greir PW, Stahlman PW (1999) EXP 31130A efficacy and corn (*Zea mays*) response in western Kansas. Weed Technol 13:404–410

Grichar WJ, Besler BA, Brewer KD, Minton BW (2004) Using soil-applied herbicides in combination with glyphosate in a glyphosate-resistant cotton herbicide program. Crop Prot 23:1007–1010

Hartzler B (2002) Absorption of soil-applied herbicides. Iowa State University Extension and Outreach. https://crops.extension.iastate.edu/encyclopedia/absorption-soil-applied-herbicides. Accessed: December 19, 2019

Kramer W, Schirmer U, eds (2007) Modern Crop Protection Compounds. 1st edn. Berscheid, Germany: Wiley-VCH. Pp 365–368

Krausz RF, Kapusta G (1998) Preemergence weed control in imidazolinone-resistant corn (*Zea mays*). Weed Technol 12:151–156

Lasserre JP, Fack F, Revets D, Planchon S, Renaut J, Hoffmann L, Gutleb AC, Muller CP, Bohn T. (2009) Effects of the endocrine disruptor atrazine and PCB 153 on the protein expression of MCF-7 human cells. J Proteome Res 12:5485–5496

Milander JJ (2015) Maize yield and components as influenced by environment and agronomic management. M.S. thesis. Lincoln, NE: University of Nebraska. 107 p

Mudhoo A, Garg VK (2011) Sorption, transport and transformation of atrazine in soils, minerals and composts: a review. Pedosphere 21:11–25

Moran GR (2005) 4-Hydroxyphenylpyruvate dioxygenase. Arch Biochem Biophys 433:117–128

[NASS] National Agricultural Statistics Service (2018) Quick stats. https://quickstats.nass.usda.gov/results/B5436325-CBF1-39FD-AF99-1B80503D598E. Accessed: October 8, 2018

Neuberger JS (1996) Atrazine and/or triazine herbicides exposure and cancer: an epidemiologic review. J Agromedicine 3:9–30

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60(Special Issue I):31–62

Odukkathil G, Vasudevan N (2013) Toxicity and bioremediation of pesticides in agricultural soil. Rev Environ Sci Bio/Technol 12:421–444

Rao VS (2000) Formulation. Principles of Weed Science. Second edn. Enfield, NH: Science Publishers Inc. 384 p

Richie SW, Hanway JJ, Benson GO (1986) How a corn plant develops. Spec Rep 48. Ames, IA: Iowa State University Cooperative Extension Service

Shaner D (2014) Herbicide handbook. 10th edn. Champaign, IL: Weed Science Society of America. 513 p

Singh S, Kumar V, Chauhan A, Datta S, Wani A, Singh N, Singh J (2018) Toxicity, degradation and analysis of the herbicide atrazine. Environ Chem Lett 16:211–237

Solomon KR, Baker DB, Richards RP, Dixon KR, Klaine SJ, La Point TW, Kendall RJ, Weisskopf CP, Giddings JM, Giesy JP (1996) Ecological risk assessment of atrazine in North America. Environ Toxic Chem 15:31–76

Sprague CL, Kells JJ, Penner D (1999) Weed control and corn tolerance from soil-applied RPA 201772. Weed Technol 13:713–725

Smith K, Scott RC (2017) Weed control in corn. Pages 47–49 *in* Espinoza L, Kelley J, eds. Corn Production Handbook. Little Rock, AR: Cooperative Extension Service, University of Arkansas

Sutton P, Richards C, Buren L, Glasgow L (2002) Activity of mesotrione on resistant weeds in maize. Pest Manag Sci 58:981–984

Taylor-Lovell S, Wax LM (2001) Weed control in field corn (*Zea mays*) with RPA 201772 combinations with atrazine and *S*-metolachlor. Weed Technol 15:249–256

Uribelarrea M, Cárcova J, Otegui ME, Westgate ME (2002) Pollen production, pollination dynamics, and kernel set in maize. Crop Sci 42:1910–1918

Webster TM, Cardina J, Loux MM (1998) The influence of weed management in wheat (*Triticum aestivum*) stubble on weed control in corn (*Zea mays*). Weed Technol 12:522–526

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145–157