Received: 13 May 2021 | Accepted: 9 August 2021

DOI: 10.1002/cft2.20128

Crop, Forage & Turfgrass Management

CROP MANAGEMENT

Evaluation of corn herbicide programs with and without atrazine

Jason K. Norsworthy[1] | **Jacob Richburg**[1] | **Tom Barber**[1] | **Trenton Roberts**[1] | **Edward Gbur**[2]

[1] Dep. of Crop, Soil, and Environmental Sciences, Univ. of Arkansas, Fayetteville, AR 72704, USA

[2] Agricultural Statistics, Univ. of Arkansas, Fayetteville, AR 72701, USA

Correspondence
Jason K. Norsworthy, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR 72704, USA.
Email: jnorswor@uark.edu

Assigned to Associate Editor Matthew Inman

Abstract

Atrazine is a foundational herbicide in corn (*Zea mays* L.) because of its broad-spectrum weed control and utility for pre-emergence or postemergence applications. Extensive atrazine use has led to traces in groundwater, surface water, and aquifers. This research explored corn herbicide regimes with little or no atrazine. Pre-emergence herbicide treatments [*S*-metolachlor (0.955 lb acre^{-1}); saflufenacil (0.054 oz acre^{-1}) plus dimethenamid-P (0.473 lb acre^{-1})] and postemergence herbicide mixtures [bicyclopyrone (0.040 lb acre^{-1}) plus mesotrione (0.161 lb acre^{-1}) plus *S*-metolachlor (1.429 lb acre^{-1}); thiencarbazone-methyl (0.013 lb acre^{-1}) plus tembotrione (0.067 lb acre^{-1}), thiencarbazone-methyl (0.033 lb acre^{-1}) plus isoxaflutole (0.082 lb acre^{-1}); acetochlor (0.964 lb acre^{-1}) plus mesotrione (0.103 lb acre^{-1}) plus clopyralid (0.065 lb acre^{-1})] were applied alone or combined with atrazine at 0.50 lb acre^{-1} to glyphosate- or glufosinate-resistant corn. All postemergence applications contained glyphosate (1.125 lb acre^{-1}) plus glufosinate (0.402 lb acre^{-1}). Palmer amaranth [*Amaranthus palmeri* (S.) Watson], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) Nash], and pitted morningglory (*Ipomoea lacunosa* L.) control were always greater than 95%. Saflufenacil plus dimethenamid-P injured corn 8 and 5% more than *S*-metolachlor 21 d after pre-emergence application. Averaged over pre-emergence herbicide and atrazine rate, thiencarbazone-methyl plus isoxaflutole injured corn by 21% in 2017. The addition of atrazine did not improve corn yield in 7 of 16 instances. According to this research, the weeds assessed at these densities can be controlled without atrazine by some programs.

1 | INTRODUCTION

Corn (*Zea mays* L.) is one of the most commonly grown grain crops in the United States. The uses of this crop include animal feed, human consumption, and renewable energy (Berenji & Dahlberg, 2004). In 2017, corn grain production added $48.4 billion to the US economy (NASS, 2018). Given the importance of this crop, high yields are essential and weed control is vital.

Weed management in corn varies greatly depending on the geographical crop production region in the United States. Webster and Nichols (2012) found that the weeds most frequently affecting corn in the southern United States include morningglories (*Ipomoea* spp.), Texas millet [*Urochloa texana* (Buckley) S.T. Blake], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) Nash], johnsongrass [*Sorghum halepense* (L.) Pers.], sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby], nutsedges (*Cyperus* spp.), and Palmer amaranth [*Amaranthus palmeri* (S.) Watson]. The

Abbreviations: SOA, site of action.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2021 The Authors. *Crop, Forage & Turfgrass Management* published by Wiley Periodicals LLC on behalf of American Society of Agronomy and Crop Science Society of America

most troublesome weed is Palmer amaranth because if left uncontrolled for as little as 4 wk, just one plant per 3.3 ft of row may reduce corn yields by up to 4% (Smith & Scott, 2017). Palmer amaranth can also grow up to 6.6 ft tall in less than 40 d in some environments (Bensch et al., 2003), meaning that late-season infestations may interfere with crop harvest. Given the problems that weeds can cause at any point during the growing season, control should be season-long.

Time, labor cost, and convenience are all reasons why growers have adopted herbicides as the main tool for weed control in corn (Armstrong et al., 1968; Mt Pleasant et al., 1994). However, there are precautions that should be taken to reduce the risk of weeds evolving resistance. A key cause of herbicide resistance evolution is the reliance of growers on one site of action (SOA) (Norsworthy et al., 2012). Although many factors may contribute, research has shown that glyphosate [2-(phosphonomethylamino)acetic acid]-resistant horseweed [*Conyza canadensis* (L.) Cronq.], common ragweed (*Ambrosia artemisiifolia* L.), and pigweeds (*Amaranthus* ssp.) evolved resistance to glyphosate from consecutive applications over a 3- to 6-yr period (Culpepper et al., 2006; Legleiter & Bradley, 2008; VanGessel, 2001). From these findings, it is apparent that multiple SOAs should be applied to effectively control weeds and mitigate the potential evolution of herbicide resistance.

One way that the crop protection industry has promoted the use of multiple SOAs is through premixtures. An example of a premixture is Acuron Flexi (Syngenta Crop Protection), which contains bicyclopyrone [(1*R*,5*S*)-3-(hydroxy-[2-(2-methoxyethoxymethyl)-6-(trifluoromethyl)pyridin-3-yl]methylidene)bicyclo(3.2.1)octane-2,4-dione] (Weed Science Society of America Group 27), mesotrione [2-(4-methylsulfonyl-2-nitrobenzoyl)cyclohexane-1,3-dione] (Weed Science Society of America Group 27), and *S*-metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-([2S]-1-methoxypropan-2-yl)acetamide] (Weed Science Society of America Group 15). This premixture can be applied pre-emergence or postemergence to corn, combines two SOAs, and provides foliar and residual control of many broadleaf and grass weeds (Syngenta, 2016). By providing more than one effective SOA, some selection pressure is alleviated for a specific herbicide, thus slowing target-site resistance evolution (Norsworthy et al., 2012).

Another reason why growers should use multiple herbicides is to reduce the chances of contaminating the environment by overusing one specific herbicide. For example, the heavy reliance of farmers on atrazine (6-chloro-4-*N*-ethyl-2-*N*-propan-2-yl-1,3,5-triazine-2,4-diamine) for weed control in corn is probably why atrazine is the most frequently found groundwater contaminant near land used for agricultural purposes (Barbash et al., 2006). Because atrazine is a prevalent groundwater contaminant, care should be taken to reduce the use of this herbicide where possible. Hence, research was initiated to explore weed control programs with a reduced rate of atrazine or entirely without it.

Core Ideas

- Weed control programs with and without postemergence atrazine were examined.
- Corn exhibited adequate tolerance to the herbicide programs evaluated.
- Effective herbicide programs were identified in the absence of atrazine.
- Several herbicide programs without atrazine allowed corn yields comparable with its use.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

In both 2017 and 2018, all field experiments were conducted on a Leaf silt loam (fine, mixed, active, thermic Typic Albaqualts) at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. The soil consisted of 34% sand, 53% silt, and 13% clay, with an organic matter content of 1.5% and a pH of 6.8.

2.2 | Study setup and data collection

All experiments used the corn hybrid 1197YHR (Pioneer, 7000 NW 62nd Ave, Johnston, IA 50131), which is resistant to glyphosate and glufosinate [2-amino-4-(hydroxy[methyl]phosphoryl)butanoic acid], planted at 32,000 seeds acre^{-1} at a 2-inch depth into conventionally tilled raised beds. Plot size was 12 ft wide by 20 ft long, and the rows were spaced 3 ft apart. All trials were furrow irrigated and otherwise managed according to the Arkansas Corn Production Handbook (Espinosa & Ross, 2018). This study was designed as a randomized complete block consisting of three factors. The three factors were (a) pre-emergence herbicide [*S*-metolachlor at 0.955 lb acre^{-1} or saflufenacil (2-chloro-4-fluoro-5-[3-methyl-2,6-dioxo-4-(trifluoromethyl)pyrimidin-1-yl]-*N*-[methyl(propan-2-yl)sulfamoyl]benzamide) at 0.054 lb acre^{-1} plus dimethenamid-P (2-chloro-*N*-[2,4-dimethylthiophen-3-yl]-*N*-[(2S)-1-methoxypropan-2-yl]acetamide) at 0.473 lb acre^{-1}], (b) herbicide premixtures applied postemergence [bicyclopyrone ([1*R*,5*S*]-3-[hydroxy-(2-[2-methoxyethoxymethyl]-6-[trifluoromethyl]pyridin-3-yl)methylidene]bicyclo[3.2.1]octane-2,4-dione) at 0.040 lb acre^{-1} plus mesotrione (2-[4-methylsulfonyl-2-nitrobenzoyl]cyclohexane-1,3-dione)

TABLE 1 List of corn herbicides, the rates used in herbicide treatments, and the manufacturers

Trade name	Common name	Rate	Timing[a]	Manufacturer
		lb a.i. or acid equivalents acre^{-1}		
Dual II Magnum	*S*-metolachlor	0.955	PRE	Syngenta Crop Protection
Verdict	Saflufenacil + dimethenamid	0.054 + 0.473	PRE	BASF Crop Protection
Acuron Flexi	Bicyclopyrone + mesotrione + *S*-metolachlor	0.040 + 0.161 + 1.429	POST	Syngenta Crop Protection
Capreno	Thiencarbazone-methyl + tembotrione	0.013 + 0.067	POST	Bayer CropScience
Corvus	Thiencarbazone-methyl + isoxaflutole	0.033 + 0.082	POST	Bayer CropScience
Resicore	Acetochlor + mesotrione + clopyralid	0.964 + 0.103 + 0.065	POST	Dow AgroSciences
Roundup PowerMax II	Glyphosate	1.125	POST	Bayer CropScience
Liberty	Glufosinate	0.401	POST	BASF Crop Protection
Aatrex	Atrazine	0.5	POST	Syngenta Crop Protection

[a]PRE, pre-emergence; POST, postemergence.

at 0.161 lb acre^{-1} plus *S*-metolachlor at 1.429 lb acre^{-1}; thiencarbazone-methyl (methyl 4-[(3-methoxy-4-methyl-5-oxo-1,2,4-triazole-1-carbonyl)sulfamoyl]-5-methylthiophene-3-carboxylate) at 0.013 lb acre^{-1} plus tembotrione (2-[2-chloro-4-methylsulfonyl-3-(2,2,2-trifluoroethoxymethyl) benzoyl]cyclohexane-1,3-dione) at 0.067 lb acre^{-1}; thiencarbazone-methyl at 0.033 lb acre^{-1} plus isoxafluotole ([5-cyclopropyl-1,2-oxazol-4-yl]-[2-methylsulfonyl-4-(trifluoromethyl)phenyl]methanone) at 0.082 lb acre^{-1}; or acetochlor (2-chloro-*N*-[ethoxymethyl]-*N*-[2-ethyl-6-methylphenyl]acetamide) at 0.964 lb acre^{-1} plus mesotrione at 0.103 lb acre^{-1} plus clopyralid (3,6-dichloropyridine-2-carboxylic acid) at 0.065 lb acre^{-1}], and (c) the rate of atrazine (0 or 0.5 lb acre^{-1}) applied with the premixture (Table 1). Overall, the study consisted of 16 herbicide treatments and a nontreated control, each replicated four times. Treatments were intended to represent herbicide programs that growers use in Arkansas for corn production, either with or without atrazine; therefore, all postemergence herbicides were applied with glyphosate at 1.125 lb acid equivalent acre^{-1} plus glufosinate at 0.401 lb acre^{-1} because the latter two herbicides are almost always applied to corn. Pre-emergence applications were made immediately following planting on 26 May 2017 and 20 Apr. 2018 onto a clean weed-free raised bed achieved through preplanting tillage, whereas the postemergence application for each treatment was made when the corn was 12 inches tall on 16 June 2017 and 20 May 2018. In 2017 and 2018, 1- to 2.5-inch tall Palmer amaranth at the postemergence application timing had a density of 0.4 and 0.5 plants ft^{-2}, respectively; 0.4- to 2-inch tall broadleaf signalgrass averaged 16 and 25 plants ft^{-2}, respectively; and 0.8- to 1.6-inch tall pitted morningglory (*Ipomoea lacunosa* L.) averaged 2 and 3 plants ft^{-2}, respectively. All applications were made with a CO_2-pressurized backpack sprayer (R&D Sprayers) at 15 gal acre^{-1}. Visual estimates of corn injury and weed control were taken 21 d after the pre-emergence application and 14 d after the postemergence application. Visible estimates of control were evaluated relative to the nontreated control on a 0 to 100% scale, with 0 being no control and 100% being complete control (Frans & Talbert, 1977). Corn injury was rated on a 0 to 100% scale, with 0 representing no crop injury and 100% indicating plant death. The middle two rows of each plot were harvested at maturity with a small-plot combine (Almaco), and yield was adjusted to 15.5% moisture.

2.3 | Statistical analysis

Data were analyzed by year because of environmental differences each year caused by the different planting dates. Weed control ratings for any weed were never below 95% at any time during the growing season; therefore, these data were not formally analyzed. Visible injury and yield data were subjected to an ANOVA via the GLIMMIX procedure in SAS Version 9.4 statistical software (SAS Institute Inc.), assuming a β distribution for corn injury ratings and a γ distribution for yield, to see if pre-emergence herbicide, herbicide premixtures, atrazine, or their interactions had an effect (Gbur et al., 2012). Given that pre-emergence herbicide was the only factor that could affect the corn at the 21 d after the pre-emergence application, this analysis was conducted as a randomized complete block with pre-emergence herbicide as the only factor. Means for all analyses were separated by Fisher's protected LSD ($\alpha = .05$) where appropriate.

3 | RESULTS AND DISCUSSION

3.1 | Pre-emergence weed control

The two pre-emergence herbicides were activated by rainfall (Figure 1) and provided exceptional control (>95%) of

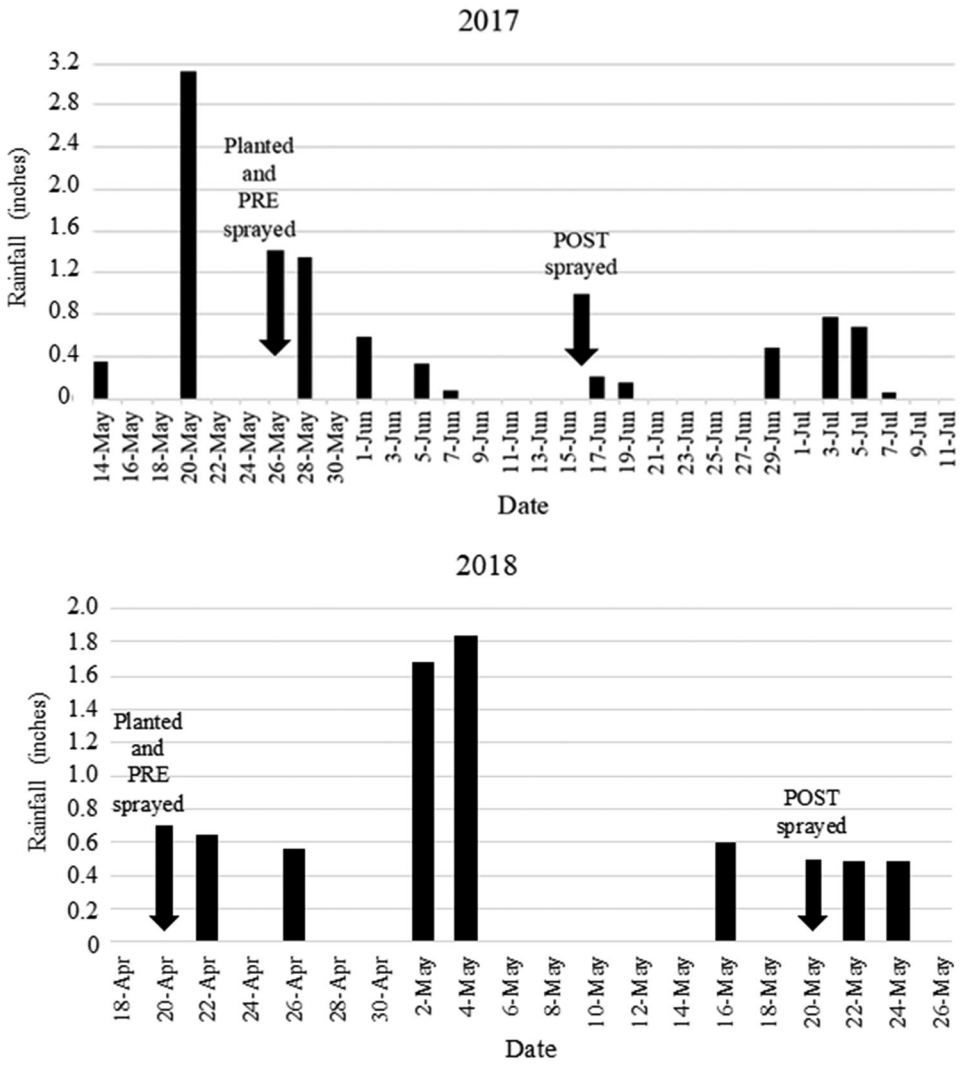


FIGURE 1 Rainfall amounts by day, indicating planting and application dates, at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, in 2017 and 2018

Palmer amaranth and broadleaf signalgrass (data not shown). As supported by other research findings, *S*-metolachlor has the ability to control small-seeded dicotyledon and monocotyledon weeds, such as the ones present in this trial (Chomas & Kells, 2004; Myers & Harvey, 1993). Liebl et al. (2008) showed that saflufenacil controls broadleaf weeds, such as redroot pigweed (*Amaranthus retroflexus* L.) and waterhemp (*Amaranthus rudis* J.D.Sauer), as well as numerous other broadleaf weeds, when applied before emergence. Therefore, when saflufenacil was applied in combination with dimethenamid-P, weed control spectrum and efficacy were increased (Moran et al., 2011). This study showed the utility of both *S*-metolachlor and saflufenacil plus dimethenamid-P as pre-emergence control options to complement or supplement current pre-emergence herbicides in corn.

3.2 | Postemergence weed control

Postemergence weed control did not fall below 95% for any treatment at 14 d after the postemergence application (data not shown). Various premixes and herbicides have been included in different treatments to provide additional foliar activity on broadleaf and grass weeds; however, most of these premixes and herbicides also provide residual control. Thiencarbazone-methyl plus isoxaflutole has been shown to control >90% of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], entireleaf morningglory (*Ipomoea hederacea* Jacq.), and Palmer amaranth for 4 wk after application (Stephenson & Bond, 2012). Likewise, Currie and Geier (2015) noted the longevity of control and efficacy (7 weeks after treatment and > 90%, respectively) of a premix of thiencarbazone-methyl plus tembotrione when applied after emergence in combination with

TABLE 2 Significance of *P*-values for the interactions and main effects of pre-emergence (PRE) herbicide, postemergence (POST) premixture herbicides, and atrazine on corn injury at 14 d after the postemergence application and grain yield × year for corn trials conducted in Fayetteville, AR, in 2017 and 2018

Year	Factor	Injury	Grain yield
		————*P*-value————	
2017	PRE	.0386*	.0011*
	POST	<.0001*	<.0001*
	Atrazine	.5467	<.0001*
	PRE × POST	.1195	.0014*
	PRE × atrazine	.7326	<.0001*
	POST × atrazine	.2785	<.0001*
	PRE × POST × atrazine	.8323	<.0001*
2018	PRE	.0054*	.0448*
	POST	.0003*	<.0001*
	Atrazine	.7094	.2255
	PRE × POST	.0001*	<.0001*
	PRE × atrazine	.3849	<.0001*
	POST × atrazine	.9838	.0029*
	PRE × POST × atrazine	.7771	.0002*

*Significant at the .05 probability level.

TABLE 3 Influence of pre-emergence herbicide (PRE) and the postemergence premixture (POST) on corn injury 14 d after postemergence application in Fayetteville, AR, in 2017 and 2018

Year	Factor	Injury[a] %
2017	PRE[b]	
	Saflufenacil plus dimethenamid-P	9a
	S-metolachlor	6b
	POST	
	Bicyclopyrone plus mesotrione plus *S*-metolachlor	3b
	Thiencarbazone-methyl plus tembotrione	2b
	Thiencarbazone-methyl plus isoxaflutole	21a
	Acetochlor plus mesotrione plus clopyralid	3b
2018	PRE × POST	
	Saflufenacil plus dimethenamid-P	
	Bicyclopyrone plus mesotrione plus *S*-metolachlor	0b
	Thiencarbazone-methyl plus tembotrione	2b
	Thiencarbazone-methyl plus isoxaflutole	3b
	Acetochlor plus mesotrione plus clopyralid	1b
	S-metolachlor	
	Bicyclopyrone plus mesotrione plus *S*-metolachlor	1b
	Thiencarbazone-methyl plus tembotrione	4b
	Thiencarbazone-methyl plus isoxaflutole	11a
	Acetochlor plus mesotrione plus clopyralid	3b

[a]Means within a factor and year followed by the same letter are not significantly different according to Fisher's protected LSD ($P = .05$).
[b]PRE data were averaged over POST and atrazine in 2017; POST data were averaged over PRE and atrazine in 2017.

glyphosate and/or atrazine. The residual control of these herbicides is important to minimize weed competition until canopy formation to lessen weed emergence (Gonzini et al., 1999). Although atrazine is the typical residual herbicide used for in-season weed control in corn, these results indicate that alternative herbicides can provide weed control comparable with atrazine-based weed control programs.

The introduction of glufosinate-resistant corn has been instrumental in the control of glyphosate-resistant weeds. Glufosinate is a nonselective herbicide that controls most annual broadleaf weeds (Van Wychen et al., 1999); however, it does have some limitations in successfully controlling grass species (Hamill et al., 2000). The inclusion of glyphosate in this trial probably eliminated grass weeds in all treatments, as seen in other research (Shaw & Arnold, 2002). The excellent control shown by the herbicides in this study demonstrates that effective options exist for weed control in the absence of atrazine.

3.3 | Pre-emergence crop injury

Corn injury at 21 d after the pre-emergence application was influenced by the pre-emergence herbicide applied ($P < .0001$) in both years. Applications of saflufenacil plus dimethenamid-P injured corn by 13% and 8% in 2017 and 2018, respectively, which was more than the injury from *S*-metolachlor (data not shown). Similarly, Sarangi and Jhala (2018) found that pre-emergence applications of saflufenacil plus dimethenamid-P injured corn by 15% when integrated into a reduced tillage system on a silt–loam soil that was similar to the soil in this experiment.

3.4 | Postemergence crop injury

In 2018, corn injury was influenced by an interaction between the pre-emergence herbicide and the postemergence premixture ($P = .0001$) (Table 2). However, in 2017, corn injury was not affected by an interaction between pre-emergence herbicide and the postemergence premixture; therefore, the data are presented separately by factor (Table 2, Table 3).

In 2017, averaged over the premixtures and atrazine, corn that received pre-emergence saflufenacil plus dimethenamid-P was injured more than corn that received pre-emergence *S*-metolachlor (Table 4). Given the higher injury that pre-emergence saflufenacil plus dimethenamid-P caused, corn may not have been able to recover in a timely manner. Injury appeared as phytotoxicity and mild chlorosis.

TABLE 4 Influence of pre-emergence herbicide (PRE) and postemergence premixtures (POST) on corn yield in Fayetteville, AR, in 2017 and 2018

Factors		Yield[b,c]	
		2017	2018
PRE × POST	Atrazine[a]	lb acre^{-1}	
S-metolachlor			
Bicyclopyrone plus mesotrione plus *S*-metolachlor	–	12,000a	15,490a
	+	10,960b	14,620ab
Thiencarbazone-methyl plus tembotrione	–	8,650d	11,240def
	+	10,540bc	12,850cde
Thiencarbazone-methyl plus isoxaflutole	–	8,660d	12,110def
	+	10,570bc	13,830bc
Acetochlor plus mesotrione plus clopyralid	–	8,570d	12,760cde
	+	10,390bc	12,620de
Saflufenacil plus dimethenamid-P			
Bicyclopyrone plus mesotrione plus *S*-metolachlor	–	12,130a	15,610a
	+	13,120a	13,130cde
Thiencarbazone-methyl plus tembotrione	–	11,020b	13,310bcd
	+	10,130c	12,625de
Thiencarbazone-methyl plus isoxaflutole	–	9,960c	12,190def
	+	8,510d	9,960g
Acetochlor plus mesotrione plus clopyralid	–	8,880d	12,290de
	+	11,010b	13,260cd

[a]+, with atrazine; –, without atrazine. Atrazine was applied at 0.5 lb acre^{-1}.
[b]The average yield of nontreated plots was 5,950 and 6,060 lb acre^{-1} in 2017 and 2018, respectively.
[c]Means within a factor followed by the same letter are not significantly different within a year according to Fisher's protected LSD ($p = .05$).

Averaged over pre-emergence herbicides and atrazine rate, thiencarbazone-methyl plus isoxaflutole injured corn by 21% in 2017 (Table 3). In 2018, treatments with pre-emergence *S*-metolachlor followed by thiencarbazone-methyl plus isoxaflutole caused 11% injury, which was higher than injury by the other treatments in 2018. In general, treatments containing thiencarbazone-methyl plus isoxaflutole were more injurious to corn 14 d after the postemergence application. Similar to these findings, Vollmer et al. (2017) found that thiencarbazone-methyl plus isoxaflutole injured corn by 13% at 21 d after application when applied before emergence; therefore, when this herbicide is applied after emergence, injury is logical.

3.5 | Grain yield

In 2017 and 2018, corn yield was influenced by a three-way interaction among pre-emergence herbicide, the postemergence premixture, and atrazine ($P < .0001$, 2017; $P = .0002$, 2018) (Table 2). In 2017, corn in treatments containing the premixture of bicyclopyrone plus mesotrione plus *S*-metolachlor yielded the most, except when following pre-emergence *S*-metolachlor combined with postemergence atrazine (Table 4). In 2018, corn in treatments containing the premixture of bicyclopyrone plus mesotrione plus *S*-metolachlor yielded the most, except when following pre-emergence saflufenacil plus dimethenamid-P combined with postemergence atrazine (Table 4). In 2018, corn in treatments that received pre-emergence saflufenacil plus dimethenamid followed by thiencarbazone-methyl plus isoxaflutole with postemergence atrazine had lower yield than all other treatments (Table 4). Averaged over atrazine, corn injury for this treatment was also higher than injury from other treatments in 2018. If we consider both years combined, atrazine at 0.5 lb acre^{-1} reduced yield in 5 of 16 instances, increased yield in 4 of 16 instances, and did not affect yield in 7 of 16 instances. Since atrazine is proven to be very safe for application in corn (Shimabukuro, 1968), something other than atrazine must have affected the plants. Fageria et al. (2006) suggested that corn yield components are developed at different times throughout the growing season. At the V3 to V5 growth stage of corn, the number of ears and number of kernels per ear are usually determined (Uribelarrea et al., 2002). Perhaps light chlorosis from the postemergence herbicide application triggered stress and hindered the corn in certain plots from setting a kernel count comparable with that in other corn plots. An overall trend by year was difficult to

establish, and more research is needed to accurately assess the yield effects that were noted in this study.

3.6 | Practical implications

The weed densities present in these trials were lower than those observed in other research (Chomas & Kells, 2004). These densities in combination with the timely application, led to a high level of weed control in both years. The intent of this study was not to show that atrazine is not necessary for effective weed control, but to highlight that it can be applied at low rates when complemented by or occasionally supplemented with other labeled herbicides to lessen the likelihood of resistance evolution and environmental contamination.

Although all the pre-emergence and postemergence herbicides used are recommended in corn and were applied at the labeled rates, some of the herbicides contained in the premixtures have been shown to cause injury in certain hybrids in different environments (Simmons & Kells, 2003). Given the results from this study, in a similar environment, with similar weed pressure, atrazine may not be needed to control certain weeds; however, these full-season programs, as well as other full-season programs, should be tested further before recommendations are made that are applicable to other regions or environments.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

Jason K. Norsworthy: conceptualization, funding acquisition, investigation, methodology, project administration, writing—review and editing. Jacob Richburg: formal analysis, writing—original draft, writing—review and editing. Tom Barber: resources, writing—review and editing. Trenton Roberts: writing—review and editing. Edward Gbur: formal analysis; writing—review and editing.

ORCID

Jason K. Norsworthy https://orcid.org/0000-0002-7379-6201

Trenton Roberts https://orcid.org/0000-0001-5558-7257

REFERENCES

Armstrong, D. L., Leasure, J. K., & Corbin, M. R. (1968). Economic comparison of mechanical and chemical weed control. *Weed Science*, *16*, 369–371. https://doi.org/10.1017/S0043174500047408

Barbash, J. E., Thelin, G. P., Kolpin, D. W., & Gilliom, R. J. (2006). Major herbicides in groundwater: Results from the national water-quality assessment. *Journal of Environmental Quality*, *30*, 831–845 https://doi.org/10.2134/jeq2001.303831x

Bensch, C. N., Horak, M. J., & Peterson, D. (2003). Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. *Weed Science*, *51*, 37–43. https://doi.org/10.1614/0043-1745(2003)051%5b0037:IORPAR%5d2.0.CO;2

Berenji, J., & Dahlberg, J. (2004). Perspectives of sorghum in Europe. *Journal of Agronomy and Crop Science*, *1905*, 332–338. https://doi.org/10.1111/j.1439-037X.2004.00102.x

Chomas, A. J., & Kells, J. J. (2004). Triazine-resistant common lambsquarters (*Chenopodium album*) control in corn with preemergence herbicides. *Weed Technology*, *18*, 551–554. https://doi.org/10.1614/WT-03-077R

Culpepper, A. S., Grey, T. L., Vencill, W. K., Kichler, J. M., Webster, T. M., Brown, S. M., York, A. C., Davis, J. W., & Hanna, W. W. (2006). Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. *Weed Science*, *54*, 620–626. https://doi.org/10.1614/WS-06-001R.1

Currie, R., & Geier, P. (2015). Weed control in irrigated corn with combinations of Corvus, Balance Flexx, Capreno, Laudis, Harness, Atrazine, Glyphosate, Dual, and Diflexx. *Kansas Agricultural Experiment Station Research Reports*, *1*(5). https://doi.org/10.4148/2378-5977.1079

Espinoza, L., & Ross, J. (2018). *Corn production handbook*. The Arkansas Cooperative Extension Service Publication.

Fageria, N., Baligar, V., & Clark, R. (2006). *Physiology of crop production*. CRC Press. https://doi.org/10.1201/9781482277807

Frans, R. E., & Talbert, R. E., (1977). Design of field experiments and the measurement and analysis of plant responses. In B. Truelove (Ed.), *Research methods in weed science* (pp. 15–23). Southern Weed Science Society.

Gbur, E. E., Stroup, W. W., McCarter, K. S., Durham, S., Young, L. J., Christman, M., West, M., & Kramer, M., (2012). *Analysis of generalized linear mixed models in the agricultural and natural resources sciences*. American Society of Agronomy, Soil Science Society of America, Crop Science Society of America.

Gonzini, L. C., Hart, S. E., & Wax, L. M. (1999). Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). *Weed Technology*, *13*, 354–360. https://doi.org/10.1017/S0890037X00041853

Hamill, A. S., Knezevic, S. Z., Chandler, K., Sikkema, P. H., Tardif, F. J., Shrestha, A., & Swanton, C. J. (2000). Weed control in glufosinate-resistant corn (*Zea mays*). *Weed Technology*, *14*, 578–585. https://doi.org/10.1614/0890-037X(2000)014%5b0578:WCIGRC%5d2.0.CO;2

Legleiter, T. R., & Bradley, K. W. (2008). Glyphosate and multiple herbicide resistance in common waterhemp (*Amaranthus rudis*) populations from Missouri. *Weed Science*, *56*, 582–587. https://doi.org/10.1614/WS-07-204.1

Liebl, R. A., Walter, H., Bowe, S. J., Holt, T. J., & Westberg, D. E. (2008). *BAS 800H: A new herbicide for preplant burndown and preemergence dicot weed control*. Weed Science Society of America.

Moran, M., Sikkema, P. H., & Swanton, C. J. (2011). Efficacy of saflufenacil plus dimethenamid-P for weed control in corn. *Weed Technology*, *25*, 330–334. https://doi.org/10.1614/WT-D-10-00147.1

Mt Pleasant, J., Burt, R. F., & Frisch, J. C. (1994). Integrating mechanical and chemical weed management in corn (*Zea mays*). *Weed Technology*, *8*, 217–223. https://doi.org/10.1017/S0890037X00038689

Myers, M. G., & Harvey, R. G. (1993). Triazine-resistant common lam bsquarters (*Chenopodium album* L.) control in field corn (*Zea*

mays L). *Weed Technology*, *7*, 884–889. https://doi.org/10.1017/S0890037X00037933

National Agricultural Statistics Service (2018). United States Acreage report. USDA. https://quickstats.nass.usda.gov/results/80471ECF-27AD-3C9D-8E6C-E9ECECEB9E12

Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webster, T. M., Bradley, K. W., Frisvold, G., Powles, S. B., Burgos, N. R., Witt, W. W., & Barrett, M. (2012). Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Science*, *60*(Special Issue I), 31–62. https://doi.org/10.1614/WS-D-11-00155.1

Sarangi, D., & Jhala, A. J. (2018). Comparison of a premix of atrazine, bicyclopyrone, mesotrione, and *S*-metolachlor with other preemergence herbicides for weed control and corn yield in no-tillage and reduced-tillage production systems in Nebraska, USA. *Soil and Tillage Research*, *178*, 82–91. https://doi.org/10.1016/j.still.2017.12.018

Shaw, D. R., & Arnold, J. C. (2002). Weed control from herbicide combinations with glyphosate. *Weed Technology*, *16*, 1–6. https://doi.org/10.1614/0890-037X(2002)016%5b0001:WCFHCW%5d2.0.CO;2

Shimabukuro, R. H. (1968). Atrazine metabolism in resistant corn and sorghum. *Plant Physiology*, *43* (12), 1925–1930. https://doi.org/10.1104/pp.43.12.1925

Simmons, J. T., & Kells, J. J. (2003). Variation and inheritance of isoxaflutole tolerance in corn (*Zea mays*). *Weed Technology*, *17*, 177–180. https://doi.org/10.1614/0890-037X(2003)017%5b0177:VAIOIT%5d2.0.CO;2

Smith, K., & Scott, R. C. (2017). Weed control in corn. In L. Espinoza & J. Kelley (Eds.), *Corn production handbook* (pp. 47–49). Univ. of Arkansas Cooperative Extension Service.

Stephenson, D. O., & Bond, J. A. (2012). Evaluation of thiencarbazone-methyl- and isoxaflutole-based herbicide programs in corn. *Weed Technology*, *26*, 37–42. https://doi.org/10.1614/WT-D-11-00053.1

Syngenta. (2016). *Acuron Flexi herbicide product label. Syngenta Crop Protection No. 100–1568*. Greensboro, NC

Uribelarrea, M., Cárcova, J., Otegui, M. E., & Westgate, M. E. (2002). Pollen production, pollination dynamics, and kernel set in maize. *Crop Science*, *42*, 1910–1918. https://doi.org/10.2135/cropsci2002.1910

VanGessel, M. J. (2001). Glyphosate-resistant horseweed in Delaware. *Weed Science*, *49*, 703–705. https://doi.org/10.1614/0043-1745(2001)049(0703:RPRHFD)2.0.CO;2

Vollmer, K. M., Vangessel, M. J., Johnson, Q. R., & Scott, B. A. (2017). Relative safety of preemergence corn herbicides applied to coarse-textured soil. *Weed Technology*, *31*, 356–363. https://doi.org/10.1017/wet.2017.17

Webster, T. M., & Nichols, R. L. (2012). Changes in the prevalence of weed species in the major agronomic crops of the southern United States: 1994/1995 to 2008/2009. *Weed Science*, *60*, 145–157. https://doi.org/10.1614/WS-D-11-00092.1

Van Wychen, L. R., Harvey, R. G., Vangessel, M. J., Rabaey, T. L., & Bach, D. J. (1999). Efficacy and crop response to glufosinate-based weed management in PAT-transformed sweet corn (*Zea mays*). *Weed Technology*, *13*, 104–111. https://doi.org/10.1017/S0890037X00044997

How to cite this article: Norsworthy, J. K., Richburg, J., Barber, T., Roberts, T., & Gbur, E. Evaluation of corn herbicide programs with and without atrazine. *Crop, Forage & Turfgrass Mgmt*. 2021;*7*:e20128. https://doi.org/10.1002/cft2.20128