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Evaluation of Crop Tolerance and Weed Control in Corn and Grain Sorghum with Atrazine Replacements

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil, and Environmental Sciences

by

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ABSTRACT

Atrazine is a foundational herbicide for weed control in both corn (*Zea mays* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] production. However, studies have shown that while atrazine may be an effective herbicide for preemergence and postemergence control of weeds, it also has risks. The low K_{oc} of atrazine as well as its extensive use over the past 50 years have led it to become the most common groundwater contaminant near agricultural soils. Given these findings, atrazine has faced severe scrutiny while under consideration for reregistration. In the event that atrazine is not reregistered, corn and grain sorghum producers will be forced to seek alternative herbicides for weed control. Therefore, research was conducted in 2017 and 2018 to test the tolerance of corn and grain sorghum to other photosystem II-inhibiting herbicides in combination with other herbicides and also to test weed control with and without atrazine in corn production systems. When applied preemergence in grain sorghum, all PSII herbicides tested reduced grain sorghum yield compared to atrazine treatments. However, when applied postemergence, diuron, fluometuron, linuron, metribuzin, prometryn, propazine, and simazine did not cause grain sorghum to suffer yield loss when compared to atrazine-containing treatments. When applied preemergence in corn, diuron, linuron, metribuzin, and simazine did not cause yield loss to corn when compared to atrazine. However, when applied postemergence in corn, only corn treated with metribuzin and simazine yielded comparable to corn treated with atrazine. Weed control studies displayed that Palmer amaranth (*Amaranthus palmeri* S. Wats), pitted morningglory (*Ipomoea lacunosa* L.), and broadleaf signalgrass [*Echinochloa crus-galli* (L.) P. Beauv.] can all be controlled without atrazine; however, weed density was low in these studies. This research demonstrates some potential PSII-inhibiting herbicides should be further

evaluated to assist corn and grain sorghum producers in controlling weeds if atrazine is not reregistered or its use is severely limited.

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I would also like to thank my colleagues at the University of Arkansas for their companionship and help throughout my time at the University of Arkansas. Each of them has played a vital role in my development, not only as a weed scientist, but also as a person. I would also like to thank my major advisor, Dr. Jason Norsworthy for his time, patience, and desire to push me to become the best at whatever I do. Lastly, I want to thank the Arkansas Corn and Grain Sorghum Board for funding this research as it certainly was not possible without their support

TABLE OF CONTENTS

LIST OF TABLES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 1

General Introduction and Review of Literature

Introduction

In 2016, over 35 million kilograms of atrazine were applied to croplands in the United States (US) (USDA 2017), making atrazine the second most applied herbicide in the US behind glyphosate. Atrazine use as a preemergence and postemergence herbicide in corn (*Zea mays* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] contributes greatly to the overall amount of herbicide applied each year in the US. High efficacy on a wide array of both grass and broadleaf weeds along with its inexpensive cost has made atrazine a foundational herbicide in these two crops.

In the recent registration review of atrazine, the Environmental Protection Agency (EPA) released a 500-page report listing the environmental impacts and associated risks of atrazine (EPA 2017). This report finished with the consideration of lowering the maximum atrazine use rate per year in corn and grain sorghum from 2,800 g ai ha^{-1} to 560 g ai ha^{-1}. A reduction in atrazine use of this magnitude would likely challenge farmers to find efficacious and economically feasible weed control programs. Hence, it is imperative that sufficient research be conducted to understand whether adequate, cost-effective alternatives exist, knowing that atrazine alone at 560 g ha^{-1} is not a recommended option, especially for residual weed control, in these two crops (Anonymous 2018).

Atrazine Use

Atrazine is mostly known for its somewhat broad-spectrum preemergence and postemergence activity on weeds common to corn production systems. Since 1990, the average application rate of atrazine in the US has stayed somewhat constant at 1,009 g ai ha^{-1} (Figure 1). With the adoption of glyphosate-resistant crops, growers began to rely on glyphosate for total postemergence applications, resulting in the reduction in atrazine as a postemergence herbicide. This in turn was responsible for lower yearly averages of total atrazine applied (Benbrook 2001). Since 2004, there has been a continued reduction in atrazine use (Figure 1), which is likely attributed to wide-spread use of glyphosate in glyphosate-resistant corn. As the occurrence of glyphosate-resistant weeds increases nationally, atrazine use may increase in coming years.

From 1991 to 2011, atrazine use per acre in grain sorghum increased slightly (Figure 2). Spectrum and length of residual control with atrazine depends mostly on application rate (Anonymous 2017). Depending on use rate and application timing (preemergence versus postemergence), atrazine has been rated effective for controlling certain weeds such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], giant foxtail (*Setaria faberi* Herrm.), yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], red rice (*Oryza sativa* L.), quackgrass [*Elymus repens* (L.) Gould], morningglory (*Ipomoea ssp.*), eastern black nightshade (*Solanum ptychanthum* Dunal), common cocklebur (*Xanthium strumarium* L.), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), jimsonweed (*Datura stramonium* L.), kochia (*Brassica scoparia* (L.) Scott), common lambsquarters (*Chenopodium album* L.), Palmer amaranth (*Amaranthus palmeri* S. Wats.), redroot pigweed (*Amaranthus retroflexus* L.), smartweeds (*Polygonaceae ssp.*), velvetleaf (*Abutilon theophrasti* Medik.), tall waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer), prickly sida (*Sida spinosa* L.), common purslane (*Portulaca oleracea* L.), and sicklepod (*Senna obtusifolia* L.) (Loux et al. 2016; Scott et al. 2018).

Potential Risks of Atrazine

One way that atrazine poses risks to the environment as well as to humans is through groundwater contamination. One major reason for groundwater contamination is the large amount of atrazine that is applied on a yearly basis as discussed earlier. Other factors that play into the risk of atrazine contaminating groundwater are its K_{oc} and soil tillage practices. K_{oc} is the soil organic carbon-water partitioning coefficient defined as the ratio of the mass of a chemical adsorbed in the soil per unit mass of organic carbon in the soil per the equilibrium chemical concentration in solution (Sabljic et al. 1995). When a herbicide has a high K_{oc}, typically it is less likely to leach because the herbicide is adsorbed to the soil. For example, glyphosate has a K_{oc} of 24,000 L kg^{-1} while atrazine has a K_{oc} of 100 L kg^{-1} (Zhou et al. 2010). Therefore, glyphosate binds 240 times better to the soil organic carbon than atrazine. When herbicides bind to soil, biodegradation occurs, with microbial metabolism being the most common degradation mechanism (Singh and Singh 2016). While the biodegradation process is seemingly simple, it is actually a very complicated function that can only be completed in the correct environment and by specific microbes.

Atrazine leaching may also be affected by tillage. Tillage can be divided into two separate categories, conventional tillage (CT) or no-tillage (NT). CT is land that has been plowed, disked, and harrowed yearly. NT is land that has only been disturbed by a NT planter. In a study conducted by Hall et al. (1989), researchers found that CT actually decreased the amount of atrazine found in the groundwater by 14% compared to NT, which has more macro-pores than in CT soils. These pores are formed by roots, organic matter, and other sources and allow for higher infiltration than micro-pores. Disturbance of the soil through CT reduces the number of macro-pores and reduces infiltration.

Because tillage practices play a large role in ability of atrazine to leach, soil texture likewise influences leachability. Hall and Hartwig (1978) found that soils that contain more than 50% sand had 21% more leaching of atrazine in a growing season than soils that contain less than 50% sand. Atrazine leaching was attributed to the large pore spacing found in sand. Clay and silt contain particles that have sizes of >0.002 mm and between 0.002 and 0.05 mm, respectively (Foth 1990). Sand contains particles larger than 0.05 mm (Foth 1990). Hence, sand may contain less total pore space than clay, which has many micro-pores, but because sand has the largest pore space, its leaching potential is high.

When atrazine is leached into groundwater or surface water, animals and humans are exposed. A study conducted by Hayes et al. (2003), concluded that when American Leopard frogs (*Rana pipiens*) were exposed to atrazine at rates as low as 0.1 part per billion (ppb), hermaphroditism occurred. Hermaphroditism is defined as a particular organism that contains both male and female reproductive organs.

Overview of Grain Sorghum

Grain sorghum belongs to the Poaceae family. Grain sorghum goes through three distinct stages of development after emergence – seedling development, panicle initiation, and reproduction (Espinoza and Kelley 2015). The plant will spend approximately 35 days in each stage. Seedling development is characterized by vegetative growth and is classified by ‘V’ with the leaf number to follow. Panicle initiation refers to the growth stage at which the reproductive structures of the panicle form, and maximum number of seeds per panicle is set. The growth classifications of the panicle initiation stage are known as boot and panicle elongation. After panicle initiation, the plant reaches the reproductive stage, which is classified by ‘R’ followed by the reproductive stage. Reproductive stages include heading, flowering, pollination, blister, milk, dough, and then maturity. These stages are R1-R7, respectively.

There are many domestic varieties of grain sorghum grown, depending on the intended use of the crop. Grain sorghum may be grown for food, feed, building material, fencing, pet food, or even for brooms (National Sorghum Producers 2007). One major advantage of grain sorghum is its ability to maintain yields under vegetative drought stress (Kebede et al. 2001). Studies have shown that heat stress during flowering can reduce yield by 35% (Prasad 2008). Though extreme drought during reproduction can greatly reduce yields, complex plant responses allow for grain sorghum to adapt to pre-reproduction drought conditions (Crasta et al. 1999). This unique feature of grain sorghum makes it a staple crop in many arid and semi-arid countries (Dicko et al. 2006).

Grain Sorghum Production in Arkansas

Grain sorghum is an under-utilized crop in Arkansas production systems. In 2017, only 2,025 hectares of grain sorghum were harvested by Arkansas growers (Dr. Jason Kelley, personal communication). The state average yield was 5380 kg ha^{-1}, which was higher than the national average of 4840 kg ha^{-1} (USDA 2017). Many factors contribute to the under-utilization of this crop. One major factor is the opportunity costs of other cash crops such as soybean [*Glycine max* (L.) Merr.], corn, and rice (*Oryza sativa* L.). Low commodity prices for grain sorghum reduce a grower’s potential for a high net return if sub-optimal yields are produced. These low yields often deter producers from planting a risky crop such as grain sorghum and causes them to rely on higher-priced cash crops.

Weed Control in Grain Sorghum

Although grain sorghum can tolerate both arid and wet climates, it is typically grown in semi-arid to arid climates (Arkin et al. 1976). These drier climates offer lower weed pressure than moist humid environments that allow weeds to thrive. Unfortunately, Arkansas has a climate that is naturally suitable for a wide assortment of weeds to thrive. While cotton (*Gossypium hirsutum* L.), corn, soybean, and rice producers may be able to cope with this issue by use of new herbicide-resistant crop technologies, grain sorghum producers are restricted to a narrow selection of labeled herbicides. This small list of herbicides has forced growers to diversify their weed management tactics in grain sorghum.

Cultural Weed Management in Grain Sorghum

Cultural practices are tactics that producers can employ that are simple yet cost effective. A good example of cultural control in grain sorghum is manipulation of row spacing. Research by Grichar et al. (2004) illustrated the value of utilizing the practice of twin rowing in grain sorghum to decrease weed seed germination. Another useful cultural practice to reduce weed pressure in grain sorghum is to utilize a cover crop to suppress weed germination and emergence prior to planting (Einhellig and Rasmussen 1989; Teasdale 1996).

Chemical Weed Control in Grain Sorghum

As noted earlier, chemical weed control in grain sorghum offers few options. Though atrazine may be used for weed control in grain sorghum, high rates (such as 2.24 kg ai ha^{-1}) may pose risks such as stand loss and delayed seedling formation (Smith and Scott 2018). A common practice in grain sorghum is to apply sequential applications of atrazine, with the first application applied at planting and the second application at or before the crop reaches 30 cm in height. Other herbicides such as 2,4-D, dicamba, prosulfuron, and bromoxynil can be used for effective postemergence control of assorted weeds. Overall, the best weed management in grain sorghum comes from a combination of cultural, mechanical, and chemical practices.

Overview of Corn

Corn belongs to the Poaceae family. Its primary growth-stage system focuses on two major stages, vegetative (V) and reproductive (R). Each major stage is divided into sub-stages. Vegetative sub-stages are illustrated by the number of fully developed leaves per plant until tasseling. For example, a corn plant with five fully matured leaves would be in the V5 growth stage. R stages are based on numbers, with each number representing a developmental stage. R1 through R6 represent silking, blister, milk, dough, dent, and physiological maturity, respectively. Critical stages in corn are found at the V1 stage, V6 stage, V12 stage, V18 stage, R1 stage and R6 stage. Though plant health is important throughout the life cycle of corn, each one of the critical stages represents a time in which potential yield is directly influenced by stress, and stress during these stages could negatively impact grain yield.

Row-crop corn can be divided into six major domesticated variants: *Zea mays* var. *saccharata* (sweet corn), *Zea mays* var. *everta* (popcorn), *Zea mays* var. *indurata* (flint corn), *Zea mays* var. *indentata* (dent corn), *Zea mays* var. *amylacea* (flour corn), and *Zea mays* var.

tunicate larranga (pod corn). *Zea mays,* is a domesticated variant of an ancient Poaceae known as teosinte, *Zea mays*. Teosinte has been domesticated throughout time to each of the varieties listed above. Though each of these varieties are grown in the United States, the main cash crop variant is dent corn.

Corn Production in Arkansas

Corn production is a major source of income for Arkansas farmers. In 2015, 180,000 hectares of corn were harvested in Arkansas, averaging 12,000 kg ha^{-1}. In 2016, there were 302,000 hectares of corn harvested, averaging 11,500 kg ha^{-1} (USDA 2017), ranking Arkansas 19th in the United States in production.

Weed control in corn

In corn, just one Palmer amaranth that goes uncontrolled for four weeks after emergence can potentially reduce yields by 4% (Smith and Scott 2018). The critical weed-free period in corn is usually the first six weeks after crop emergence. Studies have found that light infestations and heavy infestations of weeds can cause up to 15% and 50% yield loss, respectively (Hall et al. 1992). Not only do weeds pose the issue of yield loss, but they can also cause harvest issues by late-season infestation. For example, Palmer amaranth can grow up to 2 m tall in less than 40 days (Bensch et al. 2003). This means that an infestation of Palmer amaranth during the R2 stage, or silking stage, of corn could result in less than optimal conditions for a combine to harvest the crop after maturity. There are two major weed control practices in corn, mechanical and chemical.

Mechanical weed control in corn

Common mechanical weed control practices in Kansas and Texas are rotary hoeing and tine weeding. These practices can reduce weed seedling density by 39 to 74% (Mohler et al.

1997). While mechanical weeding provides certain advantages, it also has some major disadvantages. The same study by Mohler et al. in 1997 also showed that rotary hoeing and tine weeding may reduce corn stand density by up to 6%. Another disadvantage of mechanical weed control is the secondary expense of time and wear on machines. Mechanical weeding typically requires more time than a herbicide application due to reduced swath length and decreased speed.

Chemical weed control

As in any crop, herbicides in corn allow producers to control weeds in an effective, timely, and convenient manner. Use of ground applicators, such as spray rigs, and aerial applicators, such as airplanes, allows producers to utilize herbicides at any point during the season. Common preemergence and postemergence herbicide sites of action labeled for use in corn include those from Weed Science Society of America (WSSA) groups 5 (photosystem II-inhibitor), 6 (photosystem II-inhibitor), 7 (photosystem II-inhibitor), 14 (protoporphyrinogen oxidase-inhibitor), 15 (very long-chain fatty acid-inhibitor), and 27 (4-hydroxyphenylpyruvate dioxygenase-inhibitor).

Photosystem II-inhibitors

Photosystem II- (PSII) inhibitors halt electron flow within the photosynthetic electron transport chain, thus leading to oxidative stress specifically on the D1 protein (Abendroth et al. 2006). PSII-inhibiting herbicides act on one of two mechanisms: inactivation and protein damage on the acceptor side or inactivation and protein damage on the donor side of P680. After the damaged D1 protein is triggered for degradation by one of these mechanisms, it is digested by proteinase of the PSII pathway (Aro et al. 1993). The binding of the D1 protein is specific to the WSSA group 5 herbicides. WSSA groups 6 and 7 also bind to the D1 pathway. The degradation and digestion of the D1 protein halts the PSII pathway, ultimately starving the plant. There are eight different families in the PSII-inhibiting site-of-action (SOA). These families include: phenylcarbamate, triazine, triazinone, uracil, benzothiadiazole, nitrile, amide, and urea. Common PSII herbicides include atrazine, prometryn, simazine, hexazinone, metribuzin, terbacil, bentazon, bromoxynil, propanil, diuron, fluometuron, and linuron.

Hydroxyphenylpyruvate dioxygenase-inhibitors

Hydroxyphenylpyruvate dioxygenase- (HPPD) inhibitors target chelating functionality. Inhibition of chelating functions restricts the ability of a plant to protect itself from harmful ultra-violet (UV) light. In turn, the plant is damaged and ultimately killed by UV (Witschel 2009). There are four families in the HPPD-inhibiting SOA. These families include isoxazole, pyrazole, pyrazolone, and triketone. Common HPPD-inhibiting herbicides include: isoxaflutole, pyrasulfotole, topramezone, mesotrione, tembotrione, and bicyclopyrone.

Long chain fatty acid-inhibitors

Long chain fatty acid- (LCFA) inhibitors prevent cell enlargement and cell division (Böger et al. 2000). Typically, weed seed germinate, but growth is blocked, so seedlings either remain stunted or plants never emerge. When plants do emerge, initial plant leaves, such as the coleoptile or cotyledons are small and malformed. There are three families in the LCFA-inhibiting SOA including chloroacetamides, oxyacetamides, and pyrazoles. Common LCFA-inhibiting herbicides include: *S*-metolachlor, acetochlor, dimethenamid-P, and pyroxasulfone.

Relevance of this Research

Given the potential of atrazine to leach, as well as its detection in water sources close to agricultural fields, reregistration for this herbicide is becoming difficult. If atrazine does not become reregistered for use in corn and grain sorghum, producers will need alternative herbicides to control weeds in these crops. Therefore, research was initiated to find potential atrazine replacements in both corn and grain sorghum.

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Figures

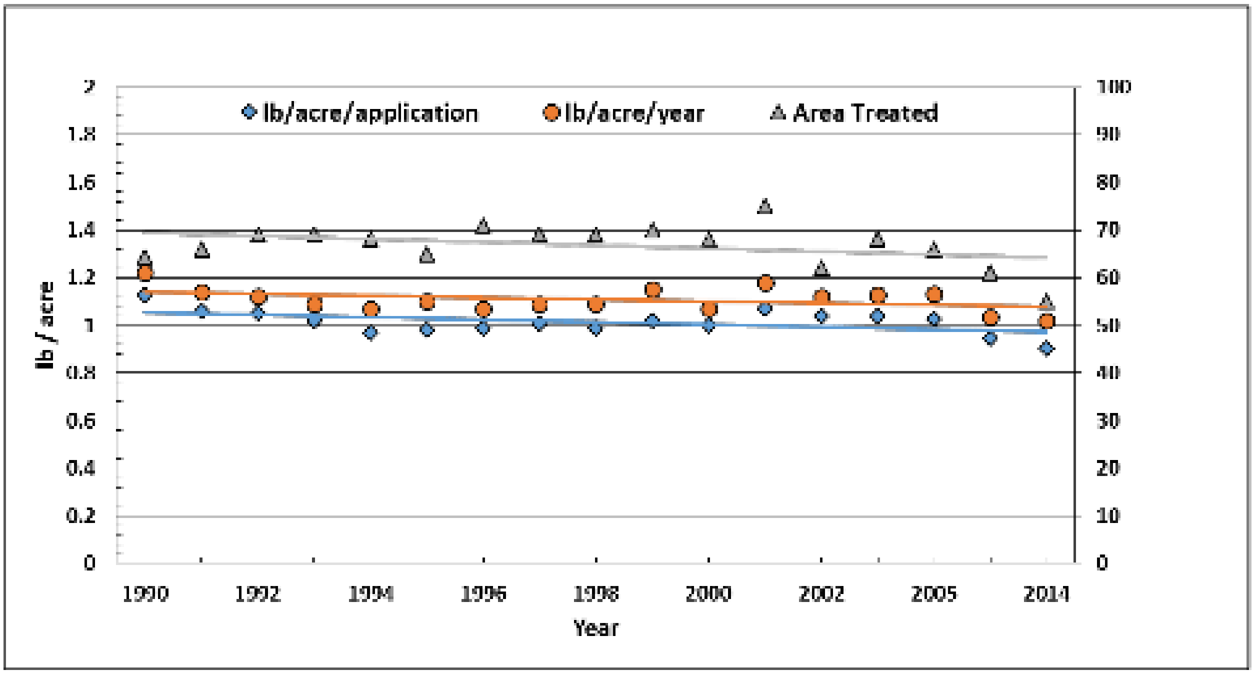

Figure 1. Use of atrazine in U.S. corn production from 1990 to 2014 (EPA 2017).

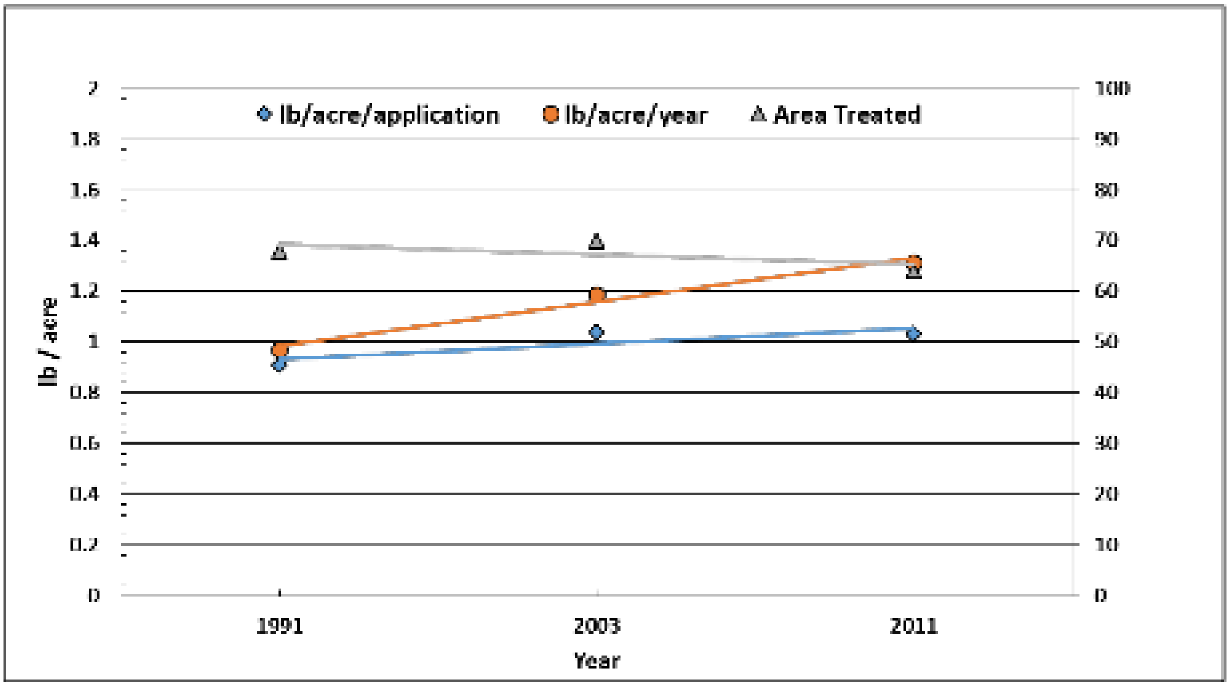

Figure 2. Use of atrazine in U.S. grain sorghum production from 1991 to 2011 (EPA 2017).

Chapter 2

Tolerance of Corn to Preemergence- and Postemergence-Applied Photosystem II-inhibiting Herbicides

Abstract

Weed control in corn has traditionally 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 harsher restrictions on its use. Therefore, field-based research trials were initiated to find atrazine alternatives were conducted in 2017 and 2018 in Fayetteville, Arkansas, by testing the tolerance of corn to preemergence and postemergence 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 herbicide and 2) the herbicide added to create the mixture. The PSII 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 following planting in the preemergence experiments and at 30-cm tall corn for the postemergence experiments. For the preemergence study, low levels of injury (<15%) were observed at 14 and 28 days after application (DAA) and corn height was negatively affected by the PSII herbicide applied. Preemergence-applied fluometuron- and ametryn-containing treatments consistently caused injury to corn, often exceeding 5%. Because of low levels of injury caused by all treatments, crop density and yield did not differ from the nontreated. For the postemergence study, crop injury, relative height, and relative yield were all impacted by PSII herbicide and herbicide added. Ametryn-, diuron-, linuron-, propazine-, and prometryn-containing treatments caused ≥25% injury to corn in at least one site-year. All PSII herbicides, except metribuzin and simazine when applied alone, caused yield loss in corn when compared to atrazine alone. Diuron-, linuron-, metribuzin-, and simazine-containing treatments applied preemergence and metribuzin- and simazine-containing treatments applied postemergence should be further investigated as atrazine replacements.

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

Keywords: Photosystem II-inhibiting herbicides, corn tolerance

Introduction

More than 36 million hectares of corn were planted in the United States (US) in 2018 (NASS 2018a). Of this area, Arkansas accounted for just over 260,000 hectares. These hectares added over $381 million in revenue to the state economy (NASS 2018a).

Weed control is a necessity for corn producers, as poor weed control can negatively impact yields. Weeds compete with corn for soil nutrients, water, and light. Smith and Scott (2017) demonstrated that just one Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] that goes uncontrolled in corn for four weeks after emergence can potentially reduce yields by 4%. Eliminating weed competition as a yield-limiting factor encourages corn to produce maximal yield potential. Weeds can also impede harvest as Bensch et al. (2003) showed that Palmer amaranth can grow up to 2 m tall in less than 40 days, meaning that late-season infestations could result in less than optimal harvest conditions. Whether it is early in the growing season or late in the growing season, weed control is vital to ensure profitable yields in corn. Troublesome weeds for corn in the southern US include morningglories (*Ipomoea spp.*), Texas millet [*Panicum texana* (Buckley) R. Webster], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R. Webster], johnsongrass [*Sorghum halepense* (L.) Pers.], sicklepod [*Senna obtusifolia* (L.) H.S. Irwin and Barneby], nutsedge (*Cyperus spp.*), and Palmer amaranth (Webster and Nichols 2012).

In 2016, over 25 million kg of atrazine were applied in the US (NASSb 2018). Atrazine, a PSII-inhibiting herbicide, has been the foundation for weed control in corn for over 70 years. PSII-inhibiting herbicides make up WSSA 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 herbicide works by binding with the D1 protein, each group binds somewhat differently.

Atrazine controls an assortment of broadleaf weeds that include common cocklebur (*Xanthium strumarium* L.), common ragweed (*Ambrosia artemisiifolia* L.), morningglories, and Palmer amaranth, as well as a plethora of 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 that works by inhibiting 4-hydroxyphenylpyruvate dioxygenase (HPPD), the enzyme that breaks down the amino acid tyrosine, thus hindering weed growth and development (Moran 2005). Previous 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 (VLCFA)-inhibitor has no postemergence (POST) activity but offers widespread residual control for 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 preemergence (PRE) at 1,820 g ha^{-1} and 1408 g ha^{-1}, respectively, provided >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. 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 that are considered harmful to humans. Studies have also shown that contamination of groundwater by endocrine disrupters may pose health concerns for the general public (Lasserre et al. 2009). One way to decrease the prevalence of atrazine in groundwater is by reducing the amount used in agriculture, specifically corn. Hence, research was initiated to test the tolerance of corn to several other PSII-inhibiting herbicides alone and in combination with mesotrione and *S*-metolachlor as potential 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. All corn experiments used corn variety 1197YHR (Pioneer, 7000 NW 62nd Ave, Johnston, IA 50131), a 111-day 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} nitrogen when the corn was

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 a period of 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. All field experiments were conducted on a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) at the Arkansas Agricultural Research and Extension Center (AAREC) 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 Setup and Data Collection. All experiments were designed as a two-factor factorial, randomized complete block with the factors being 1) PSII herbicide and 2) the herbicide added to create the mixture. The PSII 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 herbicides were applied at the same rate as they would be applied at in a labeled crop. Herbicide rates and manufacturers can be found in Table 1. All treatments were applied at 140 L ha^{-1} following corn planting (Table 2). The experimental treatments were replicated four times. Visible crop injury was rated at 14 and 28 days 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}. Yield data were then computed to relative yield by dividing each plot by the average of the nontreated plots.

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

Statistical Analysis. Data from the trials were analyzed separately by year given the different planting dates from year to year. All visual estimated crop injury for the nontreated plots in these studies was zero. Because of this, the nontreated plots were excluded from the analysis for injury at 14 and 28 DAA. Crop height, crop density, and yield were converted to be relative to 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's protected LSD (p=0.05).

Results and Discussion

PRE Study. ***Rainfall.*** 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. These include, but are 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 are dependent on rainfall timing and rate following 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 two days later (Figure 1). In 2018, PRE herbicides were applied two days after planting and received 1.6 cm of rainfall the evening immediately following the application (Figure 2).

Injury. In both years, corn injury 14 DAA was influenced by an interaction of the PSII herbicide and the additive herbicide (P=0.0305, 2017; 0.0292, 2018) (Table 3). Injury was in the form of leaf tip chlorosis with some bleaching in mesotrione-containing treatments on new leaves. 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 observed for any treatment but did not differ from fluometuron alone, and ametryn alone. In 2018, fluometuron plus mesotrione injury was higher than all other treatments. Overall, injury in 2018 may have been higher due to the shorter amount of time between planting and an activating rainfall.

Corn injury in 2018 was temporary. By 28 DAA no differences were detected among treatments, and no treatment displayed injury higher than 3% (data not shown). However, corn injury 28 DAA in 2017 was not temporary and was influenced by an interaction of PSII herbicide and 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 <20%. Excluding ametryn- and fluometuron-containing treatments, injury was <10% at 14 and 28 DAA.

Relative Stand. There was no significant effect for the main effects of PSII 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 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 herbicide that caused injury 14 DAA reduced height compared to the nontreated plots, except metribuzin- and simazine-containing treatments, which did not reduce height compared to nontreated plots in 2018.

Relative Yield. Although various treatments may have caused visible injury and height reduction in 2017 and 2018, relative yield was not significant for the main effects of PSII herbicide, herbicide added, or the interaction (Table 3). On average, corn in the nontreated plots yielded 13,180 and 12,710 kg ha^{-1}. Corn is a fairly vigorous crop with the ability to recover from early injury caused by herbicides. Corn yield components develop at different stages giving corn the ability to compensate from adverse effects throughout the growing season (Milander 2015). Yield components such as kernels row^{-1}, row ear^{-1}, and kernel weight are each primary yield components that are determined at different times after the V4 stage (Fageria et al. 2006). However, ears m^{-1} is typically a correlated with crop density. Since injury in 2017 and 2018 was minimal and in most treatments temporary and density was not affected, the corn was likely able to compensate for any yield component affected by the herbicides later in the growing season. A study conducted by Curran et al. (1991) found that corn treated PRE with clomazone, chlorimuron, imazaquin, and imazethapyr, while exhibiting injury up to 20%, did not suffer any yield loss. This reinforces that corn treated with PRE herbicides are able to compensate for early-season injury and still produce optimal yields.

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 two and ten DAA, respectively (Figure 1). In 2018, rainfall events each totaling 1.5 cm were received two and four DAA (Figure 1).

Injury. In 2017 and 2018, corn injury 14 DAA was influenced by an interaction between PSII herbicide and herbicide added (P = 0.0072, 2017; <0.0001, 2018) (Table 6). Injury was in the form of leaf tip chlorosis and necrosis with some bleaching in mesotrione-containing treatments on contacted leaves as well as new growth. In 2017, linuron plus *S*-metolachlor caused the highest injury at 45% (Table 7). In general, linuron-containing treatments, along with diuron plus *S*-metolachlor and prometryn plus *S*-metolachlor, caused greater injury compared to most other treatments. The Linex label does not allow for over-the-top use of Linex in corn due to 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 which were comparable. Atrazine-, fluometuron-, metribuzin-, and simazine-containing treatments each caused <15% injury in both years (Table 7).

Injury 28 DAA in 2017 was influenced by an interaction between PSII 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 impacted by PSII herbicide, herbicide added, or the interaction (Table 6). Overall, injury was moderate among treatments in both years, excluding fluometuron-, metribuzin-, and simazine-containing treatments, which caused injury <15% (Table 7).

Relative Height. In 2017 and 2018, height 14 DAA was influenced by an interaction between PSII herbicide and herbicide added (P = 0.0051, 2017; 0.0003, 2018) (Table 6). Generally, height followed the trend of injury. For example, in 2017, linuron plus *S*-metolachlor presented the highest injury (45%), and corn height following this treatment was only 77% of nontreated plots (Tables 7 and 8). In 2017, plots injured >10% also had heights that were reduced compared to 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 herbicide and herbicide added (P=0.0006, 2017; <0.0001, 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 yielded comparable to atrazine-containing treatments.

These applications were made while the corn was 30 cm tall or V3/V4. During this time and the proceeding weeks, 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 semi-flex 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 impacted because injury may translate into delayed maturity. Therefore, even though yield was not impacted for any preemergence-applied herbicide, certain ametryn- and fluometuron-containing treatments caused >10% injury and should therefore no longer be considered for this use in corn because safer options were identified.

Herbicides that reduce corn height should not be considered since this form of injury may delay canopy closure, which could negatively impact weed control (Anderson 2008). Given the negative effects of reduced crop height, prometryn- and propazine-containing treatments should also be eliminated from further testing. Corn tolerance to diuron-, linuron-, metribuzin-, and simazine-containing treatments applied preemergence 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 postemergence application of these herbicides. Based on 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 postemergence. Efforts should be made to evaluate these herbicides over as many diverse environments as possible.

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Tables and Figures

Table 1. Herbicides, rates, and manufacturers for preemergence and postemergence 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 postemergence 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.[a]

		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

[a] Abbreviations: PRE, preemergence; POST, postemergence.

Table 3. Significance of P-values for interactions and main factors of PSII-inhibiting herbicide and herbicide added on corn injury, relative stand, relative height, and relative yield by year for preemergence corn trials.[a,b]

Year	Factor	Injury		Relative stand	Relative height	
		14 DAA	28 DAA	14 DAA	28 DAA	Relative yield
		------------------------------------ P-value			--	
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* 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* Herbicide added	0.0292*	0.1846	0.7074	0.4607	0.0904

[a] Abbreviations: DAA, days after application.

[b] Asterisks represent significance at $P < 0.05$.

Table 4. Average visual estimates of corn injury as influenced by interactions between PSII-inhibiting herbicide and herbicide added applied preemergence in Fayetteville, AR, in 2017 and 2018.[a,b]

		Injury					
		14 DAA				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

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[a] Abbreviation: DAA, days after application.

[b] Means within a factor and year followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

Table 5. Relative corn height as influenced by PSII herbicide applied preemergence in Fayetteville, AR, in 2018.[a,b,c]

PSII herbicide	Relative corn height	
	% 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] Abbreviation: DAA, days after application.

[b] Means followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

[c] Height of corn in the nontreated plots averaged 36 cm.

Table 6. Significance of P-values for interactions and main effects of PSII-inibiting herbicide and herbicide added on corn injury, relative height, and relative yield by year for postemergence corn trials.[a,b]

		Injury		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] Asterisks represent significance at $P < 0.05$.

Table 7. Average visual estimates of corn injury and yield as influenced by interactions between PSII-inhibiting herbicide and herbicide added applied postemergence in Fayetteville, AR in 2017 and 2018.[a,b,c]

		Injury				
		14 DAA		28 DAA	Relative yield	
PSII herbicide	Herbicide added	2017	2018	2017	2017	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 bc	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

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[a] Abbreviation: DAA, days after application.

[b] Means within a column followed by the same letter are not significantly different according to Fisher's 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 postemergence in Fayetteville, AR in 2017 and 2018.[a,b,c]

		Relative corn height			
		14 DAA			
PSII herbicide	Herbicide added	2017		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

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[a] Abbreviation: DAA, days after application.

[b] Means within a factor followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

[c] Height of corn in 2017 and 2018 in the nontreated plots averaged 52 and 46 cm, respectively.

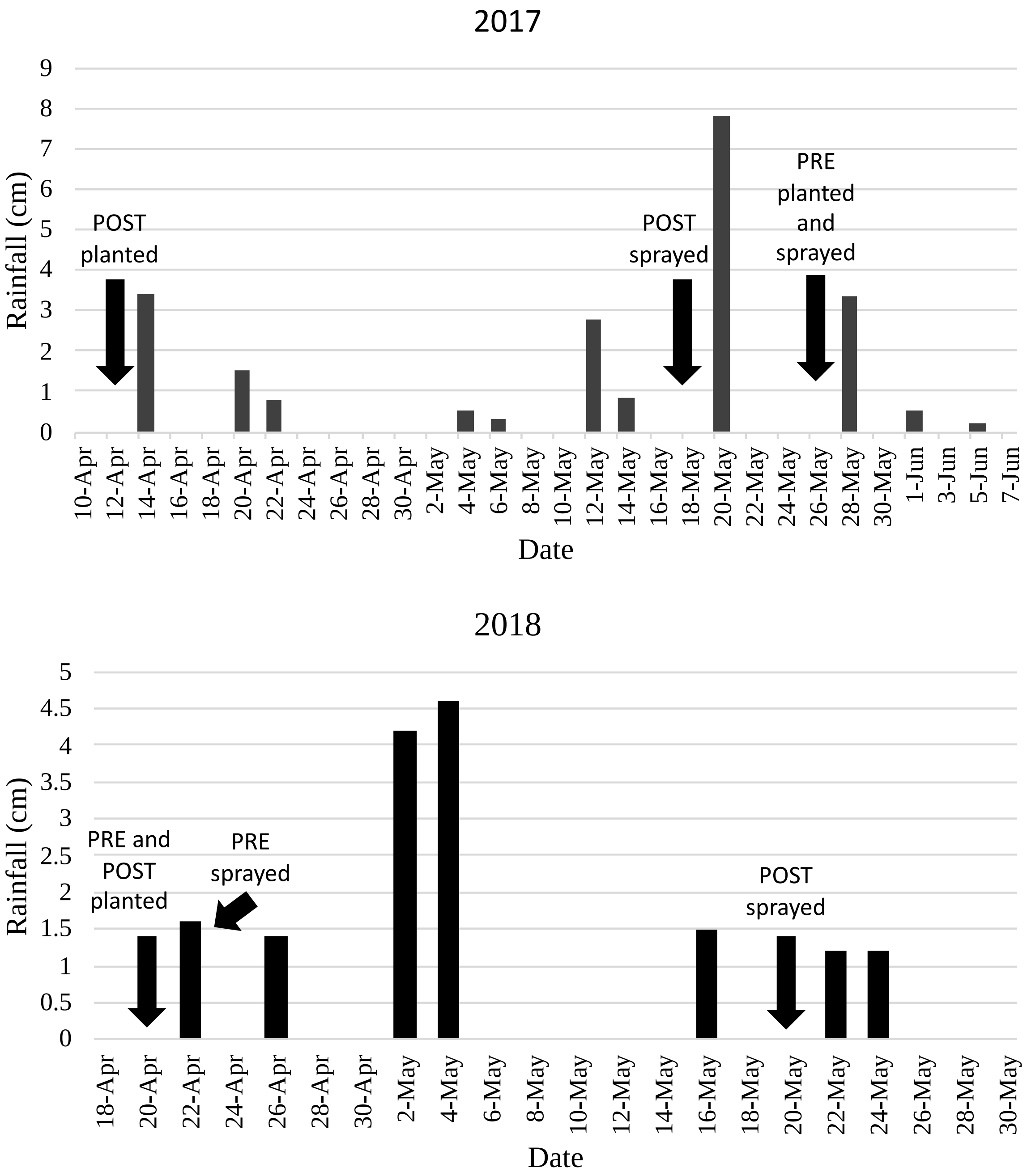

Figure 1. Rainfall amounts by day along with planting and application dates at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2017 and 2018.

Chapter 3

Tolerance of Corn to Preemergence-Applied Metribuzin

Abstract

A possible restriction on atrazine use in corn has led to exploration into alternative herbicides for control of problematic weeds. Metribuzin (WSSA Group 5) is a photosystem II- (PSII) inhibiting herbicide used to control grass and broadleaf weed species in certain row crops. Metribuzin is not currently labeled in the Midsouth for use in corn. Thus, field experiments were conducted in Arkansas in 2018 at two different locations to determine the effect of metribuzin rate on 17 different corn hybrids. The experimental design was a split-plot, randomized complete block, with corn hybrid being the whole-plot factor, and preemergence rate of metribuzin [0, 280 (1/2X), and 560 (1X) g ai ha^{-1}] being the split-plot factor. However, analysis was conducted by location and within a hybrid making metribuzin rate the only factor analyzed. Corn exhibited <5% injury at the Fayetteville location and <25% injury at the Marianna location. Yield and crop density results varied by location. Crop density was reduced by metribuzin for multiple hybrids in Fayetteville; however, crop density was reduced for only one hybrid at Marianna. Metribuzin rate reduced yield for 8 of 17 hybrids at Fayetteville and 5 of 17 hybrids at Marianna. Corn hybrid selection did not consistently explain injury or yield impacts based on differences between the two locations. Based on these results, corn tolerance to metribuzin in the Midsouth may differ based on environment more than hybrid selection.

Nomenclature: Atrazine; metribuzin; corn, *Zea mays* L.

Key words: Photosystem II-inhibiting herbicides, corn tolerance

Introduction

The United States (US) produced over 370 billion kg of corn, with 2.7 billion kg coming from Arkansas in 2017 (NASS 2017). Although the majority of US corn is produced in what is referred to as the Corn Belt, the 2.7 billion kg of grain produced in Arkansas contributes over $380 million to the state economy (NASS 2017). Common agronomic practices for corn production systems in Arkansas include wide-row spacings (91-97 cm), heavy reliance on herbicides, and the use of furrow irrigation. Some of the most problematic weeds in Arkansas corn include morningglory (*Ipomoea* spp.), pigweed (*Amaranthus* spp.), johnsongrass [*Sorghum halepense* (L.) Pers.], broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster], and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (Espinoza and Ross 2015). Because of its high efficacy on the majority of these weeds, atrazine has become a dominant herbicide in corn because it provides an extended period of broad-spectrum weed control at an inexpensive cost.

The Environmental Protection Agency (EPA) in 2016 published a registration review for atrazine (EPA 2016). In this review, concerns were raised about the potential for atrazine to leach and contaminate groundwater. This concern is not unwarranted because over 35 million kg of atrazine were applied to croplands in the US in 2016, ranking it second only to glyphosate in total amount applied (USDA 2017). Atrazine has a low K_{oc}, which is the soil organic carbon-water partitioning coefficient defined as the ratio of the mass of a chemical adsorbed in the soil per unit mass of organic carbon in the soil per the equilibrium chemical concentration in solution (Sabljic et al. 1995). Because of its low K_{oc} atrazine does not bind well to most soils and potentially leaches to groundwater. Due to these recent findings, the EPA is considering lowering the maximum annual use rate from 2,800 g ha^{-1} or banning the herbicide completely (EPA 2016).

Atrazine can be applied as a single application from 560 g ha^{-1} to 2,200 g ha^{-1}, or as a split application given the total yearly maximum is 2800 g ha^{-1}. Many growers will not apply more than 1680 g ha^{-1} at planting, allowing an additional 1,120 g ha^{-1} to be applied later in the season if necessary. A reduction in the maximum annual use rate of atrazine to 560 g ha^{-1} would render this vital tool for corn weed control marginally effective, becoming solely a postemergence herbicide. For preemergence control, atrazine would need to be mixed with other herbicides labeled for use in corn. For example, Whaley et al. (2009) found that, when applied on a Bojac sandy loam (1% OM and pH of 6.1) three different mixtures of mesotrione at 150, 230, and 310 g ha^{-1} all with atrazine preemergence at 1,120 g ha^{-1} consistently controlled morningglory species at 90%. However, morningglory control suffered when mesotrione was applied with atrazine at 560 g ha^{-1}. Findings from a study conducted by Armel et al. (2003) complement this by reinforcing the necessity for higher rates of preemergence-applied atrazine to control problematic weeds. In this study, mixtures of mesotrione plus atrazine at 560 g ai ha^{-1} provided insufficient and inconsistent control of *Amaranthus* and morningglory species when applied preemergence. However, in a study by Ferrell and Witt in 2002, postemergence applications of atrazine at 1,100 g ha^{-1} or higher offered control >90% on weed species such as morningglory, common lambsquarters (*Chenopodium album* L.), and giant ragweed (*Ambrosia trifida* L.). To summarize these studies, atrazine applied preemergence at a rate <600 g ha^{-1} does not provide adequate weed control in corn. Given this assumption, research should be conducted with the intention of replacing atrazine with a herbicide in the same chemical family that could make use of the documented synergy when mixed with a Group 27 herbicide (Abendroth et al. 2006).

Metribuzin is a WSSA Group 5 photosystem II (PSII)-inhibitor belonging to the triazinone family. Currently, metribuzin is labeled for preemergence and postemergence use in soybean [*Glycine max* (L.) Merr], potato (*Solanum tuberosum* L.), tomato (*Solanum lycopersicum* L.), and sugarcane (*Saccharum officinarum* L.) for control of many broadleaf and grass weeds, including Palmer amaranth and barnyardgrass (Anonymous 2017). Metribuzin is not labeled for use in corn in the Midsouth but is labeled in some Midwest and Great Plain states. Metribuzin has demonstrated suitable control of several troublesome weeds in soybean such as *Amaranthus* ssp., common cocklebur (*Xanthium strumarium* L.), and prickly sida (*Sida spinosa* L.) (Green et al. 1988). Although the broadleaf spectrum of control may be similar between atrazine and metribuzin, lack of consistent grass control with metribuzin is a concern (Bruff and Shaw 1992). In this study, metribuzin alone provided <85% control of fall panicum [*Panicum dichotomiflorum* (Michx.)], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and giant foxtail [*Setaria faberi* (Herrm.)]; however, the addition of alachlor, metolachlor, or pendimethalin increased grass control to >90%.

As demonstrated by Barrentine et al. (1982), soybean tolerance to metribuzin may differ by cultivar. Given varietal tolerance differences in soybean, research was initiated to see if similar differences occurred in corn hybrids. Given the weed control spectrum of metribuzin alone and in combination with other common corn herbicides such as pendimethalin and metolachlor, a study was conducted to determine the tolerance of 17 corn hybrids to preemergence-applied metribuzin. It is hypothesized that metribuzin tolerance will vary depending on corn hybrid similar to that seen for soybean.

Materials and Methods

Experimental Sites. Experiments were conducted in 2018 on a Leaf silt loam (Fine, mixed, active, thermic Typic Albaquults) and a Convent silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) at the Arkansas Agricultural Research and Extension Center in Fayetteville, Arkansas, and at the Lon Mann Cotton Research Station near Marianna, Arkansas, respectively. 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. The soil at Marianna consisted of 9% sand, 80% silt, and 11% clay, with an organic matter content of 1.8% and a pH of 6.8.

Experimental Setup and Data Collection. The experimental design for these two trials was a split-plot, randomized complete block with four replications. The whole-plot factor was the 17 most popular Arkansas corn hybrids used in the 2016 growing season (Table 1), and the split-plot factor was rate of metribuzin (Tricor 4F, UPL) [0, 280, and 560 g ai ha^{-1}]. Corn hybrids were cone planted at 79,000 seeds ha^{-1} into 7.3- by 6.2-m whole plots at a 5-cm depth. Row spacings were 91 and 97 cm between rows in Fayetteville and Marianna, respectively. Rows one and eight of each whole plot were used as buffer rows, with three, two-row subplots making up the middle six rows. Each subplot randomly received one of the three metribuzin rates. Plots were maintained weed-free throughout the growing season using postemergence applications of atrazine (Aatrex 4L, Syngenta) at 1,120 g ai ha^{-1} + 1% v/v crop oil concentrate, glyphosate (Roundup PowerMax II, Monsanto) at 1,260 g ae ha^{-1}, and halosulfuron (Permit, Gowan) at 52 g ai ha^{-1} + 0.25% v/v nonionic surfactant at both locations. Irrigation in the amount of 2.5 cm at Fayetteville was provided via an overhead lateral sprinkler when a period of 7 d without rainfall in excess of 2.5 cm occurred starting 21 days after planting. Irrigation in Marianna was provided via furrow irrigation using a similar criterion. Both experiments were fertilized and managed according to University of Arkansas Extension recommendations (Espinoza and Ross 2015). Metribuzin was applied preemergence with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1}. Dates of planting, herbicide application, and harvest at each site are displayed in Table 2.

Crop injury was visually estimated at 2 and 4 weeks after treatment (WAT) on a scale of 0 to 100 with 0 being no injury and 100 being crop death. Crop density was counted for 1 m in one of the two treated rows at 3 WAT and reported as plants m^{-1} of row. The plots were harvested for grain using a small-plot combine, and yield was adjusted to 15.5% moisture and reported as kg ha^{-1}.

Statistical Analysis. *Injury.* All estimated crop injury for the nontreated plots in this study was zero. Because of this, the nontreated was excluded from the analysis for injury at 2 and 4 WAT. Also, corn hybrids exhibited very low levels of injury from the two rates of metribuzin at 2 and 4 WAT at each location. For these reasons, injury data were not formally analyzed, but means and standard errors are reported in Table 3. Means were computed using the MEANS procedure in SAS 9.4 statistical software (SAS Institute Inc., Cary, NC).

Crop Density and Yield. Crop density and yield data were analyzed by location and hybrid using the GLIMMIX procedure in SAS Version 9.4 statistical software (SAS Institute Inc., Cary, NC) with metribuzin rate considered the only factor. A gamma distribution was assumed for each assessment. If there was no rate effect, then standard error was reported. However, if there was a rate effect then means were separated using Fisher’s protected LSD (p=0.05).

Results

Injury. *Fayetteville.* All hybrids at the Fayetteville location had less than 5% injury at each assessment timing (Table 3). The minimal injury that appeared was a mild chlorosis on the leaf tips, often on the lowest leaf. All symptoms appeared temporary.

Marianna. Every hybrid receiving an application of metribuzin at the Marianna location exhibited at least 5% at the 2 WAT assessment (Table 3). As metribuzin rate increased, injury likewise increased for most hybrids. No hybrid at 2 WAT had more than 13 and 16% injury following metribuzin applied at 280 g ha^{-1} or 560 g ha^{-1}, respectively (Table 3). By 4 WAT, injury generally lessened except in hybrids Armor 1447, Armor 1667, Dekalb 68-26, Pioneer 1197 YHR, Pioneer 2160 YHR, Terrel REV 25BHR89, and Terrel REV 27BHR79, which all exhibited injury from 10 to 24% following metribuzin at 560 g ha^{-1} (Table 3). Injury primarily appeared as leaf tip necrosis on new growth.

Crop Density. *Fayetteville.* Crop densities were generally between 6 and 7 plants m^{-1} row at Fayetteville for every hybrid (Table 4). Armor 1667, Dyna-Gro 58VC37, Dekalb 64-35, Dekalb 68-26, and Terral REV 27BHR79 all had lower crop densities following metribuzin at 560 g ha^{-1}.

Marianna. Crop density at Marianna did not differ among hybrids, except for Terral REV 25BHR79 in which stand was reduced by both metribuzin rates (Table 4). However, crop density was overall lower due to bird’s eating seeds and soil crusting.

Crop Yield. *Fayetteville.* At Fayetteville, eight of the hybrids suffered yield reduction compared to the nontreated following metribuzin at 560 g ha^{-1}, while only four suffered yield loss when metribuzin was applied at 280 g ha^{-1} (Table 4). Dyna-Gro 58VC37 showed an incremental decrease in yield as metribuzin rate increased.

Marianna. In Marianna, only three hybrids yielded lower than the respective nontreated. Dyna-Gro 57VP51 and Dekalb 64-35 each had metribuzin treatments that yielded higher than the nontreated.

Discussion

Climate. Rainfall is essential for activation of soil-applied herbicides (Riar et al. 2012). Amount and timing of rainfall in relation to metribuzin application varied across experimental locations (Figure 1). At the Fayetteville location, 1.7 cm of rain was received three days after metribuzin application. At the Marianna location, 5.7 cm of rain was received one day after the metribuzin application. Likely, general differences in injury by location are attributed to rainfall amounts after each application. Per label instructions, metribuzin applied to soybean should be activated with no less than 0.6 cm of irrigation or rainfall, and irrigation greater than 1.27 cm should not be applied immediately after application (Anonymous 2017).

Since the Marianna location received over 5 cm of rainfall one day after application, higher and more variable injury was expected. At Fayetteville, after the activation rainfall on April 14th, conditions remained dry until April 22nd (Figure 1). This break in wet conditions likely propelled the young corn hybrids into rapid growth, allowing for more rapid metabolism of the applied metribuzin. On the contrary, wet conditions in Marianna persisted for at least six days after metribuzin activation (Figure 1). Metribuzin causes a shortage in ammonia assimilation and subsequently a decrease in the formation of proteins (Alla et al. 2007). These wet conditions likely slowed growth and metribuzin metabolism in corn plants, inducing higher injury at this location as seen in other research (Darby and Bosworth 2004).

Hybrid Tolerance. The only hybrid that had yield negatively impacted by metribuzin at both locations was Dekalb 64-35. Other than this hybrid, no corn was impacted in both locations. This indicates that there may be a very slight varietal effect at most.

Practical Implications. Although stand was statistically reduced in Fayetteville for a number of hybrids, the reduction was not more than 10%. For example, the largest difference within a hybrid occurred for Armor 1667 where density was 6.8 and 6.1 for the control treatment and metribuzin at 280 g ha^{-1}, respectively. When computed on a per hectare basis, the densities are comparable to 74,500 and 67,000 plants ha^{-1}, both acceptable plant populations for corn (Kelley 2017). Like soybean, corn also shows differential tolerance by hybrid. General trends from this study show that several hybrids potentially are tolerant to metribuzin. Hybrids that showed no significant injury at either assessment or yield loss should be further assessed for tolerance across additional environments. As stated by the Tricor label, metribuzin activity increases as soil pH increases (Anonymous 2017). Therefore, if metribuzin is applied on soils with a lower pH then corn tolerance may increase.

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Tables and Figures

Table 1. List of corn hybrids with their respective companies.

Hybrid	Company	Address
1197 YHR	Pioneer	7000 NW 62nd Ave, Johnston, IA 50131
2089 YHR	Pioneer	
2160 YHR	Pioneer	
1870 YHR	Pioneer	
62-08	Dekalb	800 N Lindbergh Blvd, Saint Louis, MO 63167
64-35	Dekalb	
67-44	Dekalb	
68-26	Dekalb	
67-72	Dekalb	
70-27	Dekalb	
57 VP 51	Dyna-Gro	2775 Giant Rd, Richmond, CA 94806
58 VC 37	Dyna-Gro	
1447	Armor	2532 Alexander Dr., Jonesboro, AR 72401
1667	Armor	
REV 27 BHR 79	Terral	117 Ellington Dr., Rayville, LA 71269
REV 28 BHR 18	Terral	
REV 25 BHR 89	Terral	

Table 2. Planting, herbicide application, and harvest dates for trials in Marianna and Fayetteville in 2018.

	Dates of significance		
Location	Planting	Herbicide application	Harvest
Marianna	April 20	April 20	September 5
Fayetteville	April 11	April 11	September 26

Table 3. Mean estimates of crop injury of 17 corn hybrids in response to two different rates of metribuzin at Fayetteville and near Marianna in 2018.[a]

		Injury[b]			
		2 WAT		4 WAT	
Hybrid	Metribuzin rate	Fayetteville	Marianna	Fayetteville	Marianna
	g ai ha^{-1}	----------------------------	------------%	------------	------------------
A 1447	280	1 (0.5)	10 (1.0)	0 0.0	9 (1.2)
	560	1 (0.5)	15 (1.7)	1 (1.3)	13 (1.4)
Armor 1667	280	1 (0.8)	12 (1.2)	0 0.0	14 (0.8)
	560	1 (0.6)	16 (0.8)	2 (0.9)	19 (1.3)
DG 57VP51	280	0 0.0	6 (0.8)	0 0.0	1 (0.8)
	560	3 (0.4)	11 (0.6)	1 (1.3)	4 (1.5)
DG 58VC37	280	0 0.0	11 (0.5)	0 0.0	2 (1.2)
	560	2 (0.5)	13 (1.2)	0 0.0	3 (1.0)
DK 62-08	280	0 0.0	9 (0.9)	0 0.0	5 (0.5)
	560	2 (1.1)	11 (0.6)	0 0.0	5 0.0
DK 64-35	280	0 0.0	5 (0.8)	0 0.0	1 (1.3)
	560	4 (0.6)	9 (0.8)	3 (1.2)	2 (1.8)
DK 67-44	280	1 (0.5)	8 (1.2)	0 0.0	1 (0.8)
	560	2 (1.7)	12 (1.2)	1 (1.3)	1 (1.3)
DK 67-72	280	0 0.0	6 (0.5)	0 0.0	3 (1.4)
	560	2 (0.5)	14 (0.8)	0 0.0	3 (1.4)
DK 68-26	280	1 (0.5)	10 (0.8)	1 (1.3)	8 (2.7)
	560	2 (1.2)	15 (1.2)	3 (2.4)	12 (2.8)
DK 70-27	280	1 (0.5)	6 (0.5)	0 0.0	0 0.0
	560	2 (0.6)	7 (1.2)	0 0.0	1 (0.8)
P 1197 YHR	280	1 (0.8)	11 (0.5)	0 0.0	13 (1.2)
	560	2 (1.2)	16 (0.5)	0 0.0	10 (1.8)
P 1870 YHR	280	0 0.0	6 (1.0)	0 0.0	0 0.0
	560	1 (0.5)	11 (1.0)	1 (1.3)	0 0.0
P 2089 YHR	280	1 (0.5)	7 (1.0)	0 0.0	1 (0.8)
	560	2 (0.7)	12 (1.2)	4 (1.3)	1 (1.3)
P 2160 YHR	280	1 (0.5)	11 (1.5)	0 0.0	9 (2.2)
	560	2 (1.0)	14 (2.4)	3 (1.4)	10 (1.9)
T REV 25BHR89	280	0 0.0	13 (1.2)	0 0.0	24 (3.8)
	560	2 (0.6)	16 (1.7)	1 (1.3)	23 (3.2)
T REV 27BHR79	280	0 0.0	12 (1.2)	0 0.0	5 (0.5)
	560	1 (0.8)	15 (1.0)	0 0.0	11 (1.7)
T REV 28BHR18	280	0 0.0	12 (2.0)	0 0.0	3 (1.4)
	560	1 (0.5)	13 (1.2)	0 0.0	3 (1.0)

[a] Abbreviation: WAT, weeks after treatment; A, Armor; DG, Dyna-Gro; DK, Dekalb; P, Pioneer; T, Terral.

[b] Means of injury reported from 0 to 100% with 0 being no injury and 100 being crop death. Standard error reported in parentheses.

Table 4. Average crop density and grain yield of 17 corn hybrids in response to two different rates of metribuzin at Fayetteville and Marianna in 2018.[a]

Hybrid	Metribuzin rate	Crop density[b]				Yield[b]			
		Fayetteville		Marianna		Fayetteville		Marianna	
	g ai ha^{-1}	-------m^{-1} row-------				------------kg ha^{-1}------------			
A 1447	0	6.3	(0.3)	4.8	(0.6)	13040	a	11570	(1067)
	280	6.1	(0.3)	4.3	(0.5)	12830	a	9170	(845)
	560	6.6	(0.3)	5.3	(0.7)	11110	b	9820	(905)
A 1667	0	6.8	a	4.1	(0.5)	12900	(774)	12500	a
	280	6.1	b	4.1	(0.5)	11160	(670)	7750	b
	560	6.4	ab	4.9	(0.6)	12330	(740)	8440	b
DG 57VP51	0	6.6	(0.2)	5.5	(0.3)	12600	(1064)	10270	b
	280	6.4	(0.2)	5.7	(0.3)	12300	(1028)	11120	a
	560	6.4	(0.2)	5.1	(0.2)	10720	(901)	10150	b
DG 58VC37	0	6.3	b	5.2	(0.3)	11710	a	11950	(834)
	280	7.0	a	6.0	(0.4)	10740	b	10140	(707)
	560	6.4	b	5.4	(0.3)	10000	c	10150	(708)
DK 62-08	0	6.8	(0.2)	5.4	(0.5)	12810	a	9990	(514)
	280	6.8	(0.2)	5.3	(0.5)	11390	b	8940	(459)
	560	6.6	(0.2)	5.6	(0.5)	11100	b	9340	(480)
DK 64-35	0	6.3	b	5.5	(0.3)	13800	a	10280	b
	280	6.9	a	5.8	(0.3)	11410	b	10630	b
	560	6.6	ab	6.1	(0.3)	14120	a	11590	a
DK 67-44	0	6.7	(0.1)	6.1	(0.4)	14050	a	12600	(505)
	280	6.8	(0.1)	6.0	(0.4)	13410	a	12310	(492)
	560	6.8	(0.1)	6.1	(0.4)	10700	b	12380	(495)
DK 67-72	0	6.8	(0.2)	6.5	(0.4)	11520	(1303)	12600	a
	280	6.6	(0.2)	6.0	(0.3)	11740	(1302)	10850	b
	560	6.4	(0.2)	6.1	(0.3)	11080	(1224)	11840	ab
DK 68-26	0	6.8	a	4.5	(0.4)	11460	a	10730	(1037)
	280	6.8	a	4.9	(0.4)	11790	a	9590	(926)
	560	6.3	b	4.3	(0.4)	9300	b	7980	(771)
DK 70-27	0	6.8	(0.2)	6.2	(0.3)	10910	(733)	12290	(503)
	280	6.7	(0.2)	6.0	(0.2)	11730	(783)	11550	(473)
	560	6.6	(0.2)	6.2	(0.3)	11040	(738)	12250	(501)
P 1197 YHR	0	6.5	(0.1)	5.1	(0.5)	12740	a	10670	(692)
	280	6.6	(0.2)	5.0	(0.5)	11270	ab	9130	(591)
	560	6.3	(0.1)	4.2	(0.4)	10770	b	9870	(639)
P 1870 YHR	0	6.9	(0.2)	6.0	(0.2)	11840	(896)	11660	(496)
	280	6.3	(0.2)	6.1	(0.2)	12940	(887)	11440	(487)
	560	6.8	(0.2)	6.3	(0.2)	10930	(876)	11450	(488)

Table 4 (cont.) Average crop density and grain yield of 17 corn hybrids in response to two different rates of metribuzin at Fayetteville and Marianna in 2018[a]

		Crop density[b]				Yield[b]			
Hybrid	Metribuzin rate	Fayetteville		Marianna		Fayetteville		Marianna	
	g ai ha^{-1}	-------m^{-1} row-------				------------kg ha^{-1}------------			
P 2089 YHR	0	6.7	(0.2)	5.0	(0.3)	13830	a	12020	(934)
	280	6.8	(0.2)	5.1	(0.3)	13940	a	11490	(893)
	560	6.4	(0.2)	5.6	(0.3)	11660	b	12420	(965)
P 2160 YHR	0	6.3	(0.2)	4.9	(0.4)	12880	(1459)	9650	(892)
	280	6.3	(0.2)	5.0	(0.5)	13290	(1487)	8110	(747)
	560	6.2	(0.2)	5.1	(0.5)	11620	(1284)	10150	(938)
T REV 25BHR89	0	6.2	(0.2)	6.6	a	11430	(939)	10700	a
	280	6.5	(0.2)	2.9	b	11560	(939)	6530	b
	560	6.2	(0.2)	2.9	b	12660	(1035)	5550	b
T REV 27BHR79	0	6.4	ab	5.2	(0.5)	10750	(601)	10370	(500)
	280	6.8	a	5.3	(0.5)	11800	(659)	10190	(492)
	560	6.1	b	6.3	(0.6)	10780	(601)	9310	(449)
T REV 28BHR18	0	6.4	(0.2)	5.6	(0.4)	12520	(1157)	11990	(800)
	280	6.7	(0.2)	5.6	(0.3)	12190	(1113)	11650	(777)
	560	6.4	(0.2)	5.3	(0.3)	11690	(1067)	10600	(707)

[a] Abbreviations: WAT, weeks after treatment; A, Armor; DG, Dyna-Gro; DK, Dekalb; P, Pioneer; T, Terral.

[b] Means within a hybrid and column with the same lowercase letters are not different according to Fisher's protected LSD (p=0.05). Standard error of mean reported in parentheses for hybrids in which no rate effect occurred.

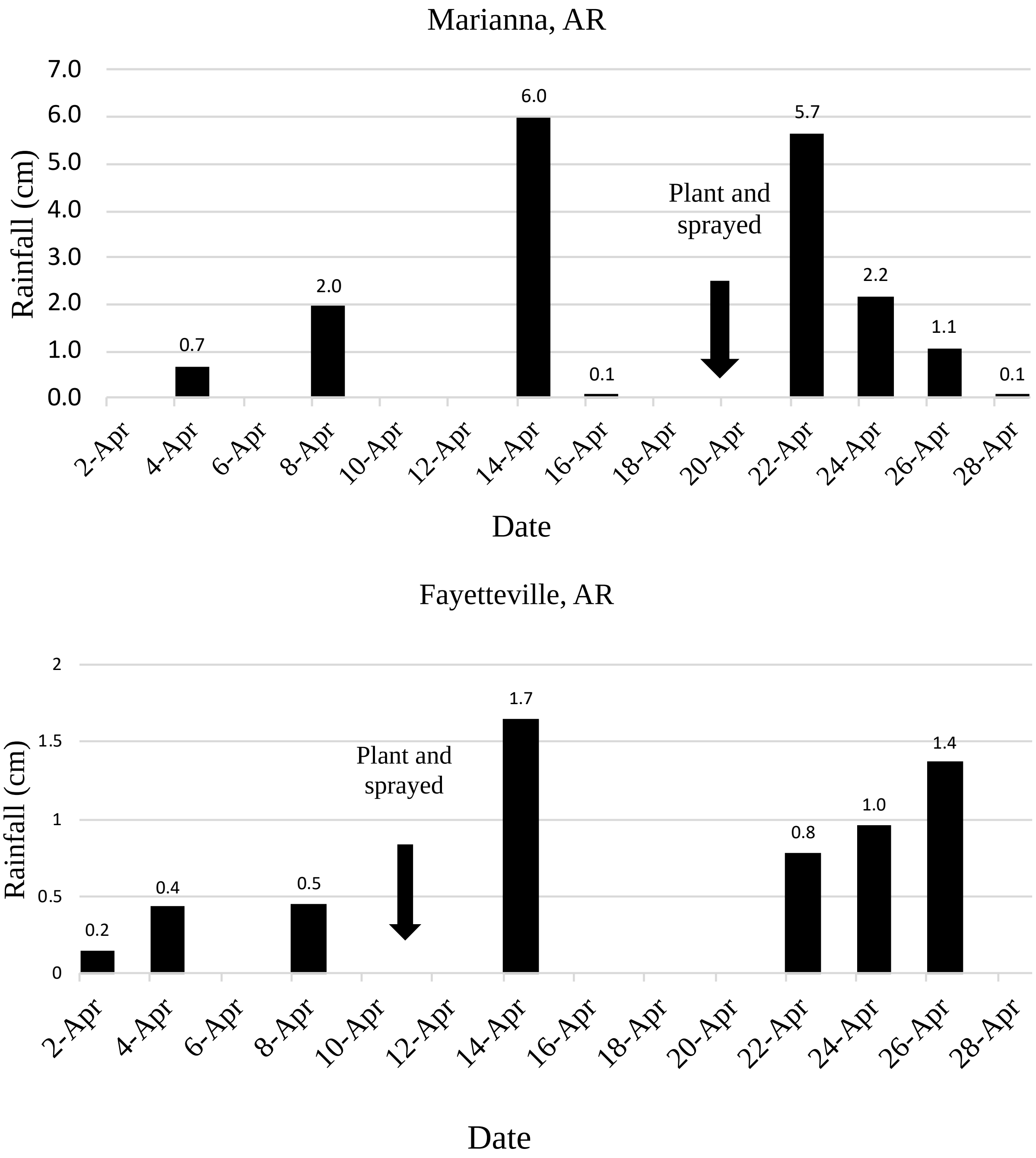

Figure 1. Rainfall amounts by day and planting and application dates in Fayetteville and Marianna, AR in 2018.

Chapter 4

Evaluation of Corn Herbicide Programs with and without Atrazine

Abstract

Atrazine has been a foundational herbicide in corn because of its broad-spectrum weed control and its utility for both preemergence or postemergence applications. The extensive use of this herbicide by growers has led to traces of atrazine being found in groundwater, surface water, and aquifers. Research was initiated in Fayetteville, AR, in 2017 and 2018 to explore different corn herbicide regimes with little or no atrazine. Different preemergence herbicide treatments (*S*-metolachlor at 1,070 g ai ha^{-1} or saflufenacil 60 g ai ha^{-1} plus dimethenamid-P at 530 g ha^{-1}), as well as various herbicide postemergence mixtures (bicyclopyrone at 45 g ai ha^{-1} plus mesotrione at 180 g ai ha^{-1} plus *S*-metolachlor at 1,600 g ha^{-1}, thiencarbazone-methyl at 15 g ai ha^{-1} plus tembotrione at 75 g ai ha^{-1}, thiencarbazone-methyl at 37 g ha^{-1} plus isoxaflutole at 92 g ai ha^{-1}, or acetochlor at 1,080 g ai ha^{-1} plus mesotrione at 115 g ha^{-1} plus clopyralid at 73 g ae ha^{-1}) were applied alone or in combination with atrazine at 560 g ai ha^{-1} to glyphosate/glufosinate-resistant corn directly after planting or at a 30-cm corn height. Each postemergence treatment was mixed with labeled rates of glyphosate and glufosinate to resemble practical treatments common in corn. Injury and yield data were analyzed by year given the two unique environments. Palmer amaranth, broadleaf signalgrass, and pitted morningglory control was always greater than 95%. Saflufenacil plus dimethenamid-P injured corn 8 and 5 percentage points higher than *S*-metolachlor 14 days after the preemergence application in 2017 and 2018, respectively. Averaged over preemergence herbicide and atrazine rate, thiencarbazone-methyl plus isoxaflutole injured corn 21% in 2017. In 2018, treatments of *S*-metolachlor preemergence followed by (fb) thiencarbazone-methyl plus isoxaflutole caused 11% injury, which was higher than all other treatments. With both years combined, atrazine at 560 g ha^{-1} did not affect yield in 7 of 16 instances. Based on this research, the weeds assessed at the densities present can be controlled without atrazine.

Nomenclature: Acetochlor; bicyclopyrone; dimethenamid-P; glufosinate; glyphosate; isoxaflutole; mesotrione; saflufenacil; *S*-metolachlor; tembotrione; thiencarbazone-methyl; broadleaf signalgrass, *Urochloa platyphylla*; pitted morningglory, *Ipomoea lacunosa* L.; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; corn, *Zea mays* L.

Keywords: Weed control, corn tolerance

Introduction

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

Weed management in corn varies greatly depending on the geographical crop production region in the US. Webster and Nichols (2012) found that the weeds most frequently affecting corn in the southern US include morningglories (*Ipomoea* spp.), Texas millet (*Urochloa texana* Buckley R. Webster), broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], johnsongrass (*Sorghum halepense* L.), sicklepod (*Senna obtusifolia* L.), nutsedges (*Cyperus* spp.), and Palmer amaranth. The most troublesome weed is Palmer amaranth because if left uncontrolled for four weeks, just one plant m^{-1} of row may reduce corn yields up to 4% (Smith and Scott 2017). Palmer amaranth can also grow up to 2 m tall in less than 40 days in some environments (Bensch et al. 2003), meaning 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.

Row spacing manipulation, crop rotation, and seeding rate are all cultural control practices that have proven effective when implemented as part of an integrated weed management program. An increase in corn seeding rate has shown to decrease biomass production of velvetleaf (*Abutilon theophrasti* Medik.) and yellow nutsedge (*Cyperus esculentus* L.) (Ghafar and Watson 1983; Teasdale 1998). Another weed control tactic is mechanical weed control, which is removal of weeds by physical methods, such as cultivation or hoeing. In practice, this usually involves tillage. Mulder and Doll (1993) found that by making three passes with a rotary hoe, at least 89% of redroot pigweed (*Amaranthus retroflexus* L.) was controlled. However, this caused an 8% reduction in corn stand. When mechanical weed control was implemented in combination with chemical weed control (one pass with a rotary hoe and atrazine at 1.8 kg ha^{-1} in combination with metolachlor at 2.2 kg ha^{-1} applied postemergence), weed control was 96%, better than mechanical control alone. No difference in weed control was observed between mechanical control plus chemical control and chemical control alone; however, any pass with a rotary hoe caused yield loss compared to treatments without mechanical control.

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; 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-resistant horseweed [*Conyza canadensis* (L.) Cronq.], common ragweed (*Ambrosia artemisiifolia* L.), and pigweed (*Amaranthus* ssp.) evolved resistance to glyphosate from consecutive applications over a three to six years (Culpepper et al. 2006; Legleiter and Bradley 2008; Pollard et al. 2004; VanGessel 2001). From these findings, it is apparent that multiple SOAs should be applied in a growing season.

One way the crop protection industry has enabled use of multiple SOAs is through premixtures. An example of a premixture is Acuron Flexi®, which contains bicyclopyrone (WSSA group 27), mesotrione (WSSA group 27), and *S*-metolachlor (WSSA group 15). This premixture can be applied preemergence or postemergence to corn and combines two SOAs and provides foliar and residual control of many broadleaf and grass weeds (Anonymous 2016). By providing more than one effective SOA, some selection is taken off of a specific herbicide, thus slowing target-site resistance evolution (Norsworthy et al. 2012).

Another reason that 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 for weed control in corn is likely why atrazine is the most frequently found groundwater contaminant near land used for agricultural purposes (Barbash et al. 2006). Because atrazine is a main groundwater contaminant, care should be taken to reduce or eliminate the use of this herbicide where possible. Hence, research was initiated to explore weed control programs with a reduced rate of atrazine or without it.

Materials and Methods

Experimental Sites. In both 2017 and 2018, all field experiments were conducted on a Leaf silt loam (Fine, mixed, active, thermic Typic Albaquults) at the Arkansas Agricultural Research and Extension Center (AAREC) in Fayetteville, AR. 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.

Study Setup and Data Collection. All experiments used corn variety 1197YHR (Pioneer, 7000 NW 62nd Ave, Johnston, IA 50131) planted at 79,000 seeds ha^{-1} at a 5-cm depth into conventionally tilled, raised beds. Plot size was 3.7 m wide by 6.1 m long, and rows were spaced 91 cm apart. All trials were furrow irrigated and otherwise managed according to the Arkansas Corn Production Handbook (Espinoza and Ross 2015). This study was designed as a randomized complete block consisting of three factors. The three factors were 1) preemergence herbicide, 2) herbicide premixture applied postemergence, and 3) rate of atrazine (0 or 560 g ha^{-1}) applied with premixture (Table 1). Overall the study consisted of 16 treatments and one nontreated check, each replicated four times. Treatments were intended to represent herbicide programs that growers use in Arkansas corn production, either with or without atrazine, and therefore all received glyphosate at 1,260 g ae ha^{-1} and glufosinate at 450 g ha^{-1} with the postemergence application. Preemergence applications were made immediately following planting into a clean weed-free raised bed while postemergence applications were made when the corn was 30 cm tall. In 2017 and 2018, 2- to 6-cm tall Palmer amaranth at the postemergence application timing had a density of 4 and 5 plants m^{-2}, respectively, 1- to 5-cm tall broadleaf signalgrass averaged 16 and 25 plants m^{-2}, respectively, and 2- to 4-cm tall pitted morningglory averaged 2 and 3 plants m^{-2}, respectively. All applications were made with a CO_2-pressurized backpack sprayer at 140 L ha^{-1}. Dates of planting, herbicide applications, and harvest for each year are shown in Table 2. Visual estimates of corn injury and Palmer amaranth, broadleaf signalgrass, and pitted morningglory control were taken 21 days after the preemergence application (DAPRE) and 14 days after the postemergence application (DAPOST). The middle two rows of each plot were harvested at maturity using a small-plot combine, and yield was adjusted to 15.5% moisture.

Statistical Analysis. Data were analyzed by year due to environmental differences each year caused by the different planting dates. Weed control ratings for any weed was 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 analysis of variance using the GLIMMIX procedure in SAS Version 9.4 statistical software (SAS Institute Inc, Cary, NC), assuming a beta distribution for corn injury ratings and a gamma distribution for yield, to see if preemergence herbicide, herbicide premixture, atrazine, or interactions had an effect (Gbur et al. 2012). Given that preemergence herbicide was the only factor that could affect the corn at the 14 DAPRE, this analysis was conducted as a randomized complete block with preemergence herbicide as the only factor. Means for all analyses were separated using Fisher's protected LSD (p=0.05).

Results and Discussion

Weed Control. ***Preemergence Weed Control.*** The two preemergence herbicides were activated via rainfall (Figures 1 and 2) and provided exceptional control (>95%) of Palmer amaranth, broadleaf signalgrass, and pitted morningglory (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 the trial (Chomas and Kells 2004; Myers and Harvey 1993). Liebl et al. (2008) showed that saflufenacil controls broadleaf weeds such as redroot pigweed, common waterhemp (*Amaranthus rudis* L.), as well as a plethora of other broadleaf weeds, when applied preemergence. Therefore, when saflufenacil is applied in combination with dimethenamid-P, weed control spectrum and efficacy is increased (Moran et al. 2011). This study shows the utility of both *S*-metolachlor and saflufenacil plus dimethenamid-P as preemergence control options to complement or supplement current preemergence herbicides in corn.

Postemergence Weed Control. Postemergence weed control did not fall below 95% for any treatment 14 DAPOST (data not shown). Various premixes and herbicides were 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 barnyardgrass, entireleaf morningglory (*Ipomoea hederacea Jacq.),* and Palmer amaranth greater than 90% for four weeks after application (Stephenson and 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 and when applied postemergence in combination with 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 there are herbicides that can provide weed control comparable to atrazine-based weed control programs.

The introduction of glufosinate-resistant corn has been instrumental in control of glyphosate-resistant weeds. Glufosinate is a non-selective herbicide that controls most annual broadleaf weeds (Wychen et al. 1999); however, it is sometimes weak on grasses (Hamill et al. 2000). The inclusion of glyphosate likely eliminated grass weeds in all treatments as seen in other research (Shaw and Arnold 2002). The excellent control shown by these herbicides in this study demonstrates that effective options exist for weed control in the absence of atrazine.

Crop Injury. ***Preemergence Application.*** Corn injury 14 DAPRE was influenced by the preemergence herbicide applied ($P<0.0001$) in both years. Applications of saflufenacil plus dimethenamid-P injured corn 13 and 8% in 2017 and 2018, respectively, which was more than injury from *S*-metolachlor (data not shown). Similarly, Sarangi and Jhala (2018) found that preemergence applications of saflufenacil plus dimethenamid-P injured corn 15% when integrated into a reduced tillage system on a silt-loam soil, much like the soil in this experiment.

Postemergence Application. In 2018, corn injury was influenced by an interaction between the preemergence herbicide and the postemergence premixture ($P = 0.0001$) (Table 3). However, in 2017, corn injury was not affected by an interaction between preemergence herbicide and postemergence premixture and therefore data are presented separately by factor (Tables 3 and 4).

In 2017, averaged over premixture and atrazine, corn that received saflufenacil plus dimethenamid-P preemergence was injured more than corn that received *S*-metolachlor preemergence (Table 5). Given the higher injury that saflufenacil plus dimethenamid-P caused preemergence, corn may not have been able to recover in a timely manner. Injury appeared as phytotoxicity and mild chlorosis. Averaged over preemergence herbicide and atrazine rate, thiencarbazone-methyl plus isoxaflutole injured corn 21% in 2017 (Table 4). In 2018, treatments of *S*-metolachlor preemergence followed by (fb) thiencarbazone-methyl plus isoxaflutole caused 11% injury, which was higher than the other treatments in 2018. In general, thiencarbazone-methyl plus isoxaflutole-containing treatments were more injurious to corn 14 DAPOST. Comparable to these findings, Vollmer et al. (2017) found that thiencarbazone-methyl plus isoxaflutole injured corn 13% at 21 days after application when applied preemergence; therefore, when applied postemergence, injury is logical.

Yield. In 2017 and 2018, corn yield was influenced by a three-way interaction between preemergence herbicide, postemergence premixture, and atrazine ($P<0.0001$, 2017; $=0.0002$, 2018) (Table 3). In 2017, corn in treatments containing the premixture of bicyclopyrone plus mesotrione plus *S*-metolachlor yielded the highest, except when following *S*-metolachlor preemergence and combined with atrazine postemergence (Table 5). In 2018, corn in treatments containing the premixture of bicyclopyrone plus mesotrione plus *S*-metolachlor yielded the highest, except when following saflufenacil plus dimethenamid-P preemergence and combined with atrazine postemergence (Table 5). In 2018, corn in treatments that received saflufenacil plus dimethenamid preemergence fb thiencarbazone-methyl plus isoxaflutole with atrazine postemergence had lower yield than all other treatments (Table 5). Averaged over atrazine, corn injury for this treatment was also higher than injury from other treatments in 2018 (Table 4).

When looking at both years combined, atrazine at 560 g ha^{-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 highly safe 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 is 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 to other corn plots. An overall trend by year was difficult to uncover and more research is needed to accurately assess the yield effects that were noted in this study.

Practical Implications. The adequate weed control in this study is not an overall implication that atrazine is not needed in corn. The weed densities present in these trials were less than those observed in other research (Chomas and Kells 2004). These densities in combination with the timely application, led to a high level of weed control in both years. This study is not intended to show that atrazine is not needed, but rather that it can be applied at low rates when complemented or occasionally supplemented with other labeled herbicides to lessen the likelihood of resistance evolution and environmental contamination.

Although all preemergence herbicides and postemergence herbicides used are recommended in corn and were applied at labeled rates, some of the herbicides contained in the premixtures have been shown to cause injury on certain hybrids in different environments (Simmons and 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 further tested before recommendations are made that are applicable to multiple environments.

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Tables and Figures

Table 1. List of corn herbicides and rates used in herbicide treatments with manufacturers. [a]

Trade name	Common name	Rate	Timing	Manufacturer
		g ai or ae ha^{-1}		
Dual II Magnum	*S*-metolachlor	1070	PRE	Syngenta Crop Protection
Verdict	Saflufenacil + dimethenamid	60 + 530	PRE	BASF Crop Protection
Acuron Flexi	bicyclopyrone + mesotrione + *S*-metolachlor	45 + 180 + 1600	POST	Syngenta Crop Protection
Capreno	thiencarbazone-methyl + tembotrione	15 + 75	POST	Bayer CropScience
Corvus	thiencarbazone-methyl + isoxaflutole	37 + 92	POST	Bayer CropScience
Resicore	acetochlor + mesotrione + clopyralid	1080 + 115 + 73	POST	Dow AgroSciences
Roundup PowerMax II	Glyphosate	1260	POST	Bayer CropScience
Liberty	Glufosinate	450	POST	BASF Crop Protection
Aatrex	Atrazine	560	POST	Syngenta Crop Protection

[a] Abbreviations: PRE, preemergence; POST, postemergence.

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

	Dates of significance			
Year	Planting	Preemergence	Postemergence	Harvest
2017	May 26	May 26	June 16	October 25
2018	April 20	April 20	May 20	October 8

Table 3. Significance of P-values for interactions and main effects of preemergence (PRE) herbicide, postemergence (POST) premixture herbicides, and atrazine on corn injury at 14 days after postemergence application and grain yield by year for corn trials conducted in Fayetteville, AR, in 2017 and 2018.[a]

Year	Factor	Injury	Grain yield
		------- P-value ------	
2017	PRE	0.0386*	0.0011*
	POST	<0.0001*	<0.0001*
	Atrazine	0.5467	<0.0001*
	PRE*POST	0.1195	0.0014*
	PRE*Atrazine	0.7326	<0.0001*
	POST*Atrazine	0.2785	<0.0001*
	PRE*POST*Atrazine	0.8323	<0.0001*
2018	PRE	0.0054*	0.0448*
	POST	0.0003*	<0.0001*
	Atrazine	0.7094	0.2255
	PRE*POST	0.0001*	<0.0001*
	PRE*Atrazine	0.3849	<0.0001*
	POST*Atrazine	0.9838	0.0029*
	PRE*POST*Atrazine	0.7771	0.0002*

[a] Asterisks represent significance at P<0.05.

Table 4. Influence of preemergence herbicide and postemergence premixture on corn injury 14 days after postemergence application in Fayetteville, AR, in 2017 and 2018.[a,b]

Year	Factor	Injury
		%
2017	PRE	
	saflufenacil plus dimethenamid-P	9 a
	S-metolachlor	6 b
	POST	
	bicyclopyrone plus mesotrione plus *S*-metolachlor	3 b
	thiencarbazone-methyl plus tembotrione	2 b
	thiencarbazone-methyl plus isoxaflutole	21 a
	acetochlor plus mesotrione plus clopyralid	3 b
2018	PRE X POST	
	saflufenacil plus dimethenamid-P	
	bicyclopyrone plus mesotrione plus *S*-metolachlor	0 b
	thiencarbazone-methyl plus tembotrione	2 b
	thiencarbazone-methyl plus isoxaflutole	3 b
	acetochlor plus mesotrione plus clopyralid	1 b
	S-metolachlor	
	bicyclopyrone plus mesotrione plus *S*-metolachlor	1 b
	thiencarbazone-methyl plus tembotrione	4 b
	thiencarbazone-methyl plus isoxaflutole	11 a
	acetochlor plus mesotrione plus clopyralid	3 b

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[a] Means within a factor and year followed by the same letter are not significantly different according to Fisher's protected LSD (P=0.05).

[b] PRE data averaged over POST and atrazine in 2017; POST data averaged over PRE and atrazine in 2017.

Table 5. Influence of preemergence herbicide and postemergence premixture on corn yield in Fayetteville, AR, in 2017 and 2018.[a,b,c,d]

Factors			Yield			
			2017		2018	
PRE	POST	Atrazine	----------kg ha^{-1}----------			
S-metolachlor						
	bicyclopyrone plus mesotrione plus *S*-metolachlor	-	13440	a	17350	a
		+	12280	b	16370	ab
	thiencarbazone-methyl plus tembotrione	-	9690	d	12590	def
		+	11800	bc	14390	cde
	thiencarbazone-methyl plus isoxaflutole	-	9700	d	13560	def
		+	11840	bc	15490	bc
	acetochlor plus mesotrione plus clopyralid	-	9600	d	14290	cde
		+	11640	bc	14130	de
saflufenacil plus dimethenamid-P						
	bicyclopyrone plus mesotrione plus *S*-metolachlor	-	13590	a	17480	a
		+	13570	a	14700	cde
	thiencarbazone-methyl plus tembotrione	-	12340	b	14910	bcd
		+	11350	c	14140	de
	thiencarbazone-methyl plus isoxaflutole	-	11150	c	13650	def
		+	9530	d	11160	g
	acetochlor plus mesotrione plus clopyralid	-	9950	d	13760	de
		+	12330	b	14850	cd

[a] Abbreviation: PRE, preemergence application; POST, postemergence application.

[b] Means within a factor followed by the same letter are not significantly different within a year according to Fisher's protected LSD (p=0.05).

[c] Atrazine applied at 560 g ha^{-1}.

[d] Average yield of nontreated plots was 6660 and 6790 kg ha^{-1} in 2017 and 2018, respectively.

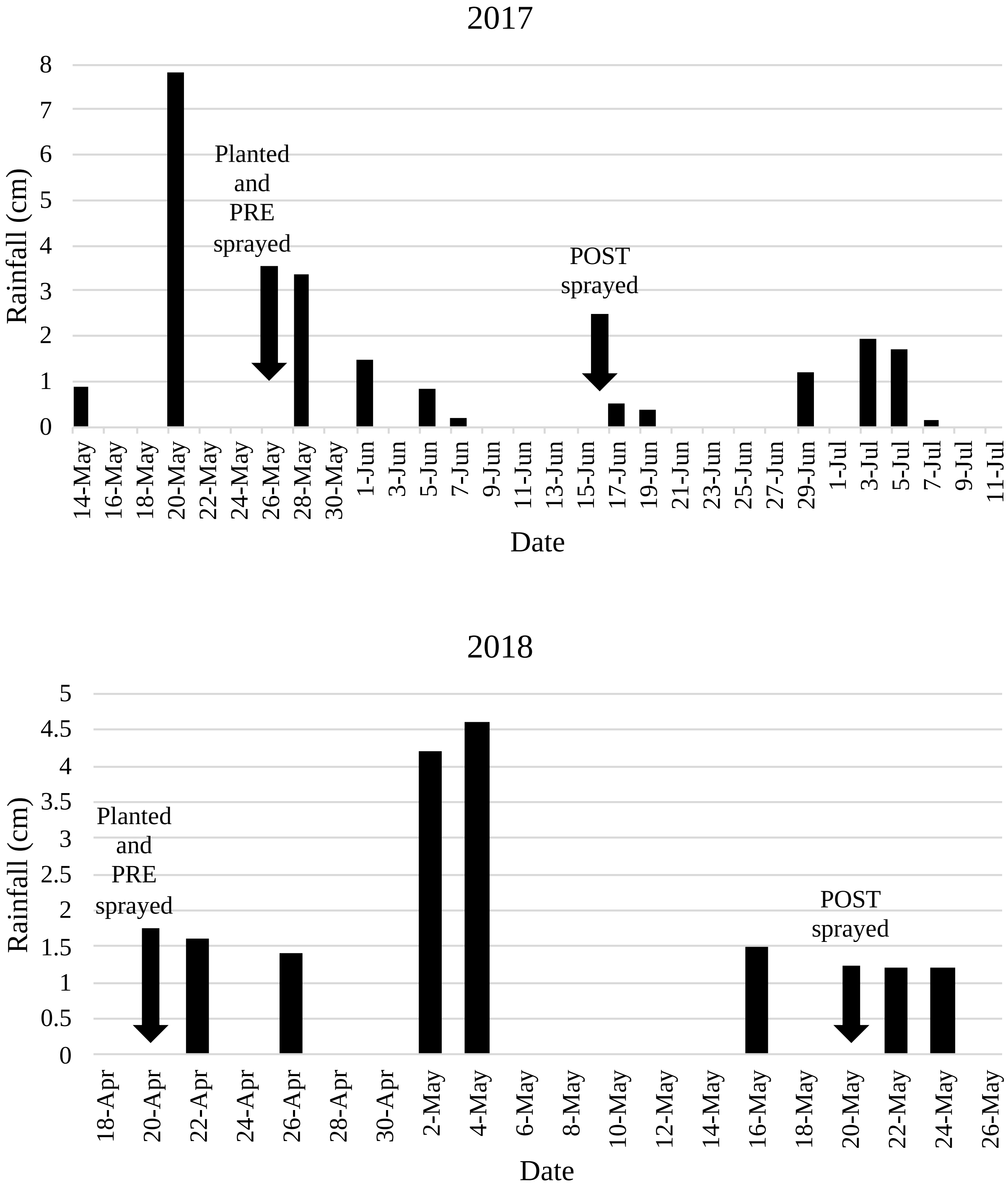

Figure 1. Rainfall amounts by day and planting and application dates at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, in 2017 and 2018.

Chapter 5

Tolerance of Grain Sorghum to Preemergence- and Postemergence-Applied Photosystem II-Inhibiting Herbicides

Abstract

Atrazine offers growers a reliable option to control a broad spectrum of weeds in grain sorghum when applied preemergence (PRE) or postemergence (POST). However, because of the extensive use of atrazine in grain sorghum and corn, it has become the most frequently found groundwater contaminant in the United States in trace amounts. Given these issues, field experiments were conducted in 2017 and 2018 in Fayetteville and Marianna, Arkansas, to explore the effects of PRE and POST applications of assorted photosystem II (PSII)-inhibiting herbicides in combination with mesotrione or *S*-metolachlor as atrazine replacements. All experiments were designed as a two-factor factorial, randomized complete block with the two factors being 1) PSII herbicide and 2) the herbicide added to create the mixture. The PSII 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; however, mesotrione was excluded in the preemergence experiments. Visual estimates of crop injury, relative height, and relative yield were collected or calculated in both studies. In the preemergence study, injury was below 10% for all treatments, except ones containing simazine, which caused 11% injury 28 days after application (DAA). Averaged over PSII herbicide, *S*-metolachlor-containing treatments caused 7% injury at 14 and 28 DAA. Grain sorghum in atrazine-containing treatments yielded 97% of the nontreated. Grain sorghum receiving other herbicide treatments had significant yield loss compared to atrazine-containing treatments. In the POST study, ametryn- and prometryn-containing treatments were more injurious than all other treatments 14 DAA. Grain sorghum yield in all POST treatments was comparable to atrazine, except prometryn plus mesotrione, which was 65% of the nontreated. More herbicides should be evaluated to find a comparable fit to atrazine when applied preemergence in grain sorghum. However, when applied POST, diuron, fluometuron, linuron, metribuzin, propazine, and simazine have some potential to replace atrazine and should be further tested as part of a weed control program across a greater range of environments.

Nomenclature: ametryn; atrazine; diuron; fluometuron; linuron; mesotrione; metribuzin; prometryn; propazine; simazine; corn, *Zea mays* L.; grain sorghum, *Sorghum bicolor* L.

Key words: Atrazine alternatives

Introduction

Grain sorghum was harvested on over 2 million hectares in the United States in 2018 (NASS 2018a). The challenges of individual management strategies, along with low commodity prices, cause grain sorghum production to fluctuate year to year. Producers that grow grain sorghum face challenges controlling disease and insects (Moore et al. 2009; Singh et al. 2004). Although disease and insects can be difficult to control, perhaps the most troublesome pests in grain sorghum are weeds. Weeds compete with grain sorghum for water, light, and soil nutrients. Burnside and Wicks (1969) found that sorghum yield may be reduced by 4, 12, and 18% when weeding is delayed by 3, 4, and 5 weeks, respectively. Since grain sorghum is a relatively low input crop, economic approaches to controlling weeds are vital.

Results from a survey conducted by Webster (2012) indicated that the top five most troublesome weeds in Arkansas grain sorghum were barnyardgrass (*Echinochloa crus-galli* (P.) Beauv.), Palmer amaranth [*Amaranthus palmeri* (S.) Wats.], morningglories (*Ipomoea spp.*), broadleaf signalgrass (*Urochloa platyphylla* Munro ex C. Wright), and johnsongrass [*Sorghum halepense* (L.) Pers.]. Given genetic similarities, johnsongrass can be especially difficult to control in grain sorghum (Kegode et al. 1994). Although all weeds pose yield loss threats to grain sorghum, Feltner et al. (1969) reported that broadleaf weeds left uncontrolled hinder yield more than weedy grasses.

Grain sorghum can tolerate both arid and wet climates: however, it is typically grown in semi-arid to arid climates (Arkin et al. 1976). These drier climates offer lower weed pressure than humid environments that allow weeds to thrive. Unfortunately, the Midsouth has a climate that is naturally suitable for a wide assortment of weeds. Although producers of cotton (*Gossypium hirsutum* L.), corn, soybean [*Glycine max* (L.) Merr.], and rice (*Oryza sativa* L.)

may be able to cope with weed pressure using new herbicide-resistant crop technologies, grain sorghum producers are restricted to a narrow selection of labeled herbicides. The restricted list of labeled herbicides has forced grain sorghum growers to diversify their weed management tactics by implementing control methods other than herbicides.

There are certain tactics producers may use to control weeds in grain sorghum. Cultural practices include twin-row planting, which may decrease weed seed germination by up to 15% (Grichar et al. 2004). As noted earlier, chemical weed control in grain sorghum offers few options. Limon-Ortega et al. (1998) eliminated velvetleaf (*Abutilon theophrasti* Medik.) and foxtail (*Setaria* spp.) by applying atrazine preemergence at 1.4 kg ha^{-1} and then atrazine at 0.9 kg ha^{-1} when grain sorghum was 25 cm tall. Other herbicides such as 2,4-D, dicamba, mesotrione, prosulfuron, and bromoxynil can be used for effective POST control of many broadleaf weeds, although timing of application according to weed size is vital for good control. However, atrazine is still today the foundational broad-spectrum herbicide used for weed control in grain sorghum as evidenced by it being applied to more than 650,000 ha annually (NASSb 2018).

Atrazine controls cocklebur (*Xanthium strumarium* L.), common ragweed (*Ambrosia artemisiifolia* L.), morningglories, and Palmer amaranth, as well as an assortment of monocot species when applied PRE or POST (Anonymous 2018; Culpepper and York 1999; Geier et al. 2009; Krausz and Kapusta 1998; Sprague et al. 1999 Webster et al. 1998). Although a highly effective herbicide, atrazine comes with potential drawbacks. Barbash et al. (2006) found that atrazine was the most frequent groundwater contaminant in underground drinking aquifers and shallow groundwater sources under agricultural areas, although at low levels not harmful to humans. According to Lasserre et al. (2009), atrazine in groundwater may harm humans, given his research on the effects of endocrine disruptors on human cells. Although this research is preliminary, it is still necessary for scientists to seriously consider a solution to these potential problems.

One simple solution to reducing atrazine detection in groundwater lies in decreasing the total amount of atrazine applied annually. By reducing the total amount of atrazine applied to agricultural soils, the chance of herbicide reaching aquifers and groundwater is lessened. However, as noted previously, atrazine is an essential tool for growers to control weeds in grain sorghum. Knowing this predicament, research was initiated to find potential replacements for atrazine. The objective of these studies was to test grain sorghum tolerance to other PSII-inhibiting herbicides alone and in combination with mesotrione and *S*-metolachlor when applied PRE or POST.

Materials and Methods

Grain Sorghum Trial Common Methodology. Field experiments were conducted in 2017 and 2018 to test grain sorghum tolerance to PRE and POST applications of PSII-inhibiting herbicides. All grain sorghum experiments were planted to variety DK553-67 (Dekalb, 800 N Lindbergh Blvd, Saint Louis, MO 63167), which was Concep®(fluxofenim)-treated and planted at 197,000 seeds ha^{-1} into conventionally tilled, raised beds at a 2-cm depth. Plot size was 3.7 m wide by 6.1 m long and all rows were spaced 91 cm and 97 cm apart in Fayetteville and Marianna, respectively. Grain sorghum was maintained weed-free with labeled applications of quinclorac and *S*-metolachlor and by hand-weeding as needed. All trials were furrow irrigated on an as-needed basis. Grain sorghum trials were otherwise managed according to the Arkansas Grain Sorghum Production Handbook (Espinoza and Ross 2015).

PRE Study Experimental Site. Field experiments were conducted in 2017 and 2018 on a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) at the Arkansas

Agricultural Research and Extension Center in Fayetteville, AR, and on a Memphis silt loam (Fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) at the Lon Mann Cotton Research Station near Marianna, AR. 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. The soil at Marianna consisted of 4% sand, 81% silt, and 15% clay, with an organic matter content of 1.25% and a pH of 6.6.

PRE Study Experimental Setup and Data Collection. All experiments were designed as a two-factor factorial, randomized complete block with the two factors being 1) PSII herbicide and 2) the herbicide added to create the mixture. The PSII herbicides were prometryn, ametryn, simazine, fluometuron, metribuzin, linuron, diuron, atrazine, and propazine (see Table 1 for rates and manufacturers). The second factor consisted of either no herbicide or *S*-metolachlor. PSII-inhibiting herbicides were applied at the same rate as they would be applied at in a labeled crop. All treatments were applied at 140 L ha^{-1} using a CO_2-pressurized backpack sprayer immediately following grain sorghum planting. The experiment consisted of 19 experimental treatments, including the nontreated, with each treatment replicated four times. Visible crop injury was estimated at 14 and 28 days after application (DAA) on a scale from 0 to 100, where 0 represented no crop injury and 100 represented complete crop necrosis. Canopy height of three random plants per plot was measured and recorded 28 DAA. Relative height was calculated by dividing the average of each plot by the overall average of the nontreated plots. Heights were not taken in Marianna in 2017 by oversight. Yield of the center two rows was collected with a small-plot combine and recorded as kg ha^{-1} after adjusting to 14% moisture and computed to relative yield by dividing the average of each plot by the overall average of the nontreated plots.

POST Study Experimental Site. Field experiments were conducted in 2017 and 2018 on a Captina silt loam in Fayetteville, AR, and on a Calloway silt loam (Fine-silty, mixed, active, thermic Aquic Fraglossudalfs) at the LMCRS near Marianna, AR. 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. The soil at Marianna consisted of 11.8% sand, 70% silt, and 18.2% clay, with an organic matter content of 1.25% and a pH of 6.4.

POST Study Experimental Setup and Data Collection. All experiments were designed as a two-factor factorial, randomized complete block with the two factors being 1) PSII herbicide and 2) the herbicide added to create the mixture. The PSII herbicides were prometryn, ametryn, simazine, fluometuron, metribuzin, linuron, diuron, atrazine, and propazine (Table 1). The second factor consisted of either no herbicide, mesotrione, or *S*-metolachlor. All treatments were applied at 140 L ha^{-1} when grain sorghum was 30 cm tall. The experiment consisted of 28 experimental treatments, including one nontreated, with each treatment replicated four times. Visible crop injury was recorded 14 and 28 DAA on a scale from 0 to 100, where 0 represented no crop injury and 100 represented complete crop necrosis. Canopy height of three random plants per plot was measured and recorded 28 DAA. Canopy height was then computed to relative height by dividing the average of each plot by the overall average of the nontreated. Heights were not taken in Marianna in 2017 by oversight. Yield of the center two rows was collected with a small-plot combine and recorded as kg ha^{-1} after adjusting to 14% moisture. Relative yield was calculated by dividing the average of each plot by the overall average of the nontreated.

Statistical Analysis. Analyses for the two trials were conducted in the same manner. To account for different environments and growing conditions between locations and years, all environments and replications nested within environments were considered random effects to permit inferences to be made over a range of conditions (Blouin et al. 2011; Carmer et al. 1989). Visual estimates of crop injury for the nontreated plots in all site-years were zero and therefore were excluded from analysis. Relative height and relative yield for nontreated plots in all site-years were equal to one and were therefore excluded from analysis. Data were 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 all assessments to see if the main PSII-inhibiting herbicide, the additive herbicide, or the interaction had an effect (Gbur et al. 2012). Mean separations were analyzed for injury, relative crop height, and relative yield using Fisher's protected LSD ($p=0.05$).

Results and Discussion

PRE Study. *Rainfall.* Amount and timing of rainfall are shown by site-year (Figures 1 and 2). Soil texture and organic matter are both important factors when considering the performance of soil-applied herbicides, but perhaps the most important is soil moisture (Curran 2001; Hartzler 2002). Because these soil-applied herbicides are taken up by the roots of germinating seedlings, at least 1 to 2 cm of irrigation or rainfall is necessary for activation within 7 days of application (Rao 2000). All studies received at least 2 cm of rainfall within 5 days of application (Table 2; Figures 1 and 2). Hence, it is assumed all herbicides were properly activated.

Injury. Grain sorghum injury 14 DAA was influenced by both main effects of PSII herbicide ($P = 0.0094$) and herbicide added ($P = 0.0018$) (Table 3), with less than 10% injury from all PSII herbicides, averaged over herbicide added (Table 4). When averaged over herbicide added, all injury was comparable to atrazine-containing treatments. When averaged over PSII herbicide, grain sorghum injury from *S*-metolachlor-containing treatments was higher than treatments with PSII herbicide alone (Table 4).

Again at 28 DAA, injury was influenced by both main effects (Table 3). Averaged over herbicide added, none of the PSII-inhibiting herbicides were different from atrazine in causing injury to grain sorghum (Table 4). When averaged over PSII herbicide at 28 DAA, *S*-metolachlor-containing treatments caused higher injury than PSII herbicides alone. Overall, injury observed at 14 and 28 DAA was minimal (<12%) for all treatments.

Relative Height. Crop height was influenced by the herbicide added ($P = 0.0104$) (Table 3). Generally, *S*-metolachlor-containing treatments, averaged over PSII herbicide, caused a 15% height reduction from nontreated plots, which was greater than PSII herbicide alone (Table 4). Similarly, in other research, Geier et al. (2009) found that *S*-metolachlor at 2.8 kg ha^{-1}, when applied PRE in combination with atrazine at 1.12 kg ha^{-1}, may cause occasional stunting in grain sorghum. Although height was reduced only by a few cm, this reduction complements the injury that was observed at 28 DAA (Table 4).

Relative Yield. Relative yield was influenced only by the main effect of PSII herbicide ($P = 0.0027$) (Table 3). Although there was minimal injury and height reduction, grain sorghum treated with atrazine had significantly less yield reduction than in plots treated with other PSII treatments (Table 4). Given the yield loss, it appears there was a yield loss component that went unmeasured. Although it was not recorded in this study, one potential reason for the yield loss observed could be attributed to a reduction in crop density caused by other non-atrazine-containing treatments. Another reason may be a hindrance in physiological development. Saeed et al. (1986) demonstrated that the period from emergence to bloom was vital for number of heads $plant^{-1}$ and seeds $head^{-1}$. If the sorghum plants are using sugars and energy towards the metabolism of herbicides during this time and not towards development, the effects would be observed in the yield. More research is needed to determine the yield loss mechanism(s) caused by these PSII herbicides and any differential effects on physiological development among them.

POST Study. ***Injury.*** Injury 14 DAA was influenced by an interaction between PSII herbicide and herbicide added (P<0.0001) (Table 3). Ametryn- and prometryn-containing treatments injured grain sorghum >28%, which was higher than other treatments (Table 5). Injury of the other treatments was less than 20%. Except for ametryn-, diuron-, and linuron-containing treatments, the addition of mesotrione to each PSII herbicide increased injury to grain sorghum (Table 5). The increased injury could be due to the synergy that occurs between some PSII herbicides and mesotrione (Abendroth et al. 2006). Except for diuron- and propazine-containing treatments, the addition of *S*-metolachlor, did not increase injury from a PSII herbicide. Unlike mesotrione, *S*-metolachlor has no foliar activity and is taken up only through the roots and shoots of plants (Fuerst 1987). Given that these applications were made to healthy, established plants, it is probable that the *S*-metolachlor had no effect on the plant.

Injury 28 DAA was influenced by the main effects of PSII herbicide (P < 0.0001) and herbicide added (P = 0.0022) (Table 3). Averaged over the herbicide added, ametryn- and prometryn-containing treatments caused 14 and 16% injury, respectively, which was higher than other PSII herbicides (Table 6). All other PSII herbicides caused comparable injury to atrazine-containing treatments, excluding linuron-containing treatments, which caused 6% injury. Averaged over PSII herbicides, mesotrione-containing treatments caused higher injury 28 DAA than treatments with no herbicide added or with *S*-metolachlor (Table 6).

Relative Height. Relative height was influenced by an interaction between PSII herbicide and herbicide added 28 DAA (P = 0.0011) (Table 3). Ametryn- and prometryn-containing treatments, excluding prometryn alone, reduced grain sorghum height compared to atrazine-containing treatments. The only other treatment that was not comparable to any atrazine-containing treatment was linuron alone, which suffered a 13% height reduction relative to the nontreated (Table 5). Plant height provides additional insight into the ability of a crop to metabolize certain herbicides. Generally, treatments that caused injury >25% 14 DAA reduced height by 10% or more. Although height was reduced by certain herbicide combinations when compared to atrazine combinations, the majority of treatments did not cause a biologically meaningful difference.

Relative Yield. Yield was influenced by an interaction between PSII herbicide and herbicide added (P = 0.0159) (Table 3). Grain sorghum yield for all treatments was comparable to atrazine-containing treatments, except for prometryn plus mesotrione, which also had the highest level of grain sorghum injury at 14 DAA and the greatest height reduction. Overall, yield from14 out of 15 treatments was comparable to atrazine-containing treatments.

Practical Implications. ***PRE Study.*** Recommending which herbicides should be further tested to potentially replace atrazine should be based on all response variables. However, yield is likely considered the most significant response when farmers grow a crop. In this study, no other treated grain sorghum yielded comparable to atrazine-containing treatments; therefore, it may be necessary to explore the possibilities of reducing these rates or testing additional herbicides other than the few tested in this experiment.

POST Study. All response variables should also be considered for POST applications of these herbicides. Herbicide treatments that failed to allow for grain sorghum to yield as much as atrazine-containing treatments should not be further tested as replacements for atrazine. Visible crop injury is the next factor that should be considered. Levels of injury greater than 15% are deemed unacceptable. Therefore, any ametryn- or prometryn-containing treatments should not be further tested at these rates. Based on both visible injury and grain sorghum yield, it is recommended that further research on weed control and crop tolerance be conducted for POST applications of diuron, fluometuron, linuron, metribuzin, prometryn, propazine, and simazine.

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Tables and Figures

Table 1. Herbicides, rates, and manufacturers for preemergence and postemergence corn trials in 2017 and 2018.

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	105[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] Mesotrione applied only in postemergence trial.

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

			Dates of significance		
Trial	Location	Year	Planting	Herbicide application	Harvest
PRE	Marianna	2017	May 17	May 17	September 18
		2018	May 25	May 25	September 19
	Fayetteville	2017	May 17	May 19	September 25
		2018	May 1	May 2	September 28
POST	Marianna	2017	May 15	June 8	September 18
		2018	May 18	June 7	September 19
	Fayetteville	2017	June 8	June 28	October 10
		2018	May 1	June 1	September 28

Table 3. Significance of P-values for interactions and main effects of PSII herbicide and herbicide added on grain sorghum injury, relative stand, relative height, and relative yield by application timing in grain sorghum trials.[a,b,c,d]

		Injury		Relative height	
Timing	Factor	14 DAA	28 DAA	28 DAA	Relative yield
		----------------------------- P-value		-----------------------------	
PRE	PSII herbicide	0.0094*	0.0002*	0.5007	0.0027*
	Herbicide added	0.0018*	0.0072*	0.0104*	0.1779
	PSII herbicide* Herbicide added	0.3106	0.5779	0.7215	0.1559
POST	PSII herbicide	<0.0001*	<0.0001*	<0.0001*	0.0741
	Herbicide added	<0.0001*	0.0022*	0.0887	0.9906
	PSII herbicide* Herbicide added	<0.0001*	0.2011	0.0011*	0.0159*

[a] Abbreviations: PRE, preemergence; POST, postemergence; DAA, days after application.

[b] Asterisks represent significance at $P < 0.05$.

[c] Data averaged across site-years within a timing.

[d] Marianna 2017 site-year was excluded from the relative height analysis.

Table 4. Grain sorghum injury, relative height, and relative yield as influenced by PSII herbicide and herbicide added in PRE trials.[a,b]

Factor	Herbicide	Injury 14 DAA	Injury 28 DAA	Relative height [e]	Relative yield [f]
PSII herbicide [c]		----------%----------		-------% of nontreated-------	
	ametryn	7 ab	5 b		86 bc
	atrazine	6 abc	6 ab		97 a
	diuron	6 abc	5 b		88 bc
	fluometuron	4 c	5 b		87 bc
	linuron	5 bc	5 b		87 bc
	metribuzin	4 c	4 b		87 bc
	prometryn	8 a	9 a		83 c
	propazine	9 a	9 a		91 b
	simazine	7 ab	11 a		90 b
Herbicide added [d]					
	none	3 b	4 b	90 a	
	S-metolachlor	7 a	7 a	85 b	

[a] Abbreviation: DAA, days after application.

[b] Means within a factor followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

[c] Injury averaged over herbicide added.

[d] Injury averaged over PSII herbicide.

[e] Height of plants in nontreated plots averaged across site-year was 26 cm. Marianna 2017 site-year was excluded from the analysis.

[f] Yield of nontreated plots averaged across site-years was 5180 kg ha^{-1}.

Table 5. Grain sorghum injury, relative height, and relative yield as influenced by interactions between PSII herbicide and herbicide added in POST trials.[a,b,c,d,e]

PSII herbicide	Herbicide added	Grain sorghum injury 14 DAA		Relative height		Relative yield	
		%		------% of nontreated------			
Ametryn	None	35	b	89	def	86	bcd
	Mesotrione	33	b	87	f	87	bcd
	S-metolachlor	29	b	87	f	88	bcd
Atrazine	None	2	kj	99	a	90	abcd
	Mesotrione	9	fghi	96	abc	88	bcd
	S-metolachlor	3	kj	96	abc	92	abc
Diuron	None	9	efgh	96	abc	88	bcd
	Mesotrione	15	cde	95	abcd	93	ab
	S-metolachlor	18	c	91	cdef	86	bcd
Fluometuron	None	4	ijk	96	abc	86	bcd
	Mesotrione	17	cd	94	bcdef	94	ab
	S-metolachlor	6	hij	92	bcdef	88	bcd
Linuron	None	13	cdefg	87	f	88	bcd
	Mesotrione	13	cdefg	93	bcdef	96	a
	S-metolachlor	14	cdef	95	abcde	92	abc
Metribuzin	None	8	ghi	93	bcdef	91	abcd
	Mesotrione	19	c	94	bcdef	90	abcd
	S-metolachlor	12	cdefg	97	ab	90	abcd
Prometryn	None	32	b	94	bcdef	94	ab
	Mesotrione	49	a	72	g	65	e
	S-metolachlor	33	b	88	ef	86	bcd
Propazine	None	1	k	96	abc	87	bcd
	Mesotrione	18	c	94	bcdef	81	de
	S-metolachlor	10	defgh	96	abc	89	bcd
Simazine	None	1	k	93	bcdef	86	bcd
	Mesotrione	13	cdefg	95	abc	82	cd
	S-metolachlor	3	kj	96	abc	87	bcd

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[a] Abbreviation: DAA, days after application.

[b] Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

[c] Grain sorghum injury, relative height, and relative yield averaged over site-years.

[d] Yield in the nontreated plots averaged across site-years was 5448 kg ha^{-1}.

[e] Height in the nontreated plots averaged across site-years was 72 cm. Marianna 2017 site-year was excluded from the analysis.

Table 6. Grain sorghum injury as influenced by PSII herbicide and herbicide added in POST trials.[a,b]

Factor	Herbicide	Grain sorghum injury	
		28 DAA	
PSII herbicide [c]		%	
	Ametryn	14	a
	Atrazine	3	cd
	Diuron	5	bc
	Fluometuron	5	bc
	Linuron	6	b
	Metribuzin	5	bc
	Prometryn	16	a
	Propazine	3	cd
	Simazine	2	d
Herbicide added [d]			
	None	4	b
	Mesotrione	8	a
	S-metolachlor	5	b

[a] Abbreviation: DAA, days after application.

[b] Means within a factor followed by the same letter are not significantly different according to Fisher's protected LSD (p=0.05).

[c] Injury averaged over herbicide added.

[d] Injury averaged over PSII herbicide.

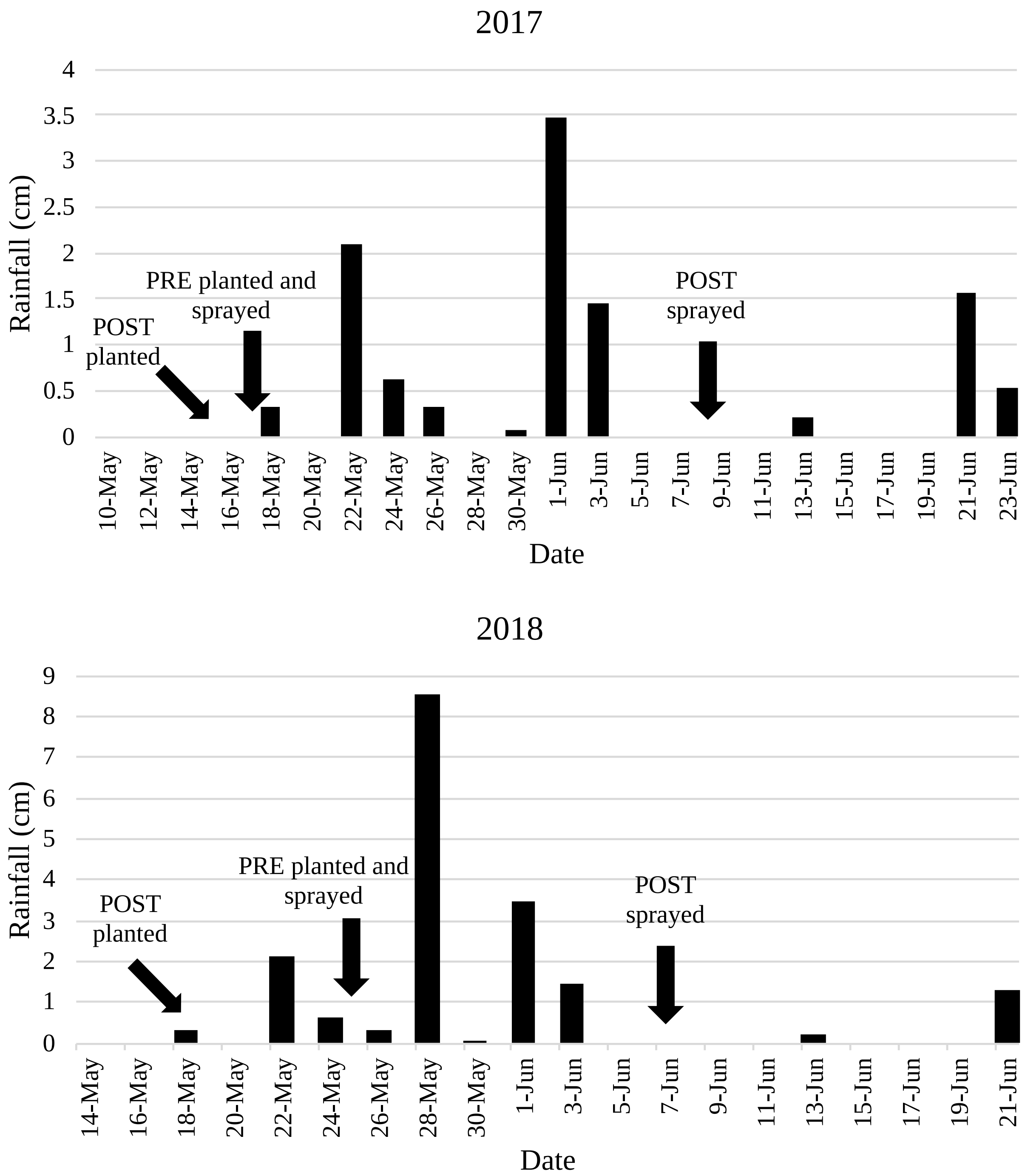

Figure 1. Rainfall amounts by day, planting dates, and preemergence (PRE) and postemergence (POST) application dates at Marianna, AR, in 2017 and 2018.

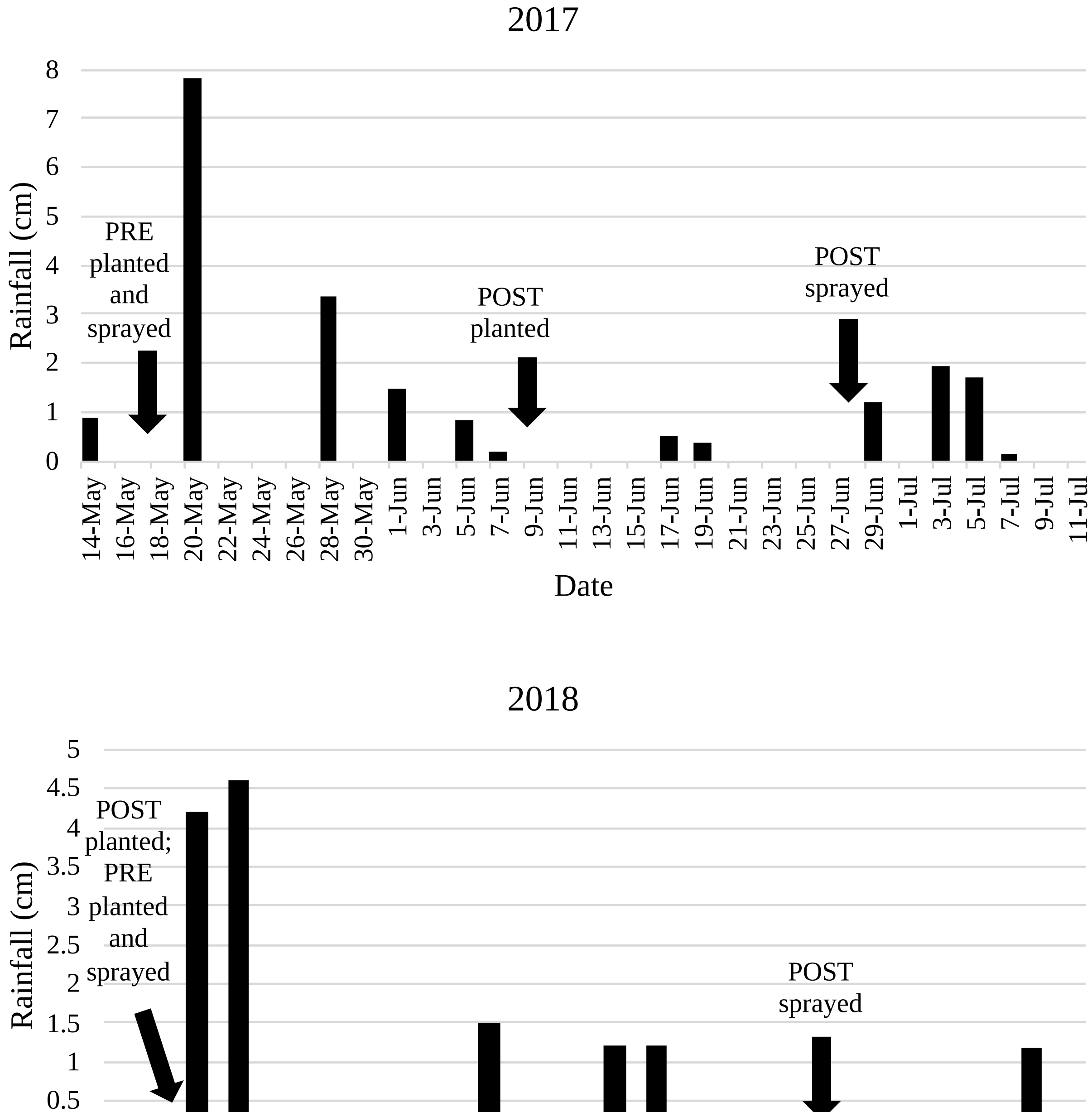

Figure 2. Rainfall amounts by day, planting dates, and preemergence (PRE) and postemergence (POST) application dates at Fayetteville, AR, in 2017 and 2018.

General Conclusions

The preliminary research conducted in these trials demonstrates potential atrazine alternatives if atrazine were to be banned. When applied preemergence in corn, diuron, linuron, metribuzin, and simazine are all herbicides that showed the most potential. When applied postemergence in corn, metribuzin and simazine were the only herbicides that were comparable to atrazine. No herbicide evaluated was comparable to atrazine when applied preemergence in grain sorghum. However, when applied postemergence, diuron, fluometuron, linuron, metribuzin, prometryn, propazine, and simazine were all herbicides that were comparable to atrazine. All tolerance trials should be repeated in a range of environments.

As demonstrated in this research, weed control in corn may be attainable without atrazine in certain areas under weed density similar to these trials. Also, current technologies, such as glyphosate- and glufosinate-resistance in corn may help control weeds in the absence of atrazine. More research should be conducted similar to this research to validate and expand upon the idea of replacing atrazine if it is banned.