12-10-2021

Mitigation of herbicide resistance development among weed species in cotton and peanut

Justin S. Calhoun
Mississippi State University, jsc625@msstate.edu

Mitigation of herbicide resistance development among weed species in cotton and peanut

By

Justin Scott Calhoun

Approved by:

Darrin M. Dodds (Major Professor)
L. Jason Krutz
Ashli Brown-Johnson
Tom Barber
Brendan Zurweller
Michael S. Cox (Graduate Coordinator)
Scott T. Willard (Dean, College of Agriculture and Life Sciences)

A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Plant and Soil Sciences
in the Department of Plant and Soil Sciences

Mississippi State, Mississippi

December 2021

Name: Justin Scott Calhoun

Date of Degree: December 10, 2021

Institution: Mississippi State University

Major Field: Plant and Soil Sciences

Major Professor: Darrin Dodds

Title of Study: Mitigation of herbicide resistance development among weed species in cotton and peanut

Pages in Study: 56

Candidate for Degree of Doctor of Philosophy

Herbicide resistance development among weed populations in cotton and peanut is becoming increasingly difficult to manage. If resistant populations continue to persist, weed control practices for producers will become less efficient and more costly. The objective of this research was to evaluate alternative weed control techniques designed to mitigate herbicide resistance development for their agronomic and economic impact on weed management systems. Studies were conducted in 2019, 2020, and 2021 at multiple locations in Mississippi and Arkansas investigating multiple techniques including the addition of soil surfactants in herbicide tank mixtures, increasing SOAs utilized in peanut herbicide programs, applying non-labeled herbicides to cotton with post-directed spray placement, and applying complete residual herbicide programs in cotton. Our results suggests that some novel strategies incorporated into existing weed management programs, can provide sufficient control of troublesome weed species and conserve crop yield and profit returns. For example, the use of post-directed application placement allowed for non-labeled herbicides to be applied to cotton without detrimental effects, thus increasing potential options for POST weed control within that crop. Additionally, weed control, seed cotton yield, and net returns were not affected when only residual herbicides were

applied in season-long weed control programs as opposed to the standard of mixed, foliar and residual programs. This indicates that high selection pressure associated with foliar chemistries which leads to resistance development, can be alleviated through the adoption of alternative strategies.

DEDICATION

To my wife, you are what has kept me going through all of this. Forever and always.

ACKNOWLEDGEMENTS

First, I would like to acknowledge my wife. Kennedy, you have followed me everywhere I have wanted to go without hesitation and have supported me in every step of the process. For that, I am forever grateful. God really did bless me with the greatest wife I could ask for. I can't wait to spend the rest of our lives exploring what He has in store for us.

Secondly, I would like to acknowledge all of my family that has supported Kennedy and I in this process. The unconditional love and sacrifices you all have made for me to make it to this point is appreciated. Specifically, dad, thank you for the love and sacrifices you have made as a father to ensure I had the best opportunities in life. Your example as a man of God and father is exactly what I hope to be one day.

To Dr. Dodds and my committee members, thank you for the mentorship you have provided me not only in the past few years but over my career thus far. I am in awe of the level of success and prominence that is represented by my committee and am proud to claim each one of you as a mentor and a model professional. Specifically, Drs. Dodds and Krutz, I can't thank you enough for your support in the later part of this journey. You guys stepped in during the darkest hour and ensured I would be successful.

Finally, I would like to thank my fellow students. The time we have spent together as a group have been some of the most fun experiences of my life. All of you I consider life-long friends and will always owe you a great debt.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

SURFACTANTS DECREASE S-METOLACHLOR AND FLUOMETURON SORPTION TO SOIL BUT DO NOT ALTER EFFICACY OF THESE HERBICIDES UNDER FIELD CONDITIONS

Abstract

Residual weed control is influenced by herbicide-soil interactions. This study was conducted to determine whether herbicide sorption to soils and subsequent residual weed control can be manipulated with surfactants included in tank mixtures. The effects of surfactants, Efficax®, Grounded®, Soiltrate™, and Sorbyx™, on *S*-metolachlor and fluometuron sorption in the laboratory and residual control of barnyardgrass with these herbicides under field conditions were investigated at the R.R. Foil Plant Science Research Center in Mississippi State, MS, on a Mantachie loam, Catalpa silty clay loam, and Marietta fine sandy loam. The addition of a surfactant never increased herbicide sorption to soil but, rather, had no effect or decreased the sorption of *S*-metolachlor and fluometuron up to 17.6- and 1.6-fold, respectively. Moreover, no surfactant influenced residual control of barnyardgrass. These data indicate that moderate effects of surfactants on sorption of *S*-metolachlor and fluometuron to soils will likely not alter efficacy of these herbicides under field conditions.

Keywords:

surfactant, *S*-metolachlor, fluometuron, barnyardgrass, sorption

Introduction

Soil-applied herbicides with residual activity can delay the development of herbicide resistance. Modeling data indicate that 74% of Palmer amaranth (*Amaranthus palmeri*) populations may develop glyphosate resistance when that chemistry is relied upon in a complete foliar weed control program (Neve et al. 2011). However, the potential for resistance development is reduced when residual, soil-applied herbicides are included as a component of a weed control program (Neve et al. 2011). Furthermore, when incorporated into tank mixtures or used in rotation, soil-applied chemistries diversify mechanisms of action, thereby reducing the potential for resistant populations to survive application and disseminate resistant traits to subsequent generations (Busi et al. 2020, Norsworthy et al. 2012). Therefore, means to extend residual activity of these chemistries may improve their ability to combat herbicide resistance development.

Surfactants may increase sorption of herbicide to soil. The commercially available surfactant Grounded® increased the sorption of amicarbazone, atrazine, hexazinone, imazapic, isoxaflutole, and pendimethalin to soil up to 32% (Fillos and Davis 2021). Surfactants Adbios 85 SL®, Adpros 85 SL®, Atpol®, Aureo®, Olbras 88 EC®, and Olejan 85 EC® increased the sorption of pendimethalin, metazachlor, and trifluralin up to 37% (Oliveria et al. 2020, Swarcewicz and Skorska et al. 1998). Atpolan®, a mineral oil and vegetable oil methyl ester surfactant, increased atrazine sorption by 1.5-fold (Swarcewicz and Skorska 2006). Increased sorption to soil may alter herbicide persistence and residual weed control.

Efficacy of soil-applied herbicides can be affected by surfactants. Parrafin oils and silicone-based adjuvants increased the control of oxyfluorfen and flurochloridone on common lambsquarters (*Chenopodium album*) and black bindweed (*Fallopia convovulus*) by up to 43% (Andr et al. 2017). Conversely, Grounded® had no effect on the efficacy of amicarbazone, atrazine, hexazinone, imazapic, isoxaflutole, and pendimethalin (Fillos and Davis 2021). Therefore, the effects of soil surfactant on residual herbicide activity may be chemistry, weed species, or soil texture dependent.

Cotton production in the Southern United States is dependent on *S*-metolachlor and fluometuron for residual control of problematic weed populations with widespread resistance development. Though these chemistries are applied in tank mixtures with soil-surfactants in some instances, there is no literature available to suggest that control of species common in Southern United States cotton production is affected by these mixtures. The objective of this research was to determine whether *S*-metolachlor and fluometuron sorption to soils and subsequent residual weed control can be manipulated with surfactants included in tank mixtures.

Materials and Methods

Sorption Study

Three soils of differing textures were collected from a depth of 0- to 15-cm at the R.R. Foil Plant Science Research Center at Mississippi State, Mississippi. Sites for each soil texture had either been in complete fallow, corn-fallow, or cotton-cotton rotations for at least two years prior to collection. Soil collection sites had no history of *S*-metolachlor or fluometuron application during the two-year period. Soil texture, organic matter content, cation exchange capacity, and pH were determined by the Mississippi State Soil Testing Laboratory (Table 1). Soil samples were sieved to remove particles >2 mm in size, dried in an air current oven at 65 ± 2˚C, and stored in plastic containers measuring 24 cm (L) x 24 cm (W) x 12 cm (H) with a sealed lid for one week prior to initiation of sorption experiments. Twenty-four hours prior to initiating sorption experiments, soils were dried at 65 ± 2˚C for 10 minutes to remove any accumulated moisture during storage.

A single point K_d was determined for all herbicide and soil combinations following the batch equilibration technique outlined by Konda et al. (2002). *S*-metolachlor and fluometuron were mixed at 10,140 and 12,773 µg mL^{-1}, respectively, in 250 mL of distilled water to represent 1x field application rates of each herbicide. Each herbicide solution was then mixed with either Efficax®, Grounded®, Soiltrate™, or Sorbyx™ surfactants (Table 2). Additionally, each herbicide was applied to each soil texture without surfactant. In 50 mL glass test tubes, a 25 mL aliquot of each herbicide solution was added to 2.5g of each soil texture resulting in a water to soil ratio of 10:1. Each herbicide treatment was replicated three times within each soil texture. Treatment combinations were then placed on an orbital shaker for 24 hours and subsequently centrifuged at 4000 rpm for 20 minutes. Ten milliliters of supernatant solution were removed from each tube and filtered through glass wool. Filtered samples were diluted with an acetonitrile/water mixture (3:1 v/v) to form a 1/10,000X solution of each treatment.

Herbicide concentrations in each diluted sample were quantified via liquid chromatography. Sample quantification was performed with an Agilent 1260 infinity liquid chromatograph coupled with an Agilent 6460 C triple quadrupole mass spectrometer. Chromatographic separation was performed using an Agilent Xorbax Eclipse Plus C18 (2.1 x 50 mm, 1.8-µm) analytical column. The mobile phases consisted of 0.1% formic acid in water for the aqueous phase (A) and 0.1% formic acid in acetonitrile as the organic phase (B). The flow rate was 0.3 mL/min with the following gradient program: 0 to 1 min of 10% A, and 1 min to 4 min of 90% B. *S*-metolachlor and fluometuron ionization was performed using electrospray ionization in positive mode with an auxiliary gas (N_2), source temperature of 300°C, and a gas flow rate of 5 L/min. Optimized multiple-reaction monitoring conditions are reported in Table 3.

Quantified herbicide concentrations within the supernatant of each sample were used to calculate a single-point K_d value for each treatment combination using the following equation:

$$K_d = C_s / C_{aq} \tag{1.1}$$

where:

C_s = herbicide concentration within solid soil matter (μg g^{-1}),

C_{aq} = concentration of herbicide in aqueous solution (μg mL^{-1}).

$$C_s = (C_{aq}^{initial} - C_{aq}^{final}) \times \frac{sample\ volume\ (mL)}{mass\ of\ solid\ (g)} \tag{1.2}$$

where all concentration units were calculated in μg mL^{-1}.

Calculated K_d values were subjected to analysis of variance (ANOVA) using a mixed effect model in RStudio where replication was treated as a random effect. Soil texture and surfactant were treated as fixed factors. In addition, potential soil texture and surfactant interactions were investigated for their contribution to variation in K_d. A significant interaction between soil texture and surfactant with respect to K_d of *S*-metolachlor (P value < $2.2e^{-16}$) and fluometuron (P value $1.934e^{-10}$) was present; therefore, data were analyzed by soil texture. Means were separated using Fisher's protected least significant difference (LSD) (α=0.05).

Herbicide Efficacy Study

Field studies were conducted at the R.R. Foil Plant Science Research Center, Mississippi State, MS in 2019 and 2020 to evaluate surfactant effects on residual weed control (Table 4). *S*-metolachlor[4] and fluometuron[5] were applied at 1.42 and 1.79 kg ha^{-1}, respectively, both alone and in combination with surfactants (Table 2). The experimental design was a randomized complete block with four replicates of each treatment in a two by four factorial arrangement. Herbicide-surfactant combinations were applied with a CO_2 pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} through four AIXR 110015 nozzles. Each experimental unit consisted of four 97 cm raised beds that were 9.1 m in length. Beds were prepared in the fall of each preceding year with a pan-style bedding implement. Forty-eight hours prior to crop planting, beds were smoothed with a rolling basket implement and existing weeds were terminated using paraquat at 1.1 kg active ingredient ha^{-1}. Cotton variety, DP 1646 B2XF, was seeded at 111,150 plants ha^{-1} with a John Deere MaxEmerge 1700 planter. Herbicide-surfactant treatments were applied to the center two rows of each experimental unit immediately after cotton planting. An incorporating rainfall of at least 1.3 cm occurred within seven days of application.

Data collection consisted of visual evaluation of barnyardgrass (*Echinochloa crus-galli*) control at 28, 35, and 42 days after treatment (DAT). Evaluations were made on a 0 to 100 scale where 0 equals no weed control and 100 equates to completed control.[10] Data were subjected to ANOVA using a mixed model in RStudio. Site-year and replication were treated as random effects. Herbicide-surfactant combinations were treated as fixed effects. Means were separated using Fisher's protected LSD (α=0.05).

Results and Discussion

Sorption Study

The primary hypothesis for this research was that inclusion of a surfactant would increase herbicide sorption to soil. Contrary to our hypothesis, the inclusion of a surfactant with *S*-metolachlor and fluometuron in tank mixtures either had no effect or decreased the sorption of the herbicides to soil up to 17.6- and 1.6-fold, respectively (Table 5). The inclusion of a soil surfactant had a greater adverse effect on the sorption of *S*-metolachlor to soil than that of fluometuron. Therefore, our data indicate that it is unlikely that the inclusion of Efficax®, Grounded®, Soiltrate™, or Sorbyx™ in a tank mixture with *S*-metolachlor or fluometuron will increase the sorption of these herbicides to soil.

Consistent with the results from our study, existing literature indicates that the effect of surfactants on sorption of herbicides to soils varies due to surfactant, herbicide, and soil texture combinations. The inclusion of Atpolan® in an isoxaflutole tank mixture had no effect on sorption when applied to a sandy loam textured soil (Swarcewicz and Skorska 2006). The addition of Grounded® increased sorption of amicarbazone, dimethenamid-P, hexazinone, pendimethalin, imazapic, and isoxaflutole up to 11.5-fold when applied to a silt loam soil (Fillos and Davis 2021, Kocarek et al. 2018). Tank mixing the oil-based adjuvants, Adbios 85 SL®, Adpros 85 SL®, Atpol®, Aureo®, Olbras 88 EC®, Olejan 85 EC®, increased sorption of metazachlor, pendimethalin, and trifluralin up to 7.7-fold when applied to soil textures ranging from loamy sand to sand (Kucharski and Sadowski 2011, Oliveira et al. 2020, Swarcewicz et al. 1998). Similarly, the addition of X-77, a non-ionic surfactant, increased the sorption of norflurazon up to 1.2-fold when applied to multiple soil textures (Locke et al. 2002). Atrazine sorption to a sandy loam soil increased 1.5-fold when applied with Atpolan® (Swarcewicz and

Skorska 2006) but decreased when applied with X-77 (Locke et al. 2002). The addition of X-77 also decreased sorption of cyanazine up to 1.4-fold. Reductions in sorption of herbicides could be due to competitive binding where organic surfactants are blocking herbicide from reaching soil pores (Wu et al. 2018, Wang et al. 2018). These data indicate that it may be necessary to screen multiple surfactants, herbicides, and soil texture combinations before accurate predictions of surfactant effects on herbicide sorption can be elucidated.

Herbicide Efficacy Study

The primary hypothesis for this research was the addition of a surfactant to herbicide tank mixtures would increase residual weed control. Contrary to our hypothesis, the addition of surfactants to tank mixtures containing *S*-metolachlor or fluometuron had no effect on the residual barnyardgrass control up to 42-days after application (Table 6). Therefore, utilization of Efficax®, Grounded®, Soiltrate™, or Sorbyx™ in tank mixtures with *S*-metolachlor or fluometuron will not increase residual barnyardgrass control.

The addition of surfactants typically has no effect on residual weed control. For example, tank mixing imazapic, hexazinone, amicarbazone, isoxaflutole, pendimethalin, and atrazine with Grounded® had no effect on the residual control of awnless barnyardgrass, crowsfoot (*Dactyloctenium aegyptium*), green summer grass (*Urachloa subquadripara*), Southern crabgrass (*Digitaria ciliaris*), blue top (*Ageratum conzoides*), sensitive weed (*Mimosa pudica*), prickly spider flower (*Cleome aculeata*), red convolvulus (*Ipomoea hederifolia*) and pink convolvulus (*Ipomoea triloba*) (Fillos and Davis 2021). Additionally, the inclusion of parrafin oils with flurochlroridone, linuron, or oxyfluorfen had no effect on control of black bindweed, barnyardgrass, European field pansy (*Violoa arvensis*), or volunteer oilseed rape (*Brassica napus*) (Andr et al. 2017). However, addition of parrafin oils to oxyfluorfen increased common lambsquarters (*Chenopodium album*) control by 33% (Andr et al. 2017). Inclusion of a silicon surfactant with flurochloridone and oxyfluorfen increased black bindweed control up to 33% and common lambsquarters up to 43% (Andr et al. 2017). Existing literature along with these data indicate that it may be necessary to screen multiple surfactants, herbicides, and weed species before making accurate predictions of surfactant effects on herbicide efficacy.

Conclusion

This research was conducted to determine whether herbicide sorption to soils and subsequent residual weed control can be manipulated with surfactants. Incorporating evaluated surfactants into tank mixes containing *S*-metolachlor or fluometuron either had no effect or decreased sorption of herbicides to soils up to 17.6- to 1.6-fold, respectively. Moreover, addition of surfactants to tank mixes had no effect on residual barnyardgrass control with *S*-metolachlor or fluometuron. Moderate effects of the evaluated surfactants on sorption of *S*-metolachlor and fluometuron to soils will not alter efficacy of these herbicides under field conditions.

Tables

Table 1.1 Characteristics of soils collected from the R.R. Foil Plant Science Research Center, Mississippi State, MS used in studies investigating sorption of *S*-metolachlor and fluometuron when using surfactants Grounded®, Sorbyx™, Efficax®, and Soiltrate™

[a]Soil Texture	Taxonomic Class	% sand[b]	% silt[b]	% clay[b]	% OM[c]	CEC[d]	pH[e]
Marietta fine sandy loam	fine-loamy, siliceous, active, thermic Fluvaquentic Eutudepts	70.9	16.6	12.5	0.4	11.1	8.1
Catalpa silty clay loam	fine, smectitic, thermic Fluvaquentic Hapludolls	17.8	52.2	30	2.8	34.0	8.0
Mantachie loam	fine-loamy, siliceous, active, acid, thermic Fluventic Endoaquepts	40	45	15	1.7	11.1	6.4

[a]Samples of each soil texture collected consist of the uppermost 0- to 15-cm of cultivated soil profile.
[b]Percent sand, silt, and clay estimated using Web Soil Survey (NRCS).
[c]Percent organic matter calculated using dry combustion method (Allison 1965).
[d]Cation exchange capacity derived by using the summation of the mille-equivalents of the major base cations (Doll and Lucas 1973, Issac and Jolmson 1977).
[e]Soil pH calculated using technique similar to those used by Schofield and Taylor (1955).

Table 1.2 Surfactants used to investigate effects of sorption and weed efficacy in *S*-metolachlor and fluometuron mixtures.

Surfactant	Ingredient	Rate (L ha^{-1})	Manufacturer Information
Grounded®	aliphatic hydrocarbons, hexahydric alcohol, ethoxylates, and fatty acids and alkanolamides	3.5	Helena Agri-Enterprises LLC, 225 Schilling Blvd., Collierville, TN 38017, USA
Sorbyx™	branched alkylphenol ethoxylate, oleic acid	0.9	Precision Laboratories, 1429 S. Shields Drive Waukegan, IL 60085, USA
Efficax®	esterified seed oil	0.6	Wilbur Ellis, 2001 SE Columbia River Dr. Vancouver, WA 98661 USA
Soiltrate™	petroleum oil, ethoxylated soybean oil, tall oil fatty acids	4.7	CHS Inc., 5500 Cenex Drive Inver Grove Heights, MN 55077 USA

Table 1.3 Liquid chromatography-mass spectrometry instrument parameters for herbicide quantification.

	LC/MS/MS MRM condition				
Herbicide	Precursor Ion (m/z)	Product Ion (m/z)	Fragmentor	Collision Energy (eV)	Polarity
S-metolachlor	284.1	252.1	69	9	+
S-metolachlor	284.1	176.2	69	25	+
fluometuron	233.1	145	89	37	+
fluometuron	233.1	56.1	89	50	+

Table 1.4 Soil textures and taxonomic classes for field sites used in barnyardgrass efficacy studies investigating surfactant with *S*-metolachlor and fluometuron mixtures.

Year	**Location**	**Soil texture**	**Taxonomic Class**
2019	R.R. Foil – Site 1	Mantachie loam	Fine-loamy, siliceous, active, acid, thermic Fluventic Endoaquepts
	R.R. Foil – Site 2	Marietta fine sandy loam	Fine-loamy, siliceous, active, thermic Fluvaquentic Eutrudepts
2020	R.R. Foil	Mantachie loam	Fine-loamy, siliceous, active, acid, thermic Fluventic Endoaquepts

Table 1.5 Calculated single-point K_d values of *S*-metolachlor and fluometuron with Efficax®, Grounded®, Soiltrate™, or Sorbyx™ surfactants in Marietta fine sandy loam, Caltapa silty clay loam, and Mantachie loam soil mixtures.

Soil Type	**Surfactant**[b]	***S*-metolachlor**[a]	**fluometuron**[a]
		------------------------K_d[c]	------------------------
Marietta fine sandy loam	Efficax®	13c	1026 ab
	Grounded®	16 c	801 bc
	Soiltrate™	40 bc	702 c
	Sorbyx™	55 b	919 abc
	none	190 a	1113 a
	P value	< 0.0001	0.0042
Catalpa silty clay loam	Efficax®	220 a	1131
	Grounded®	20 b	1028
	Soiltrate™	26 b	1177
	Sorbyx™	23 b	1109
	none	245 a	1099
	P value	< 0.0001	0.9134
Mantachie loam	Efficax®	11 b	1442
	Grounded®	6 b	1470
	Soiltrate™	10 b	1301
	Sorbyx™	6 b	1212
	none	110 a	1184
	P value	< 0.0001	0.0932

[a]S-metolachlor and Fluometuron mixed at an initial rate of 10,140 and 12,773 µg mL^{-1}, respectively.

[b]Efficax®, Grounded®, Soiltrate™, and Sorbyx™ mixed 0.6, 3.3, 4.7, and 0.9 L ha^{-1}, respectively.

[c]Means with different letters are statistically different using Fishers protected LSD (α=0.05).

Table 1.6 Control of barnyardgrass (*Echinochloa crus-galli*) to *S*-metolachlor and fluometuron when tank mixed with Efficax®, Grounded®, Soiltrate™, or Sorbyx™ surfactants on Mantachie loam and Marietta fine sandy loam soils at the R.R. Foil Plant Science Research Center, Mississippi State, MS.

	barnyardgrass control					
	***S*-metolachlor**			**fluometuron**		
Surfactant[b]	**28 DAT[c]**	**35 DAT[c]**	**42 DAT[c]**	**28 DAT[c]**	**35 DAT[c]**	**42 DAT[c]**
	-----------------------	-----------------------	-----------------------	% -----------------------	-----------------------	-----------------------
Efficax®	94	89	82	90	80	76
Grounded®	94	84	80	90	79	73
Soiltrate™	92	82	76	92	85	79
Sorbyx™	90	82	77	89	78	75
none	91	86	74	86	79	70
P value[d]	0.0772	0.0675	0.2116	0.6937	0.8669	0.6864

[a]*S*-metolachlor and fluometuron applied at a rate of 1.42 and 1.79 kg ha^{-1}, respectively.
[b]Efficax®, Grounded®, Soiltrate™, and Sorbyx™ mixed 0.6, 3.3, 4.7, and 0.9 L ha^{-1}, respectively.
[c]Days after treatment.
[d]P values determined using ANOVA in RStudio (lme4 package).

Literature Cited

1. P. Neve, J.K. Norsworthy, K.L. Smith, I.A. Zelaya, "Modeling Glyphosate Resistance Management Strategies for Palmer Amaranth (*Amaranthus palmeri*) in Cotton," *Weed Technol* 25, (2011), 335–343.

2. R. Busi, S.B. Powles, H.J. Beckie, M. Renton, "Rotations and mixtures of soil-applied herbicides delay resistance," *Pest Manag Sci* 76, (2020), 487–496.

3. J.K. Norsworthy, S.M. Ward, D.R. Shaw, R.S. Llewellyn, R.L. Nichols, T.M. Webster, K.W. Bradley, G. Frisvold, S.B. Powles, N.R. Burgos, W.W. Witt, M. Barrett, "Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations," *Weed Sci* 60, (2012), 31–62.

4. E.F. Fillols, A. Davis, "Effect of the soil-binding adjuvant Grounded® on herbicide efficacy and runoff losses in bare soil in ratoons," *Proc Aust Soc Sugar Cane Technol* 42, (2021), 555–562.

5. G.F.P.B.D. Oliveira, A.C. Langaro, A.L. Simões Araujo, R.F. Pimpinato, V.L. Tornisielo, C.F.D. Pinho, "Sorption and desorption of pendimethalin alone and mixed with adjuvant in soil and sugarcane straw," *J Environ Sci Heal - Part B Pestic Food Contam Agric Wastes* 55, (2020), 1114–1120.

6. M. Swarcewicz, Z. Muliński, I. Zbieć, "Influence of spray adjuvants on the behavior of trifluralin in the soil," *Bull Environ Contam Toxicol* 60, (1998), 569–576.

7. M. Swarcewicz, E. Skorska, "Influence of an Adjuvant on the Distribution of Herbicides in a Sediment/Water System," *Commun Agric Appl Biol Sci* 71, (2006), 147–154.

8. J. Andr, M. Kočárek, M. Jursik, V. Fendrychova, L. Tichy, "Effect of adjuvants on dissipation, efficacy, and selectivity of three different pre-emergent sunflower herbicides," *Plant Soil Environ* 63, (2017), 409–415.

9. L.N. Konda, I. Czinkota, G. Fuleky, G. Morovjan, "Modeling of single-step and multistep adsorption isotherms of organic pesticides on soil," *J Agric Food Chem* 50, (2002), 7326–7331.

10. R. Frans, R. Talbert, D. Marx, H. Crowley, "Experimental design and techniques for measuring and analyzing plant responses to weed control practices," in *Research Methods in Weed Science* ed. N.D. Camper (Madison, WI, Southern Weed Science Society, 1986), 29–46.

11. M. Kočárek, R. Kodešová, U. Sharipov, M. Jursík, "Effect of adjuvant on pendimethalin and dimethenamid-P behaviour in soil," *J Hazard Mater* 354, (2018), 266–274.

12. M. Kucharski, J. Sadowski, "Behaviour of metazachlor applied with additives in soil: laboratory and field studies," *J Food, Agric Environ* 9, (2011), 723–726.

13. M.A. Locke, K.N. Reddy, L.A. Gaston, R.M. Zablotowicz, “Adjuvant modification of herbicide interactions in aqueous soil suspensions,” *Soil Sci* 167, (2002), 444–452.

14. D Wu, Y Yun, L Jiang, C Wu, “Influence of dissolved organic matter on sorption and desorption of MCPA in ferralsol,” *Sci Total Environ* 616, (2018), 1449–1456.

15. B Wang, C Liu, Y Chen, F Dong, S Chen, D Zhang, J Zhu, “Structural characteristics, analytical techniques and interactions with organic contaminants of dissolved organic matter derived from crop straw: a critical review,” *RSC Adv* 8, (2018), 36927–36938.

16. NRCS, USDA, Web Soil Survey. https://perma.cc/LC89-UBP8

17. L.E. Allison, “Organic carbon,” in *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*, ed. A.G. Norman (Madison, WI, American Society of Agronomy, 1965) 1367–1378.

18. E.C. Doll, R.E. Lucas, “Testing soils for potassium, calcium, and magnesium,” in *Soil Testing and Plant Analysis* ed. L.M. Walsh and J.D. Beaton (Madison, WI, Soil Science Society of America, 1973) 133–151.

19. R.A. Issac, W.C. Jolmson, “Methodology for the analysis of soil, plant, feed, water and fertilizer samples,” (Athens, GA, Cooperative Extension Service, Soil Testing and Plant Analysis Laboratory, 1977).

20. R.K. Schofield, A.W. Taylor, “The Measurement of Soil pH,” *Soil Sci Soc Am J* 19, (1955), 164–167.

CHAPTER II

BROADLEAF SIGNALGRASS (*UROCHLOA PLATYPHYLLA*) RESPONSE TO INCREASING SITES OF ACTION IN PEANUT HERBICIDE

Abstract

The inclusion of multiple sites of action (SOAs) is the foundation for herbicide resistance management. The objective of this research was to determine the minimum number of SOAs required to maximize control of a model weed species as part of a resistance management program in peanut. The effects of up to eight SOAs on the control of broadleaf signalgrass when applied PRE, PRE followed by EPOST, and PRE followed by EPOST followed by LPOST in peanut were investigated at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the W.B. Andrews Agriculture Systems Research Farm, near Mississippi State, MS, and the Coastal Plain Branch Experiment Station, near Newton, MS. Currently, complete peanut herbicide programs include five to seven SOAs. Under the conditions of this experiment, the minimum number of SOAs required to maximize broadleaf signalgrass control from 7 up to 28 days after application was one PRE, three by EPOST, and six by LPOST. These data indicate that to achieve season-long broadleaf signalgrass control, the addition of more SOAs beyond current common practices is not necessary.

Nomenclature

flumioxazin; carfentrazone; lactofen; pyroxasulfone; 2,4-DB, paraquat, imazapic; ethalfluralin; bentazon; glyphosate; clethodim; broadleaf signalgrass, *Urochloa platyphylla*; peanut, *Arachis hypogaea*

Introduction

Inclusion of multiple herbicide sites of action (SOAs) is foundational for sustainable weed control programs. Sites of action are the location within plants where the herbicide affects a physiological process thereby causing inhibition of growth and development and/or plant death. Individual SOAs are used to classify herbicides into groups (Weed Science Society of America n.d.). As of late, discussion has surrounded SOA grouping as repeated applications of herbicides in the same group has facilitated herbicide resistance (Vencill et al. 2012).

Not applying more than one SOA expedites resistance development. Repeated use of glyphosate resulted in resistance development within four years in 100% of modeled weed species (Neve 2008). Up to 18% of individuals in a modeled Palmer amaranth (*Amaranthus palmeri*) population developed resistance to glyphosate after four years of repeated simulated application (Neve et al. 2011). Barnyardgrass (*Echinochloa crus-galli*) populations can produce up to 47% resistant individuals after 15 years of repeated glyphosate applications (Bagavathiannan et al. 2013). Production systems that do not utilize diversified herbicide programs are susceptible to resistance development.

In peanut (*Arachis hypogaea*) production systems, a small number of herbicide SOAs are relied on for control of troublesome weed populations. For example, flumioxazin, a SOA group 14 herbicide, was applied to 65% of the United States peanut acreage in 2018 (USDA 2019). Applied alone, flumioxazin preemergence (PRE) provides 90% or greater control of Florida beggarweed (*Desmodium tortuosum*), morningglory spp. (*Ipomoea* spp.), Palmer amaranth, bristly starbur (*Acanthospermum hispidum*), and common lambsquarters (*Chenopodium album*) (Askew et al. 1999, Grey and Wehtje 2005). Control of these species was improved up to 1.3-fold when lactofen or acifluorfen, both SOA group 14 herbicides, were tank mixed with 2,4-DB postemergence (POST) (Askew et al. 1999). Salas et al. (2016) suggested that reliance on group 14 herbicides in row crop agriculture has resulted in protoporphyrinogen oxidase resistance in Palmer amaranth. Therefore, the addition of more SOAs in peanut herbicide programs may be necessary to effectively control weed populations and mitigate resistance development.

Rotating multiple SOAs is an effective strategy to control problematic weed populations, delay resistance development, and ensure cropping system sustainability. Applying multiple SOAs in herbicide programs reduced the potential for the resistance development in model weed populations (Diggle et al. 2003). Norsworthy et al. (2012) suggested that rotating SOAs will mitigate resistance development and conserve chemistries for future use. As such, the current resistance management paradigm is to apply the minimal number of SOAs required to achieve complete control of a weed population thereby preserving herbicide chemistries for applications in subsequent growing seasons. The objective of this research was, therefore, to determine the minimum number of SOAs required to maximize control of a model weed species in peanut cropping systems.

Materials and Methods

Studies investigating the optimum number of SOAs in peanut cropping systems were conducted in 2020 and 2021. Research was conducted at the R. R. Foil Plant Science Research Center at Mississippi State, MS and at the Coastal Plain Branch Experiment Station near

Newton, MS in 2020 and at the R.R. Foil Plant Science Research Center and the W.B. Andrews Agriculture Systems Research Farm both near Mississippi State, MS in 2021 (Table 1).

Treatments were based upon herbicide programs utilized in United States peanut producing regions encompassing SOA's that are commonly used. The baseline herbicide program for these studies was flumioxazin PRE followed by paraquat and pyroxasulfone early-postemergence (EPOST) followed by lactofen and 2,4-DB at late-postemergence (LPOST) (B. Zurweller, personal communication, 2020). Preemergence applications were applied immediately following planting, EPOST applications were applied 21 days after peanut emergence, and LPOST applications were applied 21 days following EPOST applications. From this base program, herbicides were incrementally added or removed to include one to nine SOAs applied in a single growing season (Table 2). Treatments were arranged in a randomized complete block design with four replicates. Experimental units consisted of four 97 cm raised beds measuring 9.1 m in length. Beds were prepared each year within 48 hours of planting with a lister-roller implement. Georgia-O6G peanut was planted at a rate of 20 seed per meter of row with a John Deere MaxEmerge 1700 planter. Herbicide treatments were applied to the center two rows of each experimental unit with a four-nozzle CO_2 pressurized backpack-sprayer calibrated to deliver 140 L ha^{-1} using AIXR 110015 (Teejet®, 1801 Business Park Dr, Springfield, IL 62703) nozzles. An incorporating rainfall of at least 2.5 cm occurred within seven days of PRE, EPOST, and LPOST applications.

Data collection consisted of visual evaluation of broadleaf signalgrass (*Urochloa platyphylla*) control at 7-, 14-, and 21-days following PRE and EPOST applications and 7-, 14-, 21-, and 28-days following LPOST applications. Evaluations were made on a 0 to 100 scale where zero equals no control and 100 equates to complete control (Frans et al. 1986). Data were subjected to analysis of variance using RStudio (lme4 package, R Studio, Version 1.4.1106) where site-year and replication were treated as random effects and herbicide treatment was treated as a fixed effect. Means were separated with Fisher's protected least significant difference (α=0.05).

Results and Discussion

The objective of this research was to determine the minimum number of SOAs required to maximize control of a model weed species as part of a resistance management program in peanut. The minimum number of SOAs required to maximize the control of broadleaf signalgrass from seven up to 28 days after application was one PRE, three by EPOST, and six by LPOST (Tables 3, 4, and 5). Currently, peanut herbicide programs typically include a total of five to seven SOAs. Therefore, these data indicate that to achieve season-long broadleaf signalgrass control, the addition of more SOAs beyond current common practices is not necessary.

Applying a single SOA PRE in peanut typically results in effective control of problematic weed species. Preemergence applications of ethalfluralin or pendimethalin provided up to 98% control of Texas millet (*Urochloa texanum*), Southern crabgrass (*Digitaria ciliaris*), and crowfoot grass (*Dactyloctenium aegyptium*) in peanut (Prostko et al 2001). Flumioxazin alone provided up to 99% control of Florida beggarweed, morningglory spp., Palmer amaranth, bristly starbur, and common lambsquarters (Askew et al. 1999, Grey and Wehtje 2005). The addition of another SOA to flumioxazin did not improve efficacy (Grey et al. 2002). Applications of flumioxazin tank mixed with glyphosate and glufosinate improved broadleaf signalgrass control up to 1.3-fold 21 DAT (Price et al. 2008). When tank-mixed with *S*-metolachlor or acetochlor, flumioxazin increased broadleaf signalgrass control up to 1.2-fold (Clewis et al. 2007, Chaudhari et al. 2018). These findings along with our data indicate that PRE applications of flumioxazin alone can provide up to 99% control. However, season-long weed control in peanut requires additional herbicide applications.

Application of paraquat and pyroxasulfone, groups 22 and 15, EPOST optimizes weed control in peanut. Up to 95% Texas millet control 37 DAT was achieved when paraquat and pyroxasulfone were applied EPOST (Baughman et al 2018). Similarly, 89% broadleaf signalgrass control was achieved 45 DAT following EPOST application of pyroxasulfone (Mueller and Steckel 2011). These results corroborate our observations that three SOAs applied by EPOST provides adequate control of problematic weeds in peanut. However, to maintain season-long weed control in peanut an LPOST timing is often required.

Typically, season-long weed control in peanut is obtained using five to seven SOAs. Under conditions of this experiment, six SOAs were required to maximize broadleaf signalgrass control. Therefore, this data suggests that improving weed control is more dependent upon herbicide selection and application timing rather than incorporation of additional SOAs (Grichar et al 2012, Jordan et al. 2009).

Conclusion

The objective of this research was to determine the minimum number of SOAs required to maximize control of a model weed species as part of a resistance management program in peanut. The minimum number of SOAs required to maximize broadleaf signalgrass control from 7 to 28 days after application was one SOA PRE, three SOAs by EPOST, and six SOAs by LPOST. Therefore, recommendations of additional SOAs to current peanut herbicide programs will not result in improved efficacy and will hinder conservation of chemistries for future use.

Tables

Table 2.1 Soil textures and taxonomic classes for field sites used in broadleaf signalgrass (*Urochloa platyphylla*) efficacy studies investigating the effect of number of sites of action utilized in herbicide programs in Mississippi.

Year	Location	Soil texture	Taxonomic Class
2020	Coastal Plain	Prentiss very fine sandy loam	Coarse-loamy, siliceous, semiactive, thermic Glossic Fragiudults
	R.R. Foil	Myatt loam	Fine-loamy, siliceous, active, thermic Typic Endoaquults
2021	R.R. Foil	Leeper silty clay loam	Fine, smectitic, nonacid, thermic Vertic Epiaquepts
	W.B. Andrews	Marietta fine sandy loam	Fine-loamy, siliceous, active, thermic Fluvaquentic Eutrudepts

Table 2.2 Herbicide treatments for studies investigating the effect of number of herbicide sites of action on weed control at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the W.B. Andrews Agriculture Systems Research Farm, Mississippi State, MS, and the Coastal Plain Branch Experiment Station near Newton, MS in 2020 and 2021.

Treatment[a]	PRE (g ha^{-1})	EPOST (g ha^{-1})	LPOST (g ha^{-1})	# of SOAs
1	flumioxazin (108)	carfentrazone (35)	lactofen (219)	1
2	flumioxazin (108)	pyroxasulfone (125)	lactofen (219)	2
3	flumioxazin (108)	pyroxasulfone (125)	lactofen (219) + 2,4-DB (280)	3
4	flumioxazin (108)	paraquat (280) + pyroxasulfone (125)	lactofen (219) + 2,4-DB (280)	4
5	flumioxazin (108) + ethalfluralin (841)	paraquat (280) + pyroxasulfone (125)	lactofen (219) + 2,4-DB (280)	5
6	flumioxazin (108) + ethalfluralin (841)	paraquat (280) + pyroxasulfone (125)	2,4-DB (280) + imazapic (70)	6
7	flumioxazin (108) + ethalfluralin (841)	paraquat (280) + pyroxasulfone (125) + bentazon (841)	2,4-DB (280) + imazapic (70)	7
8	flumioxazin (108) + ethalfluralin (841) + glyphosate (1065)	paraquat (280) + pyroxasulfone (125) + bentazon (841)	2,4-DB (280) + imazapic (70)	8
9	flumioxazin (108) + ethalfluralin (841) + glyphosate (1065)	paraquat (280) + clethodim (136) + bentazon (841)	2,4-DB (280) + imazapic (70) + pyroxasulfone (125)	9

[a]Treatments were mixed with either 1% v/v crop oil concentrate or 0.25% v/v non-ionic surfactant when required by label.

Abbreviations: PRE, preemergence (at planting); EPOST, early-postemergence (21 days after peanut emergence); LPOST, late-postemergence (21 days after EPOST); SOAs, sites of action

Table 2.3 Broadleaf signalgrass (*Urochloa platyphylla*) control response to increasing herbicide sites of action in PRE peanut herbicide applications at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the W.B. Andrews Agriculture Systems Research Farm, Mississippi State, MS, and the Coastal Plain Branch Experiment Station near Newton, MS in 2020 and 2021.

		[a]broadleaf signalgrass control		
		7 DAT	**14 DAT**	**21 DAT**
PRE Treatment	**# of SOAs**	------------------------------%------------------------------		
flumioxazin	1	99	99	97
flumioxazin + ethalfluralin	2	99	99	98
flumioxazin + ethalfluralin + glyphosate	3	99	99	98
P value		0.4801	0.5756	0.0764

[a]Means within each column with the same letter are not statistically different from each other (α=0.05)

Abbreviations: PRE, preemergence; SOAs, sites of action; DAT, days after treatment

Table 2.4 Broadleaf signalgrass (*Urochloa platyphylla*) control response to increasing herbicide sites of action in PRE and EPOST peanut herbicide applications at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the W.B. Andrews Agriculture Systems Research Farm, Mississippi State, MS, and the Coastal Plain Branch Experiment Station near Newton, MS in 2020 and 2021.

			[a]broadleaf signalgrass control		
PRE Treatment	**EPOST Treatment**	**# of SOAs**	**7 DAT**	**14 DAT**	**21 DAT**
			--------------------%--------------------		
flumioxazin	carfentrazone	1	78 c	55 b	52 b
	pyroxasulfone	2	87 b	85 a	85 a
	paraquat + pyroxasulfone	3	92 ab	91 a	91 a
flumioxazin + ethalfluralin	paraquat + pyroxasulfone	4	93 a	90 a	90 a
	paraquat + bentazon + pyroxasulfone	5	90 ab	91 a	92 a
flumioxazin + ethalfluralin + glyphosate	paraquat + bentazon + pyroxasulfone	6	91 ab	90 a	89 a
	paraquat + bentazon + clethodim	7	95 a	90 a	91 a
P value			< 0.0001	<0.0001	<0.0001

[a]Means within each column with the same letter are not statistically different from each other (α=0.05)

Abbreviations: PRE, preemergence; EPOST, early-postemergence; SOAs, sites of action; DAT, days after early-postemergence treatment

Table 2.5 Broadleaf signalgrass (*Urochloa platyphylla*) control response to increasing herbicide sites of action in PRE, EPOST, and LPOST peanut herbicide applications at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the W.B. Andrews Agriculture Systems Research Farm, Mississippi State, MS, and the Coastal Plain Branch Experiment Station near Newton, MS in 2020 and 2021.

				[a]broadleaf signalgrass control			
PRE Treatment	**EPOST Treatment**	**LPOST Treatment**	**# of SOAs**	**7 DAT**	**14 DAT**	**21 DAT**	**28 DAT**
				---%			
flumi.	carfen.	lactofen	1	44 c	69 c	66 c	61 c
	pyrox.	lactofen	2	70 b	94 ab	92 b	93 b
		lactofen + 2,4-DB	3	80 ab	92 b	93 b	91 b
	paraquat + pyrox.	lactofen + 2,4-DB	4	85 a	96 ab	93 b	94 b
flumi. + ethalfluralin	paraquat + pyrox.	lactofen + 2,4-DB	5	89 a	97 ab	93 b	94 b
		2,4-DB + imazapic	6	89 a	99 a	99 a	99 a
	paraquat + bentazon + pyrox.	2,4-DB + imazapic	7	88 a	98 a	99 a	99 a
flumi. + ethalfluralin + glyph.	paraquat + bentazon + pyrox.	2,4-DB + imazapic	8	92 a	99 a	99 a	99 a
	paraquat + bentazon + clethodim	2,4-DB + imazapic + pyrox.	9	90 a	99 a	99 a	99 a
P value				< 0.001	< 0.001	< 0.001	<0.001

[a]Letters within each column with the same letter are not statistically different from each other (α=0.05)

Abbreviations: PRE, preemergence; EPOST, early-postemergence; LPOST, late-postemergence; SOAs, sites of action; DAT, days after late-postemergence treatment; flumi., flumioxazin; carfen., carfentrazone; pyrox., pryroxasulfone; glyph., glyphosate

Literature Cited

Askew SD, Wilcut JW, Cranmer JR (1999) Weed Management in Peanut (*Arachis hypogaea*) with Flumioxazin Preemergence. Weed Technol 13:594–598

Baughman TA, Grichar WJ, Dotray PA (2018) Weed Control and Peanut Tolerance Using Pyroxasulfone in Oklahoma. J Exp Agric Int 21:1–11

Bagavathiannan M V., Norsworthy JK, Smith KL, Neve P (2013) Modeling the Evolution of Glyphosate Resistance in Barnyardgrass (*Echinochloa crus-galli*) in Cotton-Based Production Systems of the Midsouthern United States. Weed Technol 27:475–487

Chaudhari S, Jordan DL, Grey TL, Prostko EP, Jennings KM (2018) Weed Control and Peanut (*Arachis hypogaea* L.) Response to Acetochlor Alone and in Combination with Various Herbicides. Peanut Sci 45:45–55

Clewis SB, Everman WJ, Jordan DL, Wilcut JW (2007) Weed Management in North Carolina Peanuts (*Arachis hypogaea*) with S-Metolachlor, Diclosulam, Flumioxazin, and Sulfentrazone Systems. Weed Technol 21:629–635

Diggle AJ, Neve PB, Smith FP (2003) Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. Weed Res 43:371–382

Frans R, Talbert R, Marx D, Crowley H (1986) Experimental design and techniques for measuring and analyzing plant responses to weed control practices. Pages 29–46 in Research Methods in Weed Science

Grey TL, Bridges DC, Eastin EF, MacDonald GE (2002) Influence of Flumioxazin Rate and Herbicide Combinations on Weed Control in Peanut (*Arachis hypogaea* L.). Peanut Sci 29:24–29

Grey TL, Wehtje GR (2005) Residual herbicide weed control systems in peanut. Weed Technol 19:560–567

Grichar WJ, Jordan DL, Prostko EP (2012) Weed control and peanut (*Arachis hypogaea* L.) response to formulations of imazapic. Crop Prot 36:31–36

Jordan DL, Lancaster SH, Lanier JE, Lassiter BR, Johnson PD (2009) Weed Management in Peanut with Herbicide Combinations Containing Imazapic and Other Pesticides. Weed Technol 23:6–10

Mueller TC, Steckel LE (2011) Efficacy and Dissipation of Pyroxasulfone and Three Chloroacetamides in a Tennessee Field Soil. Weed Sci 59:574–579

Neve P (2008) Simulation modelling to understand the evolution and management of glyphosate resistance in weeds. Pest Manag Sci 64:392–401

Neve P, Norsworthy JK, Smith KL, Zelaya IA (2011) Modeling Glyphosate Resistance Management Strategies for Palmer Amaranth (*Amaranthus palmeri*) in Cotton. Weed Technol 25:335–343

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations. Weed Sci 60:31–62

Price AJ, Koger CH, Wilcut JW, Miller D, Santen E Van (2008) Efficacy of Residual and Non-Residual Herbicides Used in Cotton Production Systems When Applied with Glyphosate, Glufosinate, or MSMA. Weed Technol 22:459–466

Prostko EP, Johnson WC, Mullinix BG (2001) Annual grass control with preplant incorporated and preemergence applications of ethalfluralin and pendimethalin in peanut (*Arachis hypogaea*). Weed Technol 15:36–41

Salas RA, Burgos NR, Tranel PJ, Singh S, Glasgow L, Scott RC, Nichols RL (2016) Resistance to PPO-inhibiting herbicide in Palmer amaranth from Arkansas. Pest Manag Sci 72:864–869

[USDA] United States Department of Agriculture (2019) 2018 Agricultural Chemical Use Survey: Peanut

Vencill WK, Nichols RL, Webster TM, Soteres JK, Mallory-Smith C, Burgos NR, Johnson WG, McClelland MR (2012) Herbicide Resistance: Toward an Understanding of Resistance Development and the Impact of Herbicide-Resistant Crops. Weed Sci 60:2–30

Weed Science Society of America (n.d.). https://wssa.net/wssa/weed/herbicides/. Accessed August 2, 2021

CHAPTER III

COTTON RESPONSE TO NON-LABELED HERBICIDES APPLIED BROADCAST AND POSTEMERGENCE-DIRECTED

Abstract

The development of herbicide resistance has restricted options for effective postemergence control of troublesome weed species throughout the U.S. cotton (*Gossypium hirsutum*) belt. This research was conducted to determine whether detrimental effects of herbicides not currently labeled for use in cotton could be mitigated through application placement. The effects of herbicide (ametryn, amitrole, imazapic, and topramezone) and sprayer type (broadcast, lay-by, and drop-nozzle) on visual injury and seed cotton yield were investigated at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the Black Belt Brach Experiment Station near Brooksville, MS, and at an on-farm site in Drew County, AR in 2020 and 2021. Conventional broadcast applications reduced seed cotton yield between 50 and 99%, regardless of herbicide. Conversely, lay-by applications of ametryn, amitrole, and topramezone had no effect on seed cotton yield. With the exception of ametryn, drop-nozzle application of the evaluated herbicides reduced seed cotton yield between 27 and 93%. Regardless of application placement, imazapic applied postemergence decreased seed cotton yield 71 to 90%. Visual injury following application of all herbicides was negatively correlated with seed cotton yield. Postemergence-directed placement can mitigate the detrimental effects of

some herbicides not currently labeled for use in cotton and may provide a means to incorporate new chemistries into weed management programs.

Nomenclature:

ametryn; amitrole; imazapic; topramezone; cotton, *Gossypium hirsutum*

Introduction

Development and proliferation of herbicide resistant weed populations has caused a deficit in postemergence (POST) weed control options in cotton (*Gossypium hirsutum*). Up to 62% of sampled Palmer amaranth (*Amaranthus palmeri*) populations in North Carolina, Georgia, and Texas are resistant to glyphosate (Culpepper et al 2008, Garetson 2019). In Tennessee, junglerice (*Echinochloa colona*) exhibits up to 8.5-fold resistance to glyphosate (Perkins et al. 2021). In response to widespread glyphosate resistance, other POST chemistries including glufosinate, dicamba, and 2,4-D have been heavily utilized (Sosnoskie and Culpepper 2014, USDA 2020). However, repeated applications will likely result in eventual resistance development among these chemistries as well (Diggle et al. 2003). With limited labeled herbicide options for future POST weed control, alternative chemistries should be explored to ensure sustainability of cotton production systems.

Several herbicides labeled for use in other crops may provide control options for troublesome resistant populations in cotton. Ametryn, an herbicide used in 7 million ha of sugarcane annually, provides control of several broadleaf and grass weed species (Smith et al 2008). Palmer amaranth control following application of flumioxazin and MSMA was similar to that following application of ametryn (Plumblee et al. 2016). Postemergence applications of amitrole provided 98% control of 70 weed species present in vineyards (Monteiro and Moreira 2004). Imazapic achieved up to 97% control of entireleaf morningglory (*Ipomoea hederacea var. integriuscula*), large crabgrass (*Digitaria sanguinalis*), nodding spurge (*Chamaesyce nutans*), pitted morningglory (*Ipomoea lacunosa*), yellow nutsedge (*Cyperus esculentus*), sicklepod (*Senna obtusifolia*), Florida beggarweed (*Desmodium tortuosum*), and bristly starbur (*Acanthospermum hispidum*) when applied POST in peanut (Brecke et al. 2002, Jordan et al. 2009). In POST sweet corn applications, 91% or greater control of common lambsquarters (*Chenopodium album*), velvetleaf (*Abutilon theophrasti*), common ragweed (*Ambrosia artemisifolia*), and giant foxtail (*Setaria faberi*) was attained with topramazone (Bollman et al. 2009). These herbicides, though effective weed control agents, may be deleterious to cotton growth, development, and yield.

Application of ametryn, imazapic, and topramezone typically results in unacceptable levels of cotton injury. Preemergence application of ametryn reduced cotton fresh weight up to 19-fold in sandy and clay textured soils (Eshel and Ilani 1975). Imazapic applied at 12.6 g ha^{-1} reduced lint yield by 20-fold when applied within three weeks of cotton planting (Grichar et al. 2004). Application of topramezone in corn provided up to 44% control of two- to four-leaf volunteer cotton (Pekar 2014). Detrimental effects of these herbicides may be mitigated through POST application placement.

Post-directed (POST-D) application placements reduce crop injury by placing products below crop canopy. Flumioxazin, which is detrimental to cotton when foliar contact occurs, did not injure cotton when applied POST-D (Anonymous 2021a, Askew et al. 2002, Main et al. 2000). The effect of application placement of non-labeled herbicides is not well understood in cotton. This research was conducted to determine whether detrimental effects of herbicides not currently labeled for use in cotton could be mitigated through application placement.

Materials and Methods

Field studies were conducted at the R.R. Foil Plant Science Research Center, Mississippi State, MS; the Black Belt Branch Experiment Station, near Brooksville, MS; and at grower field in Drew County, AR in 2020 and 2021. Four herbicides that are typically detrimental to cotton were applied using POST-D application placement to investigate potential crop injury and yield effects. Amitrole, ametryn, imazapic, and topramezone were applied at 0.7, 0.8, 0.07, and 0.02 kg ha^{-1}, respectively, via broadcast and two POST-D application placements (Table 1). A split-plot arrangement of treatments was utilized within a randomized complete block design with four replications. A non-treated check was included for comparison purposes. Application placement was the main-plot factor and herbicide program was the sub-plot factor. Herbicides were applied using a compressed-air, tractor-mounted sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa. Broadcast applications were made with a four-nozzle boom equipped with AIXR 11002 nozzles (Teejet®, 1801 Business Park Dr, Springfield, IL 62703). Postemergence-directed applications were made using either a conventional four-nozzle broadcast boom outfitted with four Dropleg^{UL} drop-nozzles each consisting of two IDK 11001 nozzles (445 Kautz Road, St. Charles, IL, 60174) (Figure 1) or with a lay-by boom utilizing XR 11002E nozzles to apply herbicide solution between crop rows and OC 11001 nozzles (Teejet®, 1801 Business Park Dr, Springfield, IL 62703) (Figure 2) to apply herbicide solution beneath the crop canopy. The lay-by sprayer applied herbicide to row middles with a single nozzle positioned 50 cm above the soil surface. Herbicide was applied to the base of cotton plants with two offset patterned nozzles placed 11 cm above the soil surface that directed spray in either direction toward the crop row.

All herbicide treatments were applied to the center two rows of each experimental unit when cotton reached 10- to 12-node growth stage. Each experimental unit consisted of four 97 cm raised beds that were 9.1 m in length. Beds were prepared in the fall of each preceding year with a pan-style bedding implement. Forty-eight hours prior to crop planting, beds were smoothed with a rolling basket implement. Cotton variety, DP 1646 B2XF, was seeded 2.5 cm deep at 111,150 seeds ha^{-1} with a John Deere MaxEmerge 1700 planter. Cotton seed were treated with metalaxyl, pyraclostrobin, tioxazafen, fluxapyroxad, imidacloprid, myclobuanil, acephate, clothianidin, *Bacillus fimus* I-1582, and ipconazole (Acceleron®, Bayer Crop Science, 800 N Lindbergh Blvd., St. Louis, MO 63167). Weed and insect management in cotton were conducted following local recommendations (Anonymous 2021b, Barber et al. 2021, Crow et al 2021, Bateman et al 2021). A total of 135 kg ha^{-1} of nitrogen was applied in a split application with one-half applied pre-plant and one-half side-dressed at first bloom. Cotton was defoliated at 60% boll open.

Data collection consisted of visual evaluation of cotton injury at 7-, 14-, and 21-days after treatment (DAT). Evaluations were made on a 0 to 100 scale where 0 was equal to no crop injury and 100 being death of crop plants (Frans et al. 1986). The center two rows of each experimental unit were harvested using a spindle picker modified for small plot research. Seed cotton was bagged, weighed, and yield was calculated. Data were subjected to ANOVA using a mixed split-plot model in RStudio (Version 1.4.1106, agricolae package, Boston, MA, USA). Site-year and replication were treated as random effects. Herbicide application placement was treated as a fixed whole-plot factor and herbicide program within each application placement was treated as a fixed sub-plot factor. Means were separated using Fisher's protected LSD (α=0.05).

Results and Discussion

The primary hypothesis for this research was that injurious effects of applying non-labeled herbicides to cotton could be mitigated by post-directed placement. Conventional broadcast applications reduced seed cotton yield between 50 and 90%, regardless of herbicide (Table 2). Conversely, lay-by applications of ametryn, amitrole, and topramezone had no effect on seed cotton yield. Except for ametryn, drop-nozzle applications of the evaluated herbicides reduced seed cotton yield between 27% and 93%. Regardless of application placement, imazapic applied postemergence decreased seed cotton yield 71% to 90%. Visual injury following application of all herbicides was negatively correlated with seed cotton yield (data not shown). Lay-by placement of herbicides can mitigate the detrimental effects of some chemistries not currently labeled for use in cotton.

The evaluated herbicides are not labeled in cotton and are known to cause visual injury and seed cotton yield reductions. Ametryn applied preemergence to cotton in sandy and clay soils reduced plant fresh weight up to 95% and 85%, respectively (Eshel and Ilani 1974). Applications of topramezone at 23.5 g ha^{-1} resulted in 44% control of glyphosate-resistant volunteer cotton when applied at the four- to six-leaf growth stage (Pekar 2014). Grichar et al. (2004) noted up to 100% stunting and 20-fold reduction in cotton yield when 12.6 g ha^{-1} of imazapic was applied within three weeks of planting. These results, along with our data, indicate that herbicide placement other than broadcast is required to introduce currently non-labeled products into cotton production systems.

Postemergence-directed application placement has been utilized to apply otherwise injurious herbicides to cotton. Regardless of timing, cotton was not injured by lay-by applications of flumioxazin (Askew et al. 2002, Main et al. 2000). Similarly, cotton was not affected by paraquat applied as a directed spray (Scifres and Santelmann 1966). These findings corroborate our results in that POST-D application placement can mitigate deleterious effects of some herbicides in cotton.

Conclusion

This research was conducted to determine whether detrimental effects of herbicides not currently labeled for use in cotton could be mitigated through application placement. The lay-by application method most consistently mitigated adverse effects of herbicide application on seed cotton yield. Consequently, lay-by application placement may provide a means to incorporate new chemistries into cotton weed management programs.

Tables

Table 3.1 Herbicides used to investigate cotton response to non-labeled chemistries applied with conventional broadcast, drop-nozzle, and lay-by application placement for an experiment conducted at Starkville, MS, Brooksville, MS, and Drew County, AR.

Trade Name	Active Ingredient	Rate (kg ha^{-1})	Manufacturer Information
Evik® DF	ametryn	0.7	Syngenta Crop Protection, LLC, 410 Swing Road, Greensboro, NC 27409, USA
Amitrole T	amitrole	0.8	Nufarm Americas Inc., 11901 South Austin Avenue Alsip, IL 60803, USA
Cadre®	imazapic	0.07	BASF Ag Products, 26 Davis Drive Research Triangle Park, NC 27709, USA
Impact®	topramezone	0.02	Amvac Chemical Corp., 4695 MacArthur Ct Newport Beach, CA 92660, USA

Table 3.2 Site characteristics for each location investigating cotton response to non-labeled chemistries applied with conventional broadcast, drop-nozzle, and lay-by application placement.

Year	Location	Soil Texture	Planting Date	Herbicide Application Date	Harvest Date
2020	R.R. Foil	Mantachie loam	May 22	July 7	October 21
	Black Belt	Brooksville silty clay	May 22	July 22	October 27
	Drew Co., AR	Rilla silt loam	June 3	July 2	October 16
2021	Black Belt	Sumter silty clay	May 18	July 15	
	Drew Co., AR	Rilla silt loam	May 19	July 13	

Table 3.3 Cotton response to five non-labeled herbicides when applied with conventional broadcast, drop-nozzle, and lay-by placement at Starkville, MS, Brooksville, MS, and Drew County, AR.

[a]Herbicide	Application Placement	[b]Cotton Injury 7 [c]DAT	14 [c]DAT	21 [c]DAT	[b]Seed Cotton Yield
		----------------------	%	----------------------	---kg ha^{-1}---
ametryn	conventional broadcast	23 a	15 a	19 a	1379 b
	drop-nozzle	7 b	7 b	4 b	2360 a
	lay-by	0 c	0 c	1 b	3007 a
	[d]NTC				2775 a
	P value	<0.0001	<0.0001	<0.0001	<0.0001
amitrole	conventional broadcast	24 a	37 a	33 a	268 c
	drop-nozzle	8 b	12 b	10 b	2017 b
	lay-by	2 c	3 c	2 b	2661 a
	[d]NTC				2775 a
	P value	<0.0001	<0.0001	<0.0001	<0.0001
imazapic	conventional broadcast	18 a	26 a	34 a	19 c
	drop-nozzle	14 b	20 b	19 b	188 c
	lay-by	11 c	15 c	12 b	792 b
	[d]NTC				2775 a
	P value	<0.0001	<0.0001	<0.0001	<0.0001
topramezone	conventional broadcast	19 a	24 a	13 a	1282 c
	drop-nozzle	15 a	18 a	5 b	1965 b
	lay-by	4 b	3 b	0 c	2693 a
	[d]NTC				2775 a
	P value	<0.0001	<0.0001	<0.0001	<0.0001

[a]Ametryn, amitrole, imazapic, and topramezone applied at 0.7, 0.8, 0.07, and 0.02 kg ha^{-1}, respectively.
[b]Means within each column with the same letter are not statistically different at α=0.05.
[c]Days after treatment.

Figures

Figure 3.1 Drop-nozzles utilized to evaluate cotton response to currently non-labeled herbicides.

Figure 3.2 Lay-by sprayer utilized to evaluate cotton response to currently non-labeled herbicides.

Literature Cited

Anonymous (2021a) Valor EZ label. http://www.cdms.net/ldat/ldEU7000.pdf. Accessed: August 27, 2021

Anonymous (2021b) 2021 Weed Control Guidelines for Mississippi. Mississippi State University Extension Service

Askew SD, Wilcut JW, Cranmer JR (2002) Cotton (*Gossypium hirsutum*) and Weed Response to Flumioxazin Applied Preplant and Postemergence Directed. Weed Technol 16:184–190

Barber T, Butts T, Boyd T, Cunningham K, Selden G, Norsworthy JK, Burgos N, Bertucci M (2021) Recommended Chemicals for Weed and Brush Control. University of Arkansas Division of Agriculture

Batemen N, Davis J, Hopkins JD, Thrash B, Lee J, Loftin K, Lorenz G, Spradley P, Studebaker G, Joshi N, Zawislak J, Cato A, Teague T (2021) Insect Recommendations for Arkansas. Little Rock, AR: University of Arkansas Division of Agriculture

Bollman JD, Boerboom CM, Becker RL, Fritz VA (2008) Efficacy and Tolerance to HPPD-Inhibiting Herbicides in Sweet Corn. Weed Technol 22:666–674

Brecke B, Wehtje G, Paudel K (2002) Comparison Between Diclosulam- and Imazapic-Based Weed Control Systems in Peanut. Peanut Sci 29:52–57

Crow W, Cook D, Pieralisi B, Catchot A, Layton B, Larson E, Gore J, Musser F, Irby T (2021) 2021 Insect Control Guide for Agronomic Crops. Mississippi State University Extension Service

Culpepper AS, Whitaker JR, MacRae AW, York AC (2008) Distribution of glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. J Cotton Sci 12:306–310

Diggle AJ, Neve PB, Smith FP (2003) Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. Weed Res 43:371–382

Eshel Y, Ilani S (1975) Tolerance of cotton to five triazine herbicides. Phytoparasit 1975 32 3:121–128

Frans R, Talbert R, Marx D, Crowley H (1986) Experimental design and techniques for measuring and analyzing plant responses to weed control practices. Pages 29–46 in Research Methods in Weed Science

Garetson R, Singh V, Singh S, Dotray P, Bagavathiannan M (2019) Distribution of herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in row crop production systems in Texas. Weed Technol 33:355–365

Grichar WJ, Besler BA, Baughman TA, Dotray PA, Lemon RG, Senseman SA (2004a) Cotton Response to Imazapic and Imazethapyr Residue Following Peanut. Texas J Agric Nat Resour 17:32–39

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

Jordan DL, Lancaster SH, Lanier JE, Lassiter BR, Johnson PD (2009) Weed Management in Peanut with Herbicide Combinations Containing Imazapic and Other Pesticides. Weed Technol 23:6–10

Main CL, Tredaway JA, MacDonald GE, Altom J V. (2000) Evaluation of flumioxazin for cotton (*Gossypium hirsutum*) layby weed control. Proc South Weed Sci Soc 53:220–221

Monteiro A, Moreira I (2004) Reduced rates of residual and post-emergence herbicides for weed control in vineyards. Weed Res 44:117–128

Perkins CM, Mueller TC, Steckel LE (2021) Survey of glyphosate-resistant junglerice (*Echinochloa colona*) accessions in dicamba-resistant crops in Tennessee. Weed Technol 35:412–418

Plumblee MT, Dodds DM, Barber T, Ferrell JA, Samples CA, Denton D, Franca LX (2016) Alternative Uses of ametryn in Cotton. Proc South Weed Sci Soc 69:496

Scifres CJ, Santelmann PW (1966) Response of Cotton and Sorghum to Post-emergence Applications of Paraquat. Weeds 14:86–88

Smith DT, Richard EP, Santo LT (2008) Weed Control in Sugarcane and the Role of Triazine Herbicides. Pages 185–197 in HM LeBaron, J McFarland, OC Burnside, eds. The Triazine Herbicides: 50 Years of Revolutionizing Agriculture. San Diego, CA: Elsevier

Sosnoskie LM, Culpepper AS (2014) Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) Increases Herbicide Use, Tillage, and Hand-Weeding in Georgia Cotton. Weed Sci 62:393–402

[USDA] United States Department of Agriculture (2020) 2019 Agricultural Chemical Use Survey: Cotton

CHAPTER IV

USING COMPLETE RESIDUAL PROGRAMS TO ACHIEVE SEASON-LONG WEED CONTROL IN COTTON

Abstract

Soil-applied, residual herbicides are an essential component of resistant weed management. This study was conducted to determine if *Amaranthus* spp. can be agronomically and economically controlled with only residual herbicides. The effects of herbicide program on the control of *Amaranthus* spp., cotton yield, and net returns were investigated at the R.R. Foil Plant Science Research Center, Mississippi State, MS, the Black Belt Branch Experiment Station, near Brooksville, MS, and at on-farm locations in Tunica County, MS and Drew County, AR in 2020 and 2021. Soil textures included Mantatchie loam, Leeper silty clay, Brooksville silty clay, Okolona silty clay, Sharkey clay, and Rilla silt loam. For the Delta locations, control of Palmer amaranth in the mixed herbicide program was 13 to 41% greater than that of programs composed solely of residual herbicides, and control was positively correlated with cotton seed yield and net return. For the prairie locations, herbicide program had no effect on seed cotton yield or net returns. Currently, waterhemp but not Palmer amaranth can be agronomically and economically controlled without foliar herbicides when timely and sufficient rainfall or irrigation activate soil-applied, residual herbicides.

Introduction

Reliance on foliar herbicides facilitated widespread resistance development. Repeated use of foliar chemistries with no residual activity shifted weed populations to species with extended germination periods (Peterson et al 2018). When these species are subjected to repeated application of the same herbicide, their potential for resistance development increases (Peterson et al 2018). In simulated populations, resistance development occurred at some level in 100% of modeled species within four years after repeated applications of glyphosate (Neve 2008). In simulations of Palmer amaranth (*Amaranthus palmeri*) populations, up to 74% resistance occurred after sequential glyphosate applications (Neve et al 2011). In barnyardgrass (*Echinochloa crus-galli*) populations, up to 47% resistance has been observed in populations receiving repeated applications of glyphosate (Bagavathiannan et al 2013). Repeated application of the same herbicide has resulted in weed populations composed primarily of resistant individuals (Culpepper et al 2006, Garetson 2019, Perkins et al 2021). Therefore, in order to preserve herbicides as a viable option for control of problematic species, chemistries other than those applied foliar should be included in the weed control program.

The addition of soil-applied, residual herbicides to a foliar herbicide program often increases efficacy. The addition of chlorimuron, lactofen, imazamox, imazethapyr, fomesafen, imazaquin, or acifuorfen in early-postemergence (EPOST) soybean applications increased control of ivyleaf morningglory (*Ipomoea hederacea*), Venice mallow (*Hibiscus trionum*), yellow sweetclover (*Melilotus officinalis*), common lambsquarters (*Chenopodium album*), velvetleaf (*Abutilon theophrasti*), kockia (*Bassia scoparia*), Russian thistle (*Salsola tragus*), and field bindweed (*Convovulus arvensis*) up to 2.5-fold (Knezevic et al 2009). Pitted morningglory (*Ipomoea lacunosa*) control following EPOST applications of glufosinate in soybean increased by up to 1.2-fold when *S*-metolachlor was included (Everman et al 2009). Moreover, Price et al (2008) investigated 567 weed species for a herbicide by location interaction and determined that the inclusion of residual herbicides improved efficacy up to X-fold 55% of the time. Consequently, increased efficacy and residual control associated with soil-applied herbicide tank-mixtures may alleviate the necessity for repeated applications of foliar chemistries.

Utilization of soil-applied chemistries diversify herbicide programs, thus mitigating the potential for resistance development among weed species. Because of widespread resistance to foliar applied compounds, specifically glyphosate, the area of crop land treated with preemergence (PRE) residual herbicides has increased from 200% from 2000 to 2015 (Peterson et al. 2018). The potential for herbicide resistance to develop in troublesome weed populations like Palmer amaranth is reduced up to 6-fold when soil-applied herbicides are incorporated into management programs (Busi et al 2020, Neve et al 2011). Therefore, with limited options for foliar weed control in cotton, inclusion of soil-applied herbicides into weed control programs is necessary to impede resistance development.

Implementing weed control programs based solely on soil-applied, residual herbicides will reduce selection-pressure on foliar-applied compounds thereby extending their future effectiveness. However, the effect of complete residual program on season-long weed control has been under-investigated. In corn herbicide programs, applications of only residual herbicides resulted in up to 12.3-fold reductions in Palmer amaranth control (Chahal et al 2018). In no case, did complete residual herbicide programs result in similar Palmer amaranth control compared to mixed foliar and residual programs (Chahal et al. 2018). In soybean however, overlapping residual applications resulted in up to 97% Palmer amaranth control at harvest (Sarangi and Jhala 2019). The effect of complete residual herbicide programs in cotton production is unknown.

Therefore, the objective of this research was to determine if season-long control of common weed species in U.S. cotton production could be agronomically and economically achieved by using only soil-applied herbicides.

Materials and Methods

Studies were conducted at the R.R. Foil Plant Science Research Center at Mississippi State, MS, the Black Belt Branch Experiment Station near Brooksville, MS, and at on-farm sites in Tunica County, MS and Drew County, AR in 2020 and 2021 to investigate the effect complete residual programs have on weed control and yield of cotton. Soil characteristics and dominant weed species for each site are presented in Table 1.

Treatments at each location consisted of six herbicide programs where only residual herbicides were applied. These complete residual programs were compared to two common herbicide programs commonly used throughout cotton production regions. Herbicide programs consisted of four-application timings where PRE was applied at planting, EPOST at two- to three-leaf cotton, mid-postemergence (MPOST) at four- to six-leaf cotton, and late-postemergence (LPOST) timings occurring at 10- to 12-node cotton. Commonly used standard programs applied for comparison consisted of acetochlor PRE followed by pyrithiobac, glufosinate, and clethodim EPOST followed by glufosinate and clethodim LPOST and fluometuron and fluridone PRE followed by glufosinate and S-metolachlor EPOST followed by glufosinate and dimethenamid-P MPOST followed by diuron and glyphosate LPOST. A full list of herbicide treatments and rates are presented in Table 2. Each experimental unit consisted of four 97 cm raised beds that were 9.1 m in length. Beds were prepared in the fall of each preceding year with a pan-style bedding implement. Forty-eight hours prior to crop planting, beds were smoothed with a rolling basket implement. All herbicide treatments were applied to the center two rows of each experimental unit at the aforementioned growth stages. Herbicide treatments were applied using a tractor-mounted compressed air sprayer calibrated to deliver 140 L ha^{-1} using AIXR 11002 nozzles (Teejet®, 1801 Business Park Dr, Springfield, IL 62703). LPOST applications were applied with a lay-by boom utilizing XR 11002E nozzles to apply herbicide solution between crop rows and OC 11001 nozzles (Teejet®, 1801 Business Park Dr, Springfield, IL 62703) to apply herbicide solution beneath the crop canopy. The lay-by sprayer applied herbicide to row middles with a single nozzle positioned 50 cm above the soil surface. Herbicide was applied to the base of cotton plants with two offset patterned nozzles placed 11 cm above the soil surface that directed spray in either direction toward the crop row. All residual herbicides were applied with the consideration of having an incorporating rainfall event within 48 hours of application.

Cotton variety, DP 1646 B2XF, was seeded 2.5 cm deep at 111,150 seeds ha^{-1} with a John Deere MaxEmerge 1700 planter. Cotton seed were treated with metalaxyl, pyraclostrobin, tioxazafen, fluxapyroxad, imidacloprid, myclobuanil, acephate, clothianidin, *Bacillus fimus* I-1582, and ipconazole (Acceleron®, Bayer Crop Science, 800 N Lindbergh Blvd., St. Louis, MO 63167). Insect management in cotton were conducted following local recommendations (Crow et al 2021, Bateman et al 2021). A total of 135 kg ha^{-1} of nitrogen was applied in a split application with one-half applied pre-plant and one-half side-dressed at first bloom. Cotton was defoliated at 60% boll open.

Data collection consisted of visual evaluation of Palmer amaranth and waterhemp (*Amaranthus tuberculatus*) control following each application timing. Evaluations were made on a 0 to 100 scale where zero equals no control and 100 equates to complete control (Frans et al. 1986). The center two rows of each experimental unit were harvested using a spindle picker modified for small plot research. Seed cotton was bagged, weighed, and yield was calculated. Net returns were calculated based upon herbicide and application budgets compiled by Mississippi State University and an average of cotton seed and lint prices received by producers from 2015 to 2019 (USDA n.d.). Data were subjected to analysis of variance using RStudio (lme4 package, R Studio, Version 1.4.1106) where site-year and replication were treated as random effects and herbicide treatment was treated as a fixed effect. Means were separated with Fisher's protected least significant difference (α=0.05).

Results and Discussion

The primary hypothesis for this research was that weed control, seed cotton yield, and net returns would be similar between programs composed solely of soil-applied, residual herbicides and programs containing both soil- and foliar-applied herbicides. Contrary to our hypothesis, the effect of herbicide program on agronomic and economic parameters in response to herbicide program was species and herbicide program dependent. For example, control of Palmer amaranth in the mixed herbicide program was 13 to 41% greater than that of programs composed solely of residual herbicides, and control of Palmer amaranth was positively correlated with seed cotton yield and net return (Table 3 and 4). Conversely, for waterhemp, herbicide program had no effect on seed cotton yield or net returns and only a minimal effect on weed control (Table 3 and 4). Thus, waterhemp but not Palmer amaranth can be agronomically and economically controlled without foliar herbicides when timely and sufficient rainfall or irrigation events activate soil-applied, residual herbicides.

Under the conditions of these experiments, herbicide program greatly affected Palmer amaranth control, cotton seed yield, and net return at Delta locations. At all evaluations, the standard program of fluometuron and fluridone PRE followed by glufosinate and *S*-metolachlor

EPOST followed by glufosinate and dimethenamid-P MPOST followed by diuron and glyphosate LPOST consistently resulted in Palmer amaranth control equal to or greater than 94% (Table 3). Comparatively, applying herbicide programs consisting only of residual herbicides resulted in up to 1.7-fold reductions in Palmer amaranth control (Table 3). Reductions in control directly corelated with cotton seed yields where losses of up to 46% were observed when only residual herbicides were applied in comparison to mixed, foliar and residual, programs (Table 4). Similarly, the standard mixed herbicide program resulted in the greatest net return of \$2418 ha^{-1} (Table 4). Utilization of herbicide programs consisting of only residual herbicides, resulted in losses of at least \$67 ha^{-1} due to yield reductions (Table 4). In worst cases, using only residual herbicides resulted in net return reductions of up to \$1348 ha^{-1} at Delta locations (Table 4). Therefore, our data suggests that using residual herbicides alone cannot prevent detrimental effects of prevalent Palmer amaranth populations.

Regarding Palmer amaranth, the agronomic and economic efficacy of herbicide programs composed solely of soil-applied, residual compounds appears to be crop and site specific. When applied PRE, combinations of the residual herbicides flumioxazin, metribuzin, or pyroxasulfone reduced Palmer amaranth densities up to 32-fold when evaluated at late-vegetative growth stages in soybean (de Sanctis et al 2021). Palmer amaranth control 20 days after the application of diuron, fluometuron, pendimethalin, or *S*-metolachlor was 91%, 86%, 82%, and 96%, respectively. However, the control of Palmer amaranth by these herbicides varied up to 39% across five locations, indicating that the efficacy of residual herbicides is site specific (Whitaker et al 2011). In a Nebraska soybean production system, herbicide programs composed solely of soil-applied, residual herbicides controlled Palmer amaranth up to 97%, maintained yield relative to the control, and improved profitability (Sarangi and Jhala 2019). Conversely, when only residual herbicides were applied in a Nebraska corn production system, Palmer amaranth control decreased 12-fold, corn yield declined, 4-fold, and net returns decreased 5-fold (Chahal et al 2018). Effective agronomic and economic control of Palmer amaranth may require combinations of foliar and residual herbicides depending primarily on crop and environment.

Under conditions of this experiment, herbicide program had no to minimal effect on the control of waterhemp, seedcotton yield, or net returns at the Plains locations. Compared to the standard Plains program of acetochlor PRE followed by pyrithiobac, glufosinate and clethodim EPOST followed by glufosinate and clethodim LPOST, control of waterhemp was not different among five of the six herbicide programs we evaluated (Table 3). Moreover, herbicide program had no effect on seed cotton yield (Table 4). Due primarily to an increase in herbicide costs and herbicide application costs, five of the six herbicide programs composed solely of soil-applied, residual herbicides decreased net returns up to \$89 ha^{-1} compared to the standard treatment (Table 4). However, relative the standard herbicide program, norflurazon PRE followed by *S*-metolachlor EPOST followed by pendimethalin MPOST followed by diuron LPOST increased net returns \$52 ha^{-1}. Therefore, our data suggests that season-long detrimental effects of waterhemp populations can be mitigated using only residual herbicides.

Similar to Palmer amaranth, residual herbicides provide great benefit with respect to mitigating the impact of waterhemp populations in row crops. In Illinois, application of residual herbicides including isoxaflutole, mesotrione, atrazine, acetochlor, cloransulam, imazethapyr, clomazone, flumioxazin, saflufenacil, sulfentrazone, metribuzin, pendimethalin, alachlor, dimethenamid-P, and pyroxasulfone reduced waterhemp densities up to 52-fold (Hausman 2012). Residual herbicides applied sequentially increased waterhemp control up to 1.2-fold and decreased densities by up to 3.5-fold (Steckel et al 2002). Therefore, literature corroborates our findings that waterhemp populations can be agronomically and economically controlled using programs consisting of only of residual herbicides.

Interactive effects of herbicide program by location indicate that control response to herbicide programs consisting only of residual herbicides is species dependent. In this case, waterhemp was more responsive to application of complete residual herbicide programs compared to Palmer amaranth. Therefore, in Delta regions where more aggressive Palmer amaranth populations are prevalent, current practices of using mixed programs consisting of both residual and foliar chemistries are necessary. However, in Plains regions where waterhemp is the more dominant *Amaranthus* spp., applying residual herbicides and eliminating sequential applications of foliar chemistries is plausible.

Conclusion

This study was conducted to determine if *Amaranthus* spp. can be agronomically and economically controlled with only residual herbicides. In Delta sites, Palmer amaranth control, cotton seed yield, and net returns exhibited by only applying residual herbicides were not comparable to standard programs. However, at Plains sites, waterhemp control, cotton seed yield, and net returns in several residual only programs were similar to standard mixed herbicide programs utilized in that area. Therefore, waterhemp but not Palmer amaranth can be agronomically and economically controlled without foliar herbicides when timely and sufficient rainfall or irrigation activate soil-applied, residual herbicides.

Tables

Table 4.1 Soil textures and dominant weed species for field sites investigating the effect of complete residual herbicide programs.

Year	Location	Soil texture	Taxonomic Class	Dominant Weed Species
2020	R.R. Foil	Mantachie loam	Fine-loamy, siliceous, active, acid, thermic Fluventic Endoaquepts	*Amaranthus tuberculatus*
	Black Belt	Brooksville silty clay	Fine, smectitic, thermic Aquic Hapludert	*Amaranthus tuberculatus*
	Tunica County, MS	Sharkey clay	Very-fine, smectitic, thermic Chromic Epiaquerts	*Amaranthus palmeri*
2021	R.R. Foil	Leeper silty clay loam	Fine, smectitic, nonacid, thermic Vertic Epiaquepts	*Amaranthus tuberculatus*
	Black Belt	Okolona silty clay	Fine, smectitic, thermic Oxyaquic Hapluderts	*Amaranthus tuberculatus*
	Tunica County, MS	Sharkey clay	Very-fine, smectitic, thermic Chromic Epiaquerts	*Amaranthus palmeri*
	Drew County, AR	Rilla silt loam	Fine-silty, mixed, active, thermic Typic Hapludalfs	*Amaranthus palmeri*

Table 4.2 Treatments utilized to investigate effect of complete residual herbicide programs on weed control at R.R. Foil Plant Science Research Center, Mississippi State, MS, the Black Belt Branch Experiment Station, near Brooksville, MS, and at an on-farm sites in Tunica County, MS and Drew County, AR.

[a]Treatment	PRE (kg ha^{-1})	EPOST (kg ha^{-1})	MPOST (kg ha^{-1})	LPOST (kg ha^{-1})
1	fluometuron (1.8)	*S*-metolachlor (1.42)	pendimethalin (1.07)	diuron (1.12)
2	diuron (1.12)	*S*-metolachlor (1.42)	diuron (1.12)	pendimethalin (1.07)
3	pendimethalin (1.07)	*S*-metolachlor (1.42)	diuron (1.12)	diuron (1.12)
4	norflurazon (2.2)	*S*-metolachlor (1.42)	diuron (1.12)	diuron (1.12)
5	norflurazon (2.2)	*S*-metolachlor (1.42)	diuron (1.12)	pendimethalin (1.07)
6	norflurazon (2.2)	*S*-metolachlor (1.42)	pendimethalin (1.07)	diuron (1.12)
[b]7	acetochlor (1.35)	pyrithiobac (0.06) + gluofosinate (0.66) + clethodim (0.14) + NIS (0.25% v/v)	-------------	glufosinate (0.66) + clethodim (0.14) + NIS (0.25% v/v)
[b]8	fluometuron (1.8) + fluridone (0.22)	glufosinate (0.66) + *S*-metolachlor (1.42)	glufosinate (0.66) + dimethenamid-P (1.1)	diuron (1.12) + glyphosate (1.54)

[a]All treatments applied according to label restrictions at 140 L ha^{-1}
[b]Standard herbicide programs commonly used in cotton production regions
Abbreviations: PRE, preemergence (at planting); EPOST, early-postemergence (2-3 leaf cotton); MPOST, mid-postemergence (4-6 leaf cotton); LPOST, late-postemergence (10-12 node cotton)

Table 4.3 *Amaranthus* spp. control response to complete residual herbicide programs at R.R. Foil Plant Science Research Center, Mississippi State, MS (Plains), Black Belt Branch Experiment Station, near Brooksville, MS (Plains), and on-farm sites in Tunica County, MS (Delta) and Drew County, AR (Delta).

	***Amaranthus* spp. Control**							
	Plains (waterhemp)				**Delta (Palmer amaranth)**			
[b]Herbicide Program (PRE / EPOST / MPOST / LPOST)	**14 DAP**	**14 DAE**	**14 DAM**	**14 DAL**	**14 DAP**	**14 DAE**	**14 DAM**	**14 DAL**
	-----------------------------------%				-----------------------------------			
fluometuron / *S*-metolachlor / pendimethalin / diuron	99	94 a	95	96 a	97 a	79 b	66 bc	66 cd
diuron / *S*-metolachlor / diuron / pendimethalin	99	95 a	97	94 a	99 a	81 b	81 b	80 bc
pendimethalin / *S*-metolachlor / diuron / diuron	99	84 b	91	84 b	90 b	61 c	58 c	58 d
norflurazon / *S*-metolachlor / diuron / diuron	99	94 a	95	97 a	95 a	75 b	73 bc	72 bcd
norflurazon / *S*-metolachlor / diuron / pendimethalin	99	97 a	97	98 a	98 a	77 b	76 b	82 b
norflurazon / *S*-metolachlor / pendimethalin / diuron	99	96 a	96	98 a	92 a	74 b	72 bc	73 bcd
[c]acetochlor / pyrithiobac + gluofosinate + clethodim + NIS / none / glufosinate + clethodim + NIS	99	99 a	99	99 a	---	---	---	---
[c]fluometuron + fluridone / glufosinate + *S*-metolachlor / glufosinate + dimethenamid-P / diuron + glyphosate	---	---	---		97 a	94 a	98 a	99 a
P value	0.42	<0.01	0.08	<0.01	<0.01	<0.01	<0.01	<0.01

[a]Means within each column with the same letter are not statistically different from each other (α=0.05)
[b]Treatments applied to each experimental unit at a carrier volume of 140 L ha^{-1}
[c]Standard herbicide treatments commonly used in cotton production regions
POST, early-postemergence (2-3 leaf cotton); MPOST, mid-postemergence (4-6 leaf cotton); LPOST, late-postemergence (10-12 node cotton); DAP, days after PRE; DAE, days after EPOST; DAM, days after MPOST; DAL, days after LPOST

Table 4.4 Cotton seed yield and net return response to complete residual herbicide programs at R.R. Foil Plant Science Research Center, Mississippi State, MS (Plains), Black Belt Branch Experiment Station, near Brooksville, MS (Plains), and on-farm sites in Tunica County, MS (Delta) and Drew County, AR (Delta).

[b]Herbicide Program (PRE / EPOST / MPOST / LPOST)	Plains		Delta	
	Seed Cotton Yield (kg ha^{-1})	[d]Net Return (\$ ha^{-1})	Seed Cotton Yield (kg ha^{-1})	[d]Net Return (\$ ha^{-1})
fluometuron / *S*-metolachlor / pendimethalin / diuron	2097	1245	2642 b	1608
diuron / *S*-metolachlor / diuron / pendimethalin	2039	1237	3283 ab	2070
pendimethalin / *S*-metolachlor / diuron / diuron	1962	1186	1787 c	1070
norflurazon / *S*-metolachlor / diuron / diuron	2066	1203	2800 b	1694
norflurazon / *S*-metolachlor / diuron / pendimethalin	2047	1176	2681 b	1598
norflurazon / *S*-metolachlor / pendimethalin / diuron	2258	1317	3806 a	2351
[c]acetochlor / pyrithiobac + gluofosinate + clethodim + NIS / none / glufosinate + clethodim + NIS	2061	1265	---	---
[c]fluometuron + fluridone / glufosinate + *S*-metolachlor / glufosinate + dimethenamid-P / diuron + glyphosate	---	---	3889 a	2418
P value	0.8629		<0.0001	

[a]Means within each column with the same letter are not statistically different from each other (α=0.05)
[b]Treatments applied to each experimental unit at a carrier volume of 140 L ha^{-1}
[c]Standard herbicide treatments commonly used in cotton production regions
[d] Net returns calculated based upon herbicide and application budgets compiled by Mississippi State University and average cotton seed and lint prices received by producers from 2015 to 2019 (USDA).
POST, early-postemergence (2-3 leaf cotton); MPOST, mid-postemergence (4-6 leaf cotton); LPOST, late-postemergence (10-12 node cotton); DAP, days after PRE; DAE, days after EPOST; DAM, days after MPOST; DAL, days after LPOST

Literature Cited

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2013) Modeling the Evolution of Glyphosate Resistance in Barnyardgrass (*Echinochloa crus-galli*) in Cotton-Based Production Systems of the Midsouthern United States. Weed Technology 27:475–487

Batemen N, Davis J, Hopkins JD, Thrash B, Lee J, Loftin K, Lorenz G, Spradley P, Studebaker G, Joshi N, Zawislak J, Cato A, Teague T. (2021) Insect Recommendations for Arkansas. Little Rock, AR: University of Arkansas Division of Agriculture. 336 p

Busi R, Powles SB, Beckie HJ, Renton M (2020) Rotations and mixtures of soil-applied herbicides delay resistance. Pest Management Science 76:487–496

Chahal PS, Ganie ZA, Jhala AJ (2018) Overlapping residual herbicides for control of photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant palmer amaranth (*Amaranthus palmeri* S. Watson) in glyphosate-resistant maize. Frontiers in Plant Science

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, York AC, Davis JW, Hanna WW (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Science 54:620–626

Crow W, Cook D, Pieralisi B, Catchot A, Layton B, Larson E, Gore J, Musser F, Irby T. (2021) 2021 Insect Control Guide for Agronomic Crops. Mississippi State University Extension Service

Everman WJ, Clewis SB, York AC, Wilcut JW (2009) Weed Control and Yield with Flumioxazin, Fomesafen, and S-Metolachlor Systems for Glufosinate-Resistant Cotton Residual Weed Management. Weed Technology 23:391–397

Garetson R, Singh V, Singh S, Dotray P, Bagavathiannan M (2019) Distribution of herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in row crop production systems in Texas. Weed Technology 33:355–365

Hausman NE, Tranel PJ, Riechers DE, Maxwell DJ, Gonzini LC, Hager AG (2013) Responses of an HPPD Inhibitor-Resistant Waterhemp (*Amaranthus tuberculatus*) Population to Soil-Residual Herbicides. Weed Technology 27:704–711

Knezevic SZ, Datta A, Scott J, Klein RN, Golus J (2009) Problem Weed Control in Glyphosate-Resistant Soybean with Glyphosate Tank Mixes and Soil-Applied Herbicides. Weed Technology 23:507–512

Neve P (2008) Simulation modelling to understand the evolution and management of glyphosate resistance in weeds. Pest Management Science 64:392–401

Neve P, Norsworthy JK, Smith KL, Zelaya IA (2011) Modelling evolution and management of glyphosate resistance in *Amaranthus palmeri*. Weed Research 51:99–112

Perkins CM, Mueller TC, Steckel LE (2021) Survey of glyphosate-resistant junglerice (*Echinochloa colona*) accessions in dicamba-resistant crops in Tennessee. Weed Technology 35:412–418

Peterson MA, Collavo A, Ovejero R, Shivrain V, Walsh MJ (2018) The challenge of herbicide resistance around the world: a current summary. Pest Management Science 74:2246–2259

Price AJ, Koger CH, Wilcut JW, Miller D, Santen EV (2008) Efficacy of Residual and Non-Residual Herbicides Used in Cotton Production Systems When Applied with Glyphosate, Glufosinate, or MSMA. Weed Technology 22:459–466

de Sanctis JHS, Barnes ER, Knezevic SZ, Kumar V, Jhala AJ (2021) Residual herbicides affect critical time of Palmer amaranth removal in soybean. Agronomy Journal 113:1920–1933

Sarangi D, Jhala AJ (2019) Palmer Amaranth (*Amaranthus palmeri*) and Velvetleaf (*Abutilon theophrasti*) Control in No-Tillage Conventional (Non–genetically engineered) Soybean Using Overlapping Residual Herbicide Programs. Weed Technology 33:95–105

Steckel LE, Sprague CL, Hager AG (2002) Common Waterhemp (*Amaranthus rudis*) Control in Corn (*Zea mays*) with Single Preemergence and Sequential Applications of Residual Herbicides. Weed Technology 16:755–761

United States Department of Agriculture (n.d.) World Agricultural Supply and Demand Estimates

Werth JA, Preston C, Roberts GN, Taylor IN (2008) Weed Management Impacts on the Population Dynamics of Barnyardgrass (*Echinochloa crus-galli*) in Glyphosate-Resistant Cotton in Australia. Weed Technology 22:190–194

Whitaker J, York AC, Jordan D, Culpepper AS, Sosnoskie L (2011) Residual Herbicides for Palmer amaranth control. Journal of Cotton Science 15:89–99