CONTROL OF GLYPHOSATE-RESISTANT PALMER AMARANTH IN DHT COTTON AND PEANUT RESPONSE TO 2,4-D

by

RAND MICHAEL MERCHANT

(Under the Direction of A. Stanley Culpepper and Eric P. Prostko)

ABSTRACT

Cotton (*Gossypium hirsutum*) resistant to 2,4-D could potentially allow for more POST herbicide options for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Trials were conducted to determine the most effective herbicide systems for control of Palmer amaranth using DHT technology. For most effective control (99%) growers should use a system that includes a PRE herbicide at planting followed by a POST application of 2,4-D plus glufosinate with a sequential POST application made 12 days later and a layby application prior to canopy closure. In an effort to mitigate the risk of 2,4-D drift, growers can make applications at 7:00 AM when wind speeds are lower. This is imperative since susceptible peanut (*Arachis hypogaea*) is often planted near cotton and can suffer yield losses if injured by drift rates of 2,4-D, particularly 60 days after planting.

INDEX WORDS: *Arachis hypogaea*, *Gossypium hirsutum*, *Amaranthus palmeri*, *Desmodium tortuosum*, *Jacquemontia tamnifolia*, *Mollugo verticillata*,

glyphosate-resistance, 2,4-D, amine, choline, glufosinate, glyphosate, off-target movement, drift, salvage, time of day

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DEDICATION

This is for my Grandparents. My Nene, Betty Jean Ward, for showing me so much of the world from a little red convertible and opening the eyes of a child to life outside of a small town. My Pappy, Johnny Ward, for the years of guidance. My Nanny, Betty Thurman, for teaching me how one person can nourish so many grandchildren through simple love. My Pa, Julius Rudolph Thurman, a sharecropper's son who became the greatest man I will ever know by working hard with quiet dignity for no more reward than a life well lived.

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"Cauliflower is nothing but cabbage with a college education"

-Mark Twain

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INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

The control of Palmer amaranth (*Amaranthus palmeri*) is a priority in weed management in row crops in the Southeastern US. New herbicide-resistant technologies are being made available that broaden our weed control options. One of the most successful transgenic cotton (*Gossypium hirsutum*) varieties, DP 555 BGRR, is no longer available on the general market (Scott et al., 2002). New cultivar introductions have taken advantage of this market vacuum (Duke, 2005). Most of this new technology still contains glyphosate and glufosinate resistant genes (Culpepper et al., 2009) . Glyphosate is losing effectiveness quickly on driver weeds such as Palmer amaranth (Culpepper et al., 2006). Glufosinate can be effective, but must be applied in a timely manner (Anonymous 2004).

Promising new technologies are traits that code for resistance to auxinic herbicides, including 2,4-D and dicamba. Currently these traits are being implemented in cultivars of cotton, corn (*Zea mays*), and soybean (*Glycine max*). Conventional cultivars of cotton are susceptible to auxinic herbicides (Everitt and Keeling, 2009). DHT (Dow Herbicide Tolerance) cotton cultivars will be resistant to 2,4-D, glyphosate, and glufosinate. DHT cotton is scheduled to be commercially available in 2013-2015 pending EPA approval. The combination of 2,4-D, glyphosate, and glufosinate resistance can be effective in future management of broadleaf and grass weeds. However, Palmer amaranth's development of glyphosate resistance makes the use of glyphosate-based control measures insufficient (Culpepper et al., 2008). The combination of glufosinate and 2,4-D has proven to be more effective than either of the constituents applied alone. Further trials need to be conducted to determine the effects of this tank mixture in a cropping situation.

LITERATURE REVIEW

The introduction of auxinic-resistant crops raises a special concern with the increased use of auxinic herbicides and their effect on non-target crops (Sciumbato et al., 2004). DHT will be the first of these technologies to be marketed, resulting in increased use of 2,4-D. Current formulations of 2,4-D are susceptible to drift and volatilization if applied under improper conditions (Banks and Schroeder, 2002). Tank contamination is also a possibility if sprayer tanks are not thoroughly cleaned after 2,4-D use. For growers producing several types of agronomic crops, this can be damaging to parts of their operation. Many cotton growers in the Southeast also have significant peanut (*Arachis hypogaea*) acreage. Peanut are susceptible to 2,4-D (Szmedra, 1997). Since drift, volatilization, and sprayer contamination are real possibilities, data quantifying 2,4-D damage to peanuts are needed. Although research has shown the effect of 2,4-D on specific physiological processes of peanut, readily-available published research that quantifies the relationship between 2,4-D damage and peanut yield is lacking. Proposed trials will provide data for a regression model to determine the relationship between rate and timing of 2,4-D application to peanut damage and yield.

Palmer amaranth (*Amaranthus palmeri*) has become the major weed of concern in Southern field crop production (Webster and Nichols, 2012). It is a monoecious plant of the Amaranthaceae family. A summer annual, the plant is capable of extremely rapid growth (Horak and Loughin, 2000). The family Amaranthaceae is characterized containing annual or perennial herbs. Flowers can be perfect or imperfect; each flower subtended by 3 bracts. Sepals are 3-5, united or separate, scarious or membranous, petals absent, stamens 5, often partially or completely united in a lobed stamina tube, lobes frequently extending beyond the anthers, stigmas 1-3 (Radford 1968).

The genus Amaranthus has several species that occur as weeds, including waterhemp (*Amaranthus tuberculatus*), spiny amaranth (*Amaranthus spinosus*), redroot pigweed (*Amaranthus retroflexus*), smooth pigweed (*Amaranthus hybrida*) and Palmer amaranth. The genus is characterized as monoecious or dioecious annuals with alternate or entire leaves. Flowers are in axillary, fascicled clusters or paniculate terminal thyrses. There can be 0-5 sepals with 5 separate stamens and 2-3 distinct stigmas. The utricle can be indehiscent or circumscissile with lenticular seeds 1-3mm long (Radford 1968). Palmer amaranth is a dioecious plant, meaning that male and female flowers are imperfect and occur on separate male and female plants.

Palmer amaranth is an example of an r-strategist, capable of producing 500,000 seed per growing season. An obligate outcrosser, Palmer populations are capable of great genetic diversity (Neve et al., 2011). A Palmer amaranth population of 1 plant per 10 row ft. of cotton can result in a 13 % yield loss. If that were to increase to 10 plants per row ft. a not unheard of density, then the resulting yield loss increases to 57% per row foot (Fast et al., 2009). Palmer amaranth can occur in cotton, peanut, soybean, corn (*Zea mays*) and vegetables.

R-strategists are of particular concern to management of the weed-seedbank, the collection of weed seed left behind by previous generations of weeds that were allowed to seed (Keeley et al., 1987). A mature female Palmer amaranth can refill a weed-seedbank after years of careful management (Espeland et al., 2010). Proper management of the weed-seedbank includes full management of the soil and strict control of weeds. Research has shown that Palmer amaranth populations in the weed-seedbank can be reduced by deep-turn plowing (Jha and Norsworthy, 2009). This is not an effective control every year, as when seeds are turned they must remain there for a certain period of time before they are no longer capable of germination (Jha and Norsworthy, 2009). If the soil is inverted too soon viable seeds will germinate adding to the current year's weed problem (Toler et al., 2002).

Other non-chemical control measures include planting date, row spacing, physical destruction, and hand weeding (Wilson et al., 2007) . Control measures vary between crops. There are several chemical controls available for Palmer amaranth (Everman et al., 2009). Of particular concern in future trials are glyphosate, glufosinate, and 2,4-D.

Populations of glyphosate-resistant Palmer amaranth were first confirmed in 2004 (Culpepper et al., 2006). Prior to this, Palmer amaranth could easily be controlled with a standard application rate of glyphosate (Whitaker et al., 2010). The glyphosate-resistant biotypes have caused growers to rely heavily on PRE applied herbicides or herbicides with long residuals as means of control (Price et al., 2008). Future technologies will allow for POST application of herbicide mechanism-of-actions that we cannot currently broadcast apply.

OBJECTIVE

The objective of this thesis was to determine the effectiveness of 2,4-D resistant technology and how these systems could be best applied to cotton production in the southeastern US. In addition to effective herbicide systems, trials were conducted to determine the response of peanut to off-target movement of 2,4-D so that growers could make more informed management decisions concerning the use of these systems when growing 2,4-D resistant crops nearby susceptible crops.

CHAPTER 2

WEED RESPONSE TO 2,4-D, 2-4DB, AND DICAMBA APPLIED ALONE OR WITH GLUFOSINATE[1]

[1] R. Merchant, L. Sosnoskie, A. Culpepper, L. Steckel, A. York, L. Braxton, and J. Ford. Submitted to *Journal of Cotton Science,* 12/02/12.

ABSTRACT

Cotton tolerant of 2,4-D, glufosinate, and glyphosate or dicamba, glufosinate, and glyphosate is in development. This technology will give growers additional tools to manage glyphosate-resistant weeds. A field experiment was conducted across six environments in Georgia, North Carolina, and Tennessee to determine the response of 13- to 20-cm weeds to 2,4-D, 2,4-DB, and dicamba applied alone or mixed with glufosinate. Palmer amaranth (*Amaranthus palmeri* S. Wats) was controlled 59 to 78, 68 to 80, and 59 to 83% by 2,4-DB dimethylamine (560 to 1120 g a. e. ha^{-1}), 2,4-D dimethylamine (530 to 1060 g a.e. ha^{-1}), and dicamba diglycolamine (280 to 1120 g a. e. ha^{-1}), respectively, and 74% by glufosinate ammonium (430 g a.e. ha^{-1}). Control was improved (89 to 97%) with all auxin/glufosinate mixtures when compared to respective herbicides alone. Glufosinate controlled Benghal dayflower (*Commelina benghalensis* L.) only 68%; 2,4-D at 530 g ha^{-1} and dicamba at 1120 g ha^{-1} controlled this weed at least 90%. Combinations of glufosinate and auxin herbicides were beneficial when control by auxin herbicides was 90% or less. Carpetweed (*Mollugo verticillata* L.) control by auxin herbicides ranged from 50 to 66%; glufosinate alone or in mixtures completely controlled carpetweed. All treatments completely controlled morningglory (*Ipomoea* spp.). Auxin herbicides had no activity on grasses. Texas millet (*Panicum texanum* [Buckl.] R. Webster) and broadleaf signalgrass (*Brachiaria platyphylla [Nash] R. Webster*) were controlled 89 to 90% by glufosinate alone. Both 2,4-D and 2,4-DB mixed with glufosinate reduced Texas millet control, and 2,4-D reduced broadleaf signalgrass control.

INTRODUCTION

Glyphosate-resistant Palmer amaranth has drastically changed agronomic crop production throughout the southeastern United States, most notably cotton production (Sosnoskie and Culpepper, 2012; Webster and Sosnoskie, 2010). Ninety-two percent of Georgia cotton growers hand-weeded 54% of their crop, spending an average of $63.50 per hand-weeded ha during 2010 (Sosnoskie and Culpepper, 2012). Hand-weeding is a secondary line of defense against this pest as these same growers apply over $150 ha^{-1} in herbicides with applications beginning at burndown and continuing through cotton canopy closure. Additionally, these growers have reduced conservation tillage by 7%, increased cultivation to 43% of the hectares, and increased both the use of moldboard plows (100,000 ha during 2009 and 2010) and the use of secondary preplant tillage implements to incorporate herbicides (100,000 ha during 2010) in conventionally tilled systems (Culpepper et al., 2010; Price et al., 2011; Sosnoskie and Culpepper, 2012).

Effective control of Palmer amaranth in cotton has been achieved with glufosinate-based systems (Culpepper et al., 2009; Everman et al., 2007; Gardner et al., 2006; Whitaker et al., 2011). Glufosinate must be applied to small Palmer amaranth for consistently effective control (Coetzer et al., 2002; Culpepper et al., 2010). Palmer amaranth grows rapidly (Horak and Loughin, 2000), and growers are often unable to make timely applications. Another herbicide mixed with glufosinate might improve control of larger weeds. Herbicides that could potentially be mixed with glufosinate applied postemergence include MSMA, pyrithiobac, trifloxysulfuron, and fluometuron. MSMA has poor activity on Palmer amaranth, especially at rates that can be applied overtop of cotton (Culpepper, 2012). Moreover, combinations of MSMA plus glufosinate may be antagonistic (Koger et al., 2007). The ALS-inhibiting herbicides pyrithiobac and trifloxysulfuron can control Palmer amaranth (Branson et al., 2005; Culpepper and York, 1997). However, Palmer amaranth biotypes resistant to ALS-inhibiting herbicides are widespread across the Mid-South and Southeast (Heap, 2012; Wise et al., 2009). Fluometuron mixed with glufosinate has improved control of larger Palmer amaranth (Barnett et al., 2011), but postemergence (topical) application of fluometuron has been discouraged because it injures cotton, delays maturity, and sometimes reduces yield (Byrd and York, 1987; Snipes and Byrd, 1994).

Transgenic cotton resistant to 2,4-D is being developed (Braxton et al., 2010). The traits for resistance to these auxin herbicides will be stacked with traits conferring resistance to both glufosinate and glyphosate. Auxin herbicides are effective on a number of broadleaf weeds commonly infesting cotton (Green and Owen, 2011; Mueller et al., 2005), and they will be recommended in combination with glufosinate. It is important that Extension personnel and other advisors better understand the response of weeds to these herbicide mixtures.

MATERIALS AND METHODS

The experiment was conducted in 2009 at Macon, Tift, and Colquitt counties in Georgia. Three experiments, separated in time, were conducted at the Macon County location. The experiment also was conducted in 2010 at Worth County, Georgia, Shelby County, Tennessee, and Edgecombe County, North Carolina. All sites were fallow fields with naturally occurring weed populations being evaluated (Table 2.1). Plot sizes were 1.8 by 7.6 m in Georgia, 1.5 by 6.1 m in Tennessee, and 3 by 6.1 m in North Carolina. Soils in Georgia and North Carolina were loamy sands or sandy loams low in organic matter while the soil in Tennessee a silt loam. The experimental design was a randomized complete block with four replications of each treatment. Treatments consisted of a factorial arrangement of two rates of glufosinate by 10 auxin herbicide and rate combinations. Glufosinate ammonium salt (Ignite 280 SL Herbicide, Bayer CropScience LP, Research Triangle Park, NC) was applied at 0 and 430 g a.e. ha^{-1}. The auxin herbicide and rate combinations included the following: no auxin herbicide; the dimethylamine salt of 2,4-DB (Agri Star® Butyrac® 200 Broadleaf Herbicide, Albaugh, Inc., Ankeny, IA) at 560, 840, and 1120 g a.e. ha^{-1}; the dimethylamine salt of 2,4-D (Nufarm Weedar® 64, Nufarm, Inc., Burr Ridge, IL) at 530, 800, and 1060 g a.e. ha^{-1}; and the diglycolamine salt of dicamba (Clarity® Herbicide, BASF Corp., Research Triangle Park, NC) at 280, 560, and 1120 g a.e. ha^{-1}. Herbicides were applied to weeds at the sizes indicated in Table 2.1 using CO_2-pressurized backpack sprayers calibrated to deliver 140 L/ha at 165 kPa in Georgia and North Carolina or 140 L/ha at 207 kPa in Tennessee. Nozzles included DG11002 TeeJet® Drift Guard Flat Fan Spray Tips (TeeJet Technologies, Wheaton, IL) with 45.7 cm nozzle spacing in Georgia and North Carolina and TP8002 TeeJet® Flat Spray Tips (TeeJet Technologies, Wheaton, IL) with 50.8 cm nozzle spacing in Tennessee.

Weed control was estimated visually at 10, 20, and 30 days after herbicide application using a scale of 0 to 100, where 0= no control and 100= complete control (Frans et al., 1986). With weed responses being consistent across evaluation dates, only the 20-day evaluation is reported. Data were transformed to improve normality and homogeneity of variance and then analyzed using PROC Mixed of SAS (version 9.1; SAS Institute, Inc., Cary, NC). Site and replication were considered random effects, while treatments were considered fixed effects. When significant differences were noted interaction means were present and post hoc pair-wise comparisons were made using Tukey’s HSD at $P \leq 0.05$ to specifically compare auxin plus glufosinate mixtures to the respective auxin applied alone. Non-transformed comparisons are reported.

RESULTS AND DISCUSSION

Palmer amaranth. Glufosinate applied alone controlled Palmer amaranth only 74% (Table 2.2), a level of control expected when treating 20-cm tall plants (Coetzer et al., 2002). 2,4-D controlled Palmer amaranth 68, 79, and 80% when applied at 530, 800, and 1060 g ha^{-1} respectively. Control by 2,4-DB at 840 and 1120 g ha^{-1} and dicamba at 560 and 1120 g ha^{-1} was similar to control by 2,4-D at 800 and 1060 g ha^{-1}. At the lowest application rate of 530 g ha^{-1}, 2,4-D was 9% more effective than 2,4-DB at 560 g ha^{-1} or dicamba at 280 g ha^{-1}.

None of the three auxin herbicides, regardless of application rate, or glufosinate adequately controlled Palmer amaranth (Table 2.2). Palmer amaranth can be present at densities of 100 or more plants m^{-2} early in the season in non-treated cotton (Culpepper et al., 2006; Whitaker et al., 2011), and Palmer amaranth is very competitive with cotton (Morgan et al., 2001; Rowland et al., 1999). High plant densities of Palmer amaranth, along with the competitiveness of the weed, dictate the need for near-perfect control.

We emphasize that these results are from single applications to weeds larger than the optimal size for treatment. Greater control would be expected if the Palmer amaranth had been smaller at application (Edwards et al., 2012; Voth et al., 2012). Similarly, greater control would be expected with a follow-up application of any of the four herbicides (Siebert et al., 2011). By intentionally delaying application until Palmer amaranth was 15 to 20 cm tall, we were better able to determine differences in efficacy of the herbicides and also better able to determine the effect of mixing auxin herbicides with glufosinate.

Compared with 74% control by glufosinate alone, auxin herbicides mixed with glufosinate increased Palmer amaranth control to 89 to 97% (Table 2.2). Control by all glufosinate/auxin combinations was greater than control by the auxin herbicides alone or glufosinate alone.

Improved control of Palmer amaranth (Voth et al., 2012; York et al., 2012) and other weeds (Chahal and Johnson, 2012; Steckel et al., 2006) with mixtures of glufosinate and auxin herbicides has been observed in other studies .

Benghal dayflower. Control of Benghal dayflower in this study was as expected (Protsko, 2012). 2,4-D controlled Benghal dayflower 90 to 99% and was much more effective than 2,4-DB or glufosinate (Table 2.2). Dicamba was as effective as 2,4-D only when applied at 1120 g ha^{-1}. Glufosinate applied alone controlled Benghal dayflower only 68%, but mixtures of glufosinate plus either 2,4-D or dicamba increased control to 94 to 99%. Control by mixtures of glufosinate plus 2,4-DB was greater than control by 2,4-DB or glufosinate alone, but combinations of glufosinate plus 2,4-DB were less effective than mixtures of glufosinate plus either 2,4-D or dicamba.

Carpetweed. Auxin herbicides controlled carpetweed only 50 to 66% regardless of product or rate used (Table 2.2). Glufosinate completely controlled carpetweed when applied alone or in combination with any of the auxin herbicides.

Morningglory. Regardless of rate Glufosinate and each auxin herbicide controlled morningglory species completely (Table 2.3). Complete control also was obtained with all glufosinate plus auxin herbicide combinations. Auxin herbicides and glufosinate are expected to be effective on *Ipomoea* morningglory species (Corbett et al., 2004; Prostko, 2011a, 2011b).

Broadleaf signalgrass and Texas millet. Auxin herbicides did not control the two annual grass species (Table 2.3). However, glufosinate controlled these grasses 89 to 90%. Texas millet control by mixtures of glufosinate plus dicamba was similar to control by glufosinate alone. In contrast, both 2,4-D and 2,4-DB mixed with glufosinate reduced Texas millet control 9 to 21 percentage points. Neither dicamba nor 2,4-DB mixed with glufosinate adversely affected broadleaf signalgrass control by glufosinate, but control with glufosinate plus 2,4-D was less than control by glufosinate alone in two of the three combinations.

Previously published research shows that 2,4-D and 2,4-DB can reduce control of grassy weeds when these auxins are mixed with cyclohexanedione and aryloxyphenoxy propionate herbicides (Blackshaw et al., 2006; Mueller et al., 1989; York et al., 1993). Mixtures of glyphosate plus auxin herbicides have usually been additive, or sometimes synergistic, on dicot species (Chahal and Johnson, 2012; Culpepper et al., 2001; Jordan et al., 1997; Wehtje and Walker, 1997). Varying results have been reported with mixtures of glyphosate plus auxin herbicides applied to grassy weeds. 2,4-DB mixed with glyphosate had no effect on control of large crabgrass (Culpepper et al., 2001) or barnyardgrass (Jordan et al., 1997). 2,4-D mixed with glyphosate reduced control of johnsongrass, quackgrass, wheat, barley, and wild oat (O'Sullivan and O'Donnell, 1982). Dicamba and 2,4-D mixed with glyphosate reduced control of johnsongrass (Flint and Barrett, 1989).

Research with mixtures of auxin herbicides and glufosinate is much more limited. Dicamba and 2,4-D mixed with glufosinate have generally increased control of horseweed [*Conyza canadensis* (L.) Cronq.], common lambsquarters (*Chenopodium album* L.), and Palmer amaranth (Chahal and Jordan, 2012; Steckel et al., 2006; Voth et al., 2012; York et al., 2012). However, Botha et al. (2012) reported antagonism with dicamba plus reduced rates of glufosinate applied to Palmer amaranth. No results have been published on grass weed control by mixtures of glufosinate plus 2,4-D, 2,4-DB, or dicamba. However, quinclorac and triclopyr are auxin herbicides, and Lanclos et al. (2002) reported antagonism on barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and broadleaf signalgrass with mixtures of glufosinate plus quinclorac or triclopyr.

New technologies allowing topical application of auxin herbicides to cotton will provide additional tools desperately needed by cotton growers to manage glyphosate-resistant weeds. However, auxin herbicides applied alone will likely not adequately control glyphosate-resistant Palmer amaranth. Glufosinate/auxin combinations will more effectively control Palmer amaranth and a broader spectrum of dicot weeds as compared to either of these chemistries applied alone. Additionally, the use of glufosinate/auxin combinations can potentially extend the useful life of both herbicides and technologies. Our results with glufosinate/auxin combinations on Texas millet and broadleaf signalgrass indicate the need for more research to better understand potential problems with the mixtures.

Table 2.1. Weed size and density at time of herbicide application.

Location	Year	Weeds Present	Weed size at application	Weed density at application
			cm	**plants m^{-2}**
Macon County, GA[Y]	2009	Palmer amaranth	15-20	125
Tift County, GA	2009	Palmer amaranth	18-25	7
		Carpetweed	13-18	4
Colquitt County, GA	2009	Pitted morningglory	18-23	4
		Benghal dayflower	15-20	22
		Broadleaf signalgrass	20	12
Shelby County, TN	2010	Palmer amaranth	20	65
Worth County, GA	2010	Texas millet	15-20	18
		Entireleaf morningglory	15-20	10
Edgecombe County, NC	2010	Broadleaf signalgrass	15 cm	60

[z] Size refers to height of Palmer amaranth, Benghal dayflower, broadleaf signalgrass, and Texas millet, diameter of carpetweed, and runner length of pitted morningglory and entireleaf morningglory.

[y] Three trials were conducted at the Macon site, each with Palmer amaranth.

Table 2.2. Control of Palmer amaranth, Benghal dayflower, and carpetweed 20 days after application of 2,4-DB, 2,4-D, and dicamba alone and mixed with glufosinate.[z]

	Auxin	Palmer amaranth		Benghal dayflower		Carpetweed	
Auxin herbicide	herbicide rate	No glufosinate	+ glufosinate[y]	No glufosinate	+ glufosinate	No glufosinate	+ glufosinate
	g ha^{-1}	%					
No Auxin	---	--	74	--	68	--	100
2,4-DB	560	59	92*[w]	60	78*	59	100*
2,4-DB	840	71	93*	72	83*	50	100*
2,4-DB	1120	78	95*	71	80*	55	100*
2,4-D	532	68	90*	90	98*	66	100*
2,4-D	798	79	93*	99	98	59	100*
2,4-D	1064	80	97*	98	99	63	100*
Dicamba	280	59	89*	69	97*	55	100*
Dicamba	560	76	92*	84	94*	58	100*
Dicamba	1120	83	94*	94	94	60	100*
LSD (0.05)		9		9		13	

[z]Results for Palmer amaranth, tropical spiderwort, and carpetweed combined over 6, 1, and 1 locations, respectfully.

[y]Glufosinate applied 431 g ha^{-1}.

[w]Means followed by an asterisk (*) indicate the mixture of glufosinate plus auxin herbicide was more effective than the respective auxin herbicide and rate applied alone using Tukey's HSD at $P \leq 0.05$ post hoc pair-wise comparisons.

Table 2.3. Control of morningglory, broadleaf signalgrass, and Texas millet 20 days after application of 2,4-DB, 2,4-D, and dicamba alone and mixed with glufosinate.[z]

	Auxin	Morningglory[y]		Broadleaf signalgrass		Texas millet	
Auxin herbicide	herbicide rate	No glufosinate	+ glufosinate[x]	No glufosinate	+ glufosinate	No glufosinate	+ glufosinate
	g ha^{-1}	———————	———————	——————— %	———————	———————	———————
No Auxin	---	--	100	--	89	--	90*
2,4-DB	560	100	100	0	95*[w]	0	78*
2,4-DB	840	100	100	0	95*	0	70*
2,4-DB	1120	100	100	0	90*	0	69*
2,4-D	532	100	100	0	81*	0	81*
2,4-D	798	100	100	0	85*	0	81*
2,4-D	1064	100	100	0	82*	0	70*
Dicamba	280	100	100	0	90*	0	91*
Dicamba	560	100	100	0	89*	0	94*
Dicamba	1120	100	100	0	84*	0	95*
LSD (0.05)		NS		7		9	

[z]Results for morningglory, broadleaf signalgrass, and Texas millet combined over 2, 2, and 1 locations, respectfully.

[y]Results for morningglory combined over one location with pitted morningglory and one with entireleaf morningglory..

[x]Glufosinate applied 431 g ha^{-1}.

[w]Means followed by an asterisk (*) indicate the mixture of glufosinate plus auxin herbicide was more effective than the respective auxin herbicide and rate applied alone using Tukey’s HSD at $P \leq 0.05$ post hoc pair-wise comparisons.

CHAPTER 3

CONTROLLING GLYPHOSATE-RESISTANT PALMER AMARANTH (*AMARANTHUS PALMERI*) IN COTTON WITH RESISTANCE TO GLYPHOSATE, 2,4-D AND GLUFOSINATE[1]

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[1] R.M. Merchant, A.S. Culpepper, P.M. Eure, J.S. Richburg, and L.B. Braxton. To be submitted to *Weed Technology*.

ABSTRACT

Field experiments were conducted in Macon County, Georgia, during 2010 and 2011 to determine the impact of new herbicide resistant cotton and respective herbicide systems on the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats). Sequential POST applications of 2,4-D or glufosinate followed by diuron plus MSMA directed at layby controlled Palmer amaranth 62 to 79% and 46 to 49% at harvest when the initial application was made to 8 or 18 cm tall Palmer amaranth, respectively. Mixtures of glufosinate plus 2,4-D applied sequentially followed by the layby controlled Palmer amaranth 95 to 97% regardless of Palmer amaranth height. Seed cotton yield was at least 30% higher with 2,4-D plus glufosinate systems as compared to systems with either herbicide alone. The addition of pendimethalin and/or fomesafen PRE did not improve Palmer amaranth control or yields when applying glufosinate plus 2,4-D sequentially and the layby. However the addition of these residual herbicides improved control when making sequential applications of glufosinate or 2,4-D at harvest (87 to 96%); yields from these systems were similar to those recorded with glufosinate plus 2,4-D systems. Comparison 2,4-D and 2,4-DB treatments confirmed that 2,4-D is a more effective option for the control of Palmer amaranth in the glyphosate, 2,4-D, and glufosinate weed management system. Results from these experiments suggest cotton technology with resistance to glufosinate, glyphosate, and 2,4-D will improve Palmer amaranth management. Numerous effective systems can be developed but results encourage growers to use mixtures of glufosinate plus 2,4-D when controlling emerged Palmer amaranth. At-plant residual herbicides will be recommended for consistent performance of all 2,4-D systems across environments, although this technology will allow greater flexibility in selecting PRE herbicide(s) which should reduce input costs, carryover concerns, and crop injury when compared to current systems

INTRODUCTION

First confirmed in 2004, glyphosate-resistant Palmer amaranth remains the primary weed of concern for cotton producers (Culpepper et al. 2006; Gaines et al. 2011; Whitaker et al. 2011a and 2011b). Efforts to control this pest have become more successful, but remain challenging and costly (Ford et al. 2011; Price et al. 2011; Neve et al. 2011). A grower survey conducted in 2010 reported that Georgia growers are spending $168/ha on herbicides for the control of glyphosate-resistant Palmer amaranth, 2.5 times more herbicide active ingredient than that applied prior to resistance confirmation (Sosnoskie and Culpepper 2012). Use of residual herbicides (acetochlor, diuron, flumioxazin, fomesafen, pendimethalin, trifluralin, and *S*-metolachlor) applied throughout the crop as well as use of paraquat for preplant burndown and glufosinate for topical in-crop applications have increased significantly. In conjunction with increased glufosinate use has been the adoption of cotton cultivars tolerant to topical applications of glufosinate; increasing from 0% of Georgia's acreage in 2004 up to 49% of the acres during 2012 (USDA 2004; USDA 2012). Even after an aggressive herbicide system, 92% of Georgia growers are hand weeding 52% of the cotton crop at an average cost of $60/ha for each hand weeded acre. Loss of conservation tillage is also occurring as growers adopt both primary and secondary tillage methods to aid in the battle against glyphosate-resistant Palmer amaranth (Sosnoskie and Culpepper 2012)

Agricultural biotechnology companies are developing new technologies that will increase the portfolio of herbicide-resistant crops. Herbicides labeled for use in these crops may provide effective options for the control of Palmer amaranth with resistance to currently used herbicides. One such technology will be cotton resistant to preplant or topical applications of 2,4-D (Braxton et al. 2010). 2,4-dichlorophenoxyacetic acid was the first selective herbicide widely used in agriculture (Peterson 1967). Much research has quantified its effectiveness and limitations as a broadleaf herbicide in the decades since its discovery (Colby 1967; Triplett and Lytle 1972; Migo et al. 1986). Although 2,4-D is a member of the synthetic auxin family of herbicides, its site of action is currently unknown. Application of growth regulators, such as 2,4-D, induce an imbalance in phytohormone levels that causes epinasty of leaf stems and leaves and results in necrosis of meristematic tissue (Jursik et al. 2011). Synthetic auxins can be used to effectively control problematic broadleaves such as common cocklebur (*Xanthium strumarium* L.), sicklepod (*Senna obtusifolia* L.), Palmer amaranth, and morningglory spp. (*Ipomoea spp.*) (Ferrell and Witt 2002; Lancaster et al. 2005; Norsworthy et al. 2008).

Cotton tolerance to 2,4-D is conferred by the insertion of a gene that codes for the enzyme aryloxyalkanoate dioxygenase. This gene may come from a number of sources including *Sphingobium herbicidovorans* and *Delftia acidovorans*. Plants transformed to include this gene can metabolize auxin herbicides to a non-lethal form (Richburg et al. 2012). This technology is being commercialized in cultivars of cotton, soybean, and corn from Dow AgroSciences (Dow AgroSciences; Indianapolis, IN). The objective of this study was to determine the most effective weed management system for the control of glyphosate-resistant Palmer amaranth in cotton resistant to glyphosate, 2,4-D and glufosinate.

MATERIALS AND METHODS

Two experiments were conducted twice in Macon County, Georgia, during 2010 and 2011 for a total of 4 site-years. Macon County was chosen for each site because the population of Palmer amaranth is among the most highly glyphosate-resistant Palmer amaranth populations known and because the crop is grown under dryland conditions usually offering extremely stressful environments. AAD-12:1910 cotton (Dow AgroScience; Indianapolis, IN), resistant to

2,4-D, was planted across each study at a seeding rate of 2 seeds placed every 22 cm in-row with rows spaced 91 cm apart. Soil was conventionally prepared with individual plots 3.6 m wide by 7.6 m in length having treatments replicated 4 times. Soil type was a Dothan loamy sand with 1.9-2.1% organic matter and a pH of 6.2-6.4. One location for each experiment was planted on May 1st 2010 with a second location for the 2,4-D experiment planted on May 10th and the second location for the 2,4-D vs. 2,4-DB experiment planted on June 16th 2011.

Methods Specific To the 2,4-D Experiment: A factorial treatment design including three PRE herbicide options and three POST herbicide options was implemented. PRE options included no herbicide, pendimethalin (Prowl H_20; BASF, Research Triangle Park, NC) at 1118 g ai ha^{-1}, or fomesafen (Reflex; Syngenta Crop Protection, Research Triangle Park, NC) at 280 g ai ha^{-1}. POST options were sequentially applied and included 2,4-D (Weedar 64; NuFarm, Burr Ridge, IL) at 1118 g ai ha^{-1}, 2,4-D at 1118 g ha^{-1}plus glyphosate (Roundup WeatherMax; Monsanto, St. Louis, MO) at 840 g ai ha^{-1}, or 2,4-D at 1118 g ha^{-1}plus glufosinate at 471 g ai ha^{-1} (Ignite; Bayer CropScience, Research Triangle Park, NC). Five additional treatments without PRE herbicides included sequential applications of 1) 2,4-D at 840 g ha^{-1}; 2) 2,4-D 840 g ha^{-1} plus glyphosate; 3) 2,4-D at 840 g ha^{-1} plus glufosinate; 4) glyphosate alone, and 5) glufosinate alone. PRE applications were made the day of planting, POST 1 applications were made when Palmer amaranth reached 8 cm in height when no herbicide was applied PRE, and POST 2 applications were made 15 d after the POST 1 application.

Methods Specific To the 2,4-D vs. 2,4-DB Experiment: A factorial treatment arrangement having three PRE herbicide options and five POST options was conducted. The three PRE options included no PRE, pendimethalin alone, or pendimethalin plus fomesafen. POST options included sequential applications of 1) 2,4-D at 840 g ha^{-1}, 2) 2,4-DB at 840 g ha^{-1},

3) 2,4-D + glufosinate at 471 g ae ha^{-1}, 4) 2,4-DB + glufosinate, and 5) glufosinate alone. PRE applications were made the day of planting, POST 1 applications were made when Palmer amaranth reached 18 cm in height in plots not receiving a PRE herbicide, and POST 2 applications were made 15 d after the POST 1 application.

Methods Common to Both Experiments: Layby directed applications of diuron (Direx; DuPont Crop Protection, Wilmington, DE) plus MSMA (MSMA 6 Plus; Drexel Chemical Company, Memphis, TN) plus Crop Oil (AGRI-DEX; Helena Chemical Company, Colliervile, TN) were applied to all herbicide systems just prior to cotton canopy closure. All applications were made with a CO_2-pressurized backpack sprayer equipped with 11002 DG flat-fan nozzles calibrated to deliver 140 L ha^{-1} at 165 kPa. No adjuvants were included with any PRE or POST application and a non-treated control was included for comparison. Insect control, fertilization, and defoliation practices were standard for dryland production in middle Georgia (Collins and Whitaker 2012)

Cotton plant heights were taken at layby and or at harvest by measuring the height of 20 plants per plot randomly. Cotton was harvested with a spindle picker modified for small-plot harvesting in November. Visual estimates of Palmer amaranth control were made prior to each herbicide application and at harvest using a visual scale of 0-100 with 0 = no control and 100 = complete plant death (Frans et al. 1986) Seed utilized in these studies were segregating populations and crop response is not indicative of the herbicide tolerance that will be present in commercial cultivars. Thus, cotton tolerance data is not reported. Cotton stand was not influenced by treatments (data not shown) and seed cotton yield differences followed closely with late-season Palmer amaranth control suggesting visual crop response had little impact on cotton yield. Palmer amaranth densities were obtained by counting all plants present between the two center rows of each plot following the layby application. Data were combined over locations within experiments and analyzed using PROC Mixed of SAS (SAS 9.2; SAS Institute, Cary, NC). Site and replication were considered fixed effects while treatments were considered random effects. Means were separated using Fisher's LSD at $P>0.05$. Treatments compromising the factorial arrangement in the 2,4-D experiment were segregated and analyzed as a factorial in PROC Mixed of SAS but did not alter the hierarchy of treatments when compared to all treatments analyzed using a non-factorial RCB design. Therefore, comparisons are made including all treatments.

RESULTS AND DISCUSSION

2,4-D Experiment: Glyphosate applied sequentially provided no control at layby or harvest (Table 3.1), and is to be expected with this population of Palmer amaranth (Culpepper et al. 2006). Sequential applications of 2,4-D, with the first application targeting 8 cm Palmer amaranth, provided only 62 to 66% control at layby and control was less than that noted with sequential glufosinate applications (79%). Control was poor at harvest with both the 2,4-D or glufosinate system after the layby was applied (62-79%); although the 2,4-D system using 1118 g ha^{-1} was at least 11% more effective than when using the lower rate of 2,4-D or when using glufosinate. The layby herbicide was more effective when following 2,4-D as compared to glufosinate because of better spray coverage with surviving Palmer amaranth plants being more prostrate. Mixing glyphosate with 2,4-D improved control beyond that noted with 2,4-D alone but control was still only 79 to 86% at harvest depending on 2,4-D rate. Mixing glufosinate with 2,4-D controlled Palmer amaranth at least 95% throughout the season, regardless of 2,4-D rate used. The addition of pendimethalin or fomesafen PRE to sequential 2,4-D or glyphosate plus 2,4-D systems improved control to at least 93% at harvest with no differences between the two

PRE options. Sequential applications of glufosinate plus 2,4-D following either PRE herbicide controlled Palmer amaranth 98 to 99% at harvest.

Cotton plant heights were 22 to 48% taller in systems including a PRE herbicide as compared to total POST systems at layby (Table 3.1). Early season-competition from Palmer amaranth has been well documented (Keeley and Thullen 1989; Morgan et al. 2001; Rowland et al. 1999) and even when making timely applications with effective POST herbicides, Palmer amaranth reduced cotton plant heights. When comparing POST programs, cotton was 27 cm tall when glufosinate or glufosinate plus 2,4-D was applied as compared to 18 to 22 cm when other herbicide systems were implemented.

Intense Palmer amaranth competition can reduce seed cotton yields and interfere with harvest efficiency. As expected, increasing Palmer amaranth control directly increases seed cotton yield (Fast et al 2009; Morgan et al. 2001; Price et al. 2011). A Palmer amaranth population of 1 plant per 3 m of row can cause 13% yield loss; if the population increases to 10 plants per 0.3 m of row, yield losses can increase to 57% (Fast et al. 2009). Palmer amaranth control at harvest ranged from 93 to 99% when systems included a PRE herbicide or when glufosinate plus 2,4-D was the POST option; these systems also contained similar and the greatest yields ranging from 1290 to 1380 kg ha^{-1}. Total POST systems of 2,4-D at 840 g ha^{-1}, 2,4-D at 1118 g ha^{-1}, glufosinate, or glyphosate produced yields of 715, 960, 850, and 270 kg ha^{-1}, respectively.

2,4-D and 2,4-DB Experiment: As expected, delaying initial POST herbicide applications until Palmer amaranth reached 18 cm in height negatively impacted control (Table 3.2). At layby, sequential 2,4-D (54%) or glufosinate (69%) programs provided unacceptable control and the addition of the layby had little affect with these two systems controlling Palmer amaranth only 46 to 49% at harvest. The 2,4-DB program was 13 and 30% less effective than comparative 2,4-D system at layby or harvest, respectively. When applied in a timely manner, 2,4-DB is more effective than observed in this experiment but Palmer amaranth control is still often not adequate (Grichar 1997). Mixtures of glufosinate and 2,4-D or 2,4-DB were far more effective than any herbicide applied alone with control ranging from 88 to 91% at layby and 87 to 97% at harvest. Although mixtures were extremely effective, glufosinate plus 2,4-D was the more effective mixture at harvest providing 47 to 51% more control than either 2,4-D or glufosinate applied alone. The addition of pendimethalin PRE improved late-season control of sequential 2,4-D (87%), 2,4-DB (58%), and glufosinate (91%) systems but did not improve control when POST options included an auxin mixed with glufosinate (95-98%). Fomesafen is extremely effective in controlling Palmer amaranth (Everman et al., 2009) but the addition of fomesafen to pendimethalin PRE only improved control of the sequential 2,4-DB system.

Palmer amaranth densities following the layby were 139,000 plants ha^{-1} in the non-treated control. Systems including an auxin plus glufosinate POST and the layby eliminated all Palmer amaranth plants; regardless of presence of a PRE herbicide. The only other two systems that eliminated Palmer amaranth populations included pendimethalin plus fomesafen PRE followed by sequential 2,4-D or glufosinate applications, and the layby.

Cotton heights followed trends noted with Palmer amaranth control. Cotton was at least 70 cm tall after the layby with all programs including glufosinate plus an auxin POST, fomesafen PRE, or pendimethalin plus 2,4-D POST. Total POST programs with 2,4-D, 2,4-DB, or glufosinate consisted of shorter cotton ranging between 43 and 62 cm in height. Seed cotton yield also followed trends noted with Palmer amaranth populations present after the layby. Yields of 1390 to 1565 kg ha^{-1} were recorded from all systems including 2,4-D or 2,4-DB plus glufosinate and the layby, with or without a PRE herbicide. Other systems with similar yields exceeding 1390 kg ha^{-1} included pendimethalin or pendimethalin plus fomesafen followed by sequential 2,4-D or glufosinate applications and the layby. When directly comparing auxin programs with and without PRE herbicides, yields were always higher with the 2,4-D alone system as compared to the 2,4-DB alone system.

Cotton technology with resistance to glufosinate, glyphosate, and 2,4-D will improve grower flexibility and management of Palmer amaranth. Numerous effective systems can be developed with this technology but results strongly suggest growers should utilize tank mixtures of glufosinate plus 2,4-D when controlling emerged Palmer amaranth. Additionally, at-plant residual herbicides will be recommended for consistent performance of all 2,4-D systems although the technology will allow greater flexibility in selecting at-plant herbicide(s) reducing input costs, carryover concerns, and crop injury when compared to current systems (Monks et al. 2012; Sosnoskie et al. 2011; Sosnoskie and Culpepper 2012).

Table 3.1. Palmer amaranth control, cotton height, and seed cotton yield with POST systems including 2,4-D, glyphosate and glufosinate.[a]

PRE herbicides		Sequential POST herbicides[b,c]	Palmer amaranth control		Cotton height prior to layby	Seed cotton yield
Pendimethalin g ha^{-1}	Fomesafen g ha^{-1}		At layby (%)	At harvest (%)	(cm)	(kg ha^{-1})
0	0	none	--[d]	--	18 e	0 g
0	0	2,4-D fb 2,4-D	66 ef	79 c	20 cde	960 cd
0	0	2,4-D + glyphosate fb 2,4-D + glyphosate	74 cd	86 bc	22 c	1100 bc
0	0	2,4-D + glufosinate fb 2,4-D + glufosinate	97 a	95 a	27 b	1360 a
1118	0	2,4-D fb 2,4-D	86 b	93 ab	32 a	1310 a
1118	0	2,4-D + glyphosate fb 2,4-D + glyphosate	87 b	95 a	33 a	1375 a
1118	0	2,4-D + glufosinate fb 2,4-D + glufosinate	95 a	99 a	33 a	1290 ab
0	280	2,4-D fb 2,4-D	89 b	95 a	34 a	1355 a

0	280	2,4-D + glyphosate fb 2,4-D + glyphosate	98 a	96 a	35 a	1350 a
0	280	2,4-D + glufosinate fb 2,4-D + glufosinate	99 a	98 a	34 a	1350 a
0	0	2,4-D* fb 2,4-D*	62 f	68 d	19de	715 e
0	0	glyphosate fb glyphosate	0 g	0 f	20 cde	270 f
0	0	glufosinate fb glufosinate	79 c	62 d	27 b	850 de
0	0	2,4-D* + glyphosate fb 2,4-D* + glyphosate	71 de	79 c	22 cd	980 cd
0	0	2,4-D* + glufosinate fb 2,4-D* + glufosinate	95 a	96 a	27 b	1380 a

[a] Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P \leq 0.05$. Data pooled over two locations. Diuron plus MSMA layby directed for all treatments except the non-treated control at time of canopy closure.

[b] Initial POST application made once Palmer amaranth reached 8 cm in height when no PRE was applied; sequential POST application made 15 d after the initial application.

[c] 2,4-D applied at 1118 g ai ha^{-1} except when noted with an * indicating 2,4-D applied at 840 g ha^{-1}. Glyphosate and glufosinate applied at 840 and 471 g ha^{-1}, respectively.

[d] Data not included in the analysis since it was assigned values of 0.

Table 3.2. Palmer amaranth control, cotton height, and seed cotton yield with POST systems including 2,4-D, 2,4-DB, and glufosinate.[a]

PRE herbicides			Palmer amaranth control		Palmer amaranth density		
Pendimethalin g ha^{-1}	Fomesafen g ha^{-1}	Sequential POST herbicides[b,c]	At layby (%)	At harvest (%)	after layby (plants ha^{-1})	Cotton height after layby (cm)	Seed cotton yield (kg ha^{-1})
0	0	none	--[d]	--	139000 a	27 f	70 g
0	0	2,4-D fb 2,4-D	54 e	46 e	11900 d	62 c	590 e
0	0	2,4-DB fb 2,4-DB	41 e	16 f	72200 b	43 e	295 f
0	0	2,4-D + glufosinate fb 2,4-D + glufosinate	91 abc	97 a	0 h	71 ab	1480 ab
0	0	2,4-DB + glufosinate fb 2,4-DB + glufosinate	88 bc	87 b	0 h	71 ab	1390 b
0	0	glufosinate fb glufosinate	69 d	49 e	9400 e	64 c	705 de
1118	0	none	10 g	0 g	23800 c	57 d	105 g
1118	0	2,4-D fb 2,4-D	86 c	87 b	300 h	71 ab	1400 b
1118	0	2,4-DB fb 2,4-DB	67 d	58 d	4400 g	62 c	780 d
1118	0	2,4-D + glufosinate fb 2,4-D +	97 ab	98 a	0 h	73 ab	1485 ab

		glufosinate					
1118	0	2,4-DB + glufosinate fb 2,4-DB + glufosinate	98 ab	95 ab	0 h	72 ab	1565 a
1118	0	glufosinate fb glufosinate	92 abc	91 ab	300 h	76 a	1315 bc
1118	280	none	66 d	19 f	7500 f	74 ab	435 f
1118	280	2,4-D fb 2,4-D	92 abc	93 ab	0 h	70 b	1485 ab
1118	280	2,4-DB fb 2,4-DB	86 c	77 c	600 h	75 ab	1235 c
1118	280	2,4-D + glufosinate fb 2,4-D + glufosinate	99 a	99 a	0 h	70 b	1455 ab
1118	280	2,4-DB + glufosinate fb 2,4-DB + glufosinate	98 ab	99 a	0 h	72 ab	1500 ab
1118	280	glufosinate fb glufosinate	99 a	96 ab	0 h	74 ab	1410 b

[a] Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P \leq 0.05$. Data pooled over two locations. Diuron plus MSMA layby directed for all treatments except the non-treated control at time of canopy closure.

[b] Initial POST application made once Palmer amaranth reached 18 cm in height when no PRE was applied; sequential POST application made 15 d after the initial application.

[c] Glyphosate, glufosinate, 2,4-D, and 2,4-DB applied at 840, 471, 840, and 840 g ha^{-1}, respectively.

CHAPTER 4

SALVAGE PALMER AMARANTH (*AMARANTHUS PALMERI*) PROGRAMS CAN BE EFFECTIVE IN COTTON RESISTANT TO GLYPHOSATE, 2,4-D, AND GLUFOSINATE[1]

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[1] R.M. Merchant, A.S. Culpepper, P.M. Eure, J.S. Richburg, and L.B. Braxton. To be submitted to *Weed Technology*.

ABSTRACT

Glyphosate-resistant Palmer amaranth escaping residual herbicides is difficult to manage in cotton because of its rapid growth and a limited number of effective herbicide options to control emerged plants. An experiment was conducted at two dryland and two irrigated sites in Georgia during 2011 and 2012 to determine if cotton resistant to glyphosate, 2,4-D, and glufosinate and respective herbicide programs could be used to salvage a crop infested with large plants of Palmer amaranth. Three POST herbicide systems, including sequential applications of 2,4-D, sequential applications of 2,4-D plus glufosinate, or 2,4-D followed by (fb) glufosinate, were applied with intervals of 5, 10, or 15 d between POST applications and were followed by diuron plus MSMA directed at layby. At the dryland sites under stressful conditions, no program provided greater than 90% control. However, the 2,4-D plus glufosinate system was at least twice as effective in controlling 20 cm tall Palmer amaranth and produced at least three times more cotton than the other two systems, when pooled over POST application intervals. Intervals of 10 or 15 d between POST applications were 23 to 27% more effective than a 5 d interval in controlling Palmer amaranth when pooled over POST herbicide systems; yields were nearly twice as much with the 10 d interval as compared to 5 d. At the irrigated site, overall weed control was greater with less treatment differences noted. Twenty cm Palmer amaranth was controlled 98 to 99%, 92 to 93%, and 81 to 94% by glufosinate plus 2,4-D, 2,4-D fb glufosinate, and 2,4-D systems at harvest, respectively. Intervals between POST applications only influenced control by the POST 2,4-D system and the 10 d interval was more effective than the 5 d interval. Carpetweed, Florida beggarweed, and smallflower morningglory were controlled 99% at harvest by all systems; however, control of carpetweed and Florida beggarweed prior to layby noted sequential applications of 2,4-D being less effective than systems including glufosinate. In the

event of an at-plant residual herbicide failure, this technology offers growers an effective option to salvage a crop infested with large Palmer amaranth by applying glufosinate plus 2,4-D sequentially with applications spaced 10 to 15 d apart and followed by diuron plus MSMA applied prior to surviving plants becoming erect. Success of this system, however, will depend on Palmer amaranth size and environmental conditions.

INTRODUCTION

Glyphosate-resistant Palmer amaranth continues to be the greatest challenge facing Southeastern cotton producers, even nine years after its discovery (Culpepper et al. 2006; Norsworthy et al. 2008; Steckel et al. 2008). Successful control measures are costly, relying heavily on residual herbicides, conventional tillage, and hand-weeding (Sosnoskie and Culpepper 2012). The greatest production challenge occurs when residual at-plant herbicides fail to control Palmer amaranth due to a lack in rainfall or irrigation (Kleifeld et al. 1988; Faircloth et al. 2001; Steckel 2012). Once glyphosate-resistant Palmer amaranth escapes at-plant residual herbicides in cotton, pyrithiobac and glufosinate are the only topically applied herbicide options (Anonymous 2006; Anonymous 2011; Collins and Whitaker 2012). Palmer amaranth resistance to pyrithiobac greatly limits its effectiveness (Branson et al. 2005; Culpepper and York 1997; Heap 2012; Wise et al. 2009). Thus in many fields, glufosinate is the only potentially effective option in selected cultivars (Everman et al. 2007; Gardner et al. 2006; Whitaker et al. 2011). Glufosinate controls Palmer amaranth at heights of 8 cm or smaller but control is usually unacceptable when Palmer amaranth exceeds this height at time of application (Coetzer et al. 2002; Culpepper et al. 2010). Since emerged Palmer amaranth can grow so quickly and because glufosinate effectiveness is limited to a small plant, salvage herbicide programs for Palmer amaranth do not currently exist (Fast et al. 2009).

Agricultural biotechnology companies are developing new technologies that will increase the portfolio of herbicide-resistant crops and respective herbicides for use in those crops (Braxton et al. 2010; Seifert-Higgins and Arnevik 2012). These new herbicidal tools may provide effective options for the control of larger emerged Palmer amaranth and other troublesome weeds, with or without resistance to currently used herbicides. One such technology expecting commercialization will be cotton with resistance to topical applications of glufosinate and glyphosate as well as resistance to preplant or topical applications of 2,4-D choline (Braxton et al. 2010). Synthetic auxins such as 2,4-D can be used to effectively control problematic broadleaves such as common cocklebur (*Xanthium strumarium* L.), sicklepod (*Senna obtusifolia* L.), Palmer amaranth, and morningglory spp. (*Ipomoea spp.*) (Ferrell and Witt 2002; Lancaster et al. 2005; Norsworthy et al. 2008).

Herbicide mixtures of 2,4-D plus glufosinate or glyphosate will improve a grower's ability to control emerged troublesome weeds because mixtures of 2,4-D plus glufosinate or glyphosate have been shown to control larger and more diverse weed populations as compared to current standards (Braxton et al. 2010; Beckie 2011; Shaw and Arnold 2002). In an event where at-plant residual herbicides fail and Palmer amaranth becomes large, mixtures of glufosinate, 2,4-D, and/or glyphosate in resistant cotton may improve the likelihood of salvaging the crop. Therefore, the objectives of this study were to first determine the most effective herbicide systems available in glyphosate-, 2,4-D-, and glufosinate-resistant cotton for the control of large emerged Palmer amaranth, and secondly, determine how the time interval between topically applied herbicides influence control.

MATERIALS AND METHODS

The field experiment was conducted during 2011 and 2012 at four sites, two sites each in Macon and Decatur Counties, Georgia. These sites were chosen because they offered a unique opportunity to study both glyphosate-resistant and glyphosate-sensitive Palmer amaranth as well as to compare herbicide responses in a low yield dryland production site and a high yield intensely irrigated production site (Table 4.1). At both locations, two AAD-12:1910 cotton seed (Dow AgroScience; Indianapolis, IN), resistant to 2,4-D, were planted conventionally every 22 cm down the row using the hill-drop method with a row spacing of 91 cm. Plot size consisted of 3.6 m in width by 7.6 m in length with treatments replicated 3 or 4 times. Insect control, fertilization, and defoliation practices were standard for either dryland or irrigated production in Georgia (Collins and Whitaker 2012).

The experiment was a RCB design implementing a factorial treatment arrangement including three POST herbicide options and three timing intervals between POST herbicide applications. POST herbicide options included sequential applications of 2,4-D amine (Weedar 64; NuFarm, Burr Ridge, IL) at 840 g ae ha^{-1}, sequential applications of 2,4-D amine tank-mixed with glufosinate (Liberty; Bayer CropScience, Research Triangle Park, NC) at 600 g ae ha^{-1}, and 2,4-D followed by (fb) glufosinate. Although 2,4-D choline will be the only 2,4-D formulation registered for use in cotton, 2,4-D amine was used in this experiment due to limited availability of 2,4-D choline. Interval options between POST herbicide applications within each system included 5, 10, or 15 d. All herbicide systems received a layby of diuron (Direx; DuPont Crop Protection, Wilmington, DE) at 1120 g ai ha^{-1} plus MSMA (MSMA 6 Plus; Drexel Chemical Company, Memphis, TN) at 1680 g ai ha^{-1} plus crop oil (AGRI-DEX; Helena Chemical Company, Collierville, TN) at 2.3 L ha^{-1} directed to the base of the cotton just prior to canopy closure. A non-treated control was included for comparison and no adjuvants were used with POST applications. All applications were made with a CO_2-pressurized backpack sprayer equipped with 11002 DG flat-fan nozzles calibrated to deliver 140 L ha^{-1} at 165 kPa.

Macon County consisted of a Dothan loamy sand soil characterized to have 86% sand, 6% silt, and 8% clay with 1.9-2.1% organic matter and a pH of 6.2. Cotton was planted on 16 June 2011 and 26 April 2012 and the initial POST application was made on 1 July 2011 and 31 May 2012. An intense (1.5 million plants ha^{-1}) and highly resistant population of glyphosate-resistant Palmer amaranth was present at the site (Culpepper et al. 2006). The location was a dryland production site plagued with typical environmental conditions that are stressful during times in which herbicides were applied (Table 1).

Decatur County consisted of a Dothan loamy sand soil characterized to have 86% sand, 6% silt, and 8% clay with 1.9-2.1% organic matter and a pH of 6.2. Cotton was planted on 24 May 2011 and 7 June 2012 and the initial POST application was made on 10 June 2011 and 2 July 2012. A glyphosate-sensitive Palmer amaranth population was present with 95,700 plant ha^{-1}. Carpetweed, Florida beggarweed and smallflower morningglory also infested the experiment with populations ranging from 23,900 to 95,700 plant ha^{-1} with heights between 1 and 3 cm at time of the initial POST application. At this intensely irrigated location, drought stress was avoided throughout the season (Table 4.1).

Cotton plant heights were taken prior to layby by randomly measuring 20 plants per plot. Cotton was harvested from the center two rows of each plot with a spindle picker modified for small-plot harvesting in November of each year. Visual estimates of weed control were made prior to each herbicide application, after layby, and at harvest using a visual scale of 0 (no control) to 100 (plant death) (Frans et al. 1986). Cotton seed utilized in these studies were segregating populations and crop response is not indicative of the herbicide tolerance that will be present in commercial cultivars. Thus, cotton tolerance data is not reported. Palmer amaranth population densities were quantified between the two center rows of each plot just prior to layby.

Data were analyzed using PROC Mixed (SAS 9.2; SAS Institute, Cary, NC), with herbicide treatments, timings, and locations as fixed effects, while random effects included replications, years, and their interactions with fixed effects. Prior to analysis, weed control ratings and Palmer amaranth counts were square-root transformed, but presented in original form in the tables. Treatment means were separated using Fisher's Protected LSD at $P \leq 0.05$. The non-treated control was not included in the statistical analysis in order to maintain the treatment factorial.

RESULTS AND DISCUSSION

Macon County: There were significant main effects of herbicide treatments on Palmer amaranth control and population density, cotton canopy height and seed cotton yield, but no interactions between treatment type and timing (Table 4.2). Sequential applications of glufosinate plus 2,4-D controlled Palmer amaranth (86%) more effectively than sequential 2,4-D applications (54%) or 2,4-D fb glufosinate (54%). Palmer amaranth densities were at least 75% lower and cotton heights were at least 21% higher with sequential glufosinate plus 2,4-D applications (3.9 plants m^{-2} and 33 cm tall, respectively) as compared to 2,4-D applied sequentially (16.8 plants m^{-2} and 24 cm tall, respectively) and 2,4-D fb glufosinate (15.7 plants m^{-2} and 26 cm tall, respectively). Following the layby application, the differences among the treatments at the conclusion of the season were consistent, with the sequential application of the 2,4-D plus glufosinate controlling Palmer amaranth 72%, while the other treatments were less effective (≤36%). Differences in Palmer amaranth control among the systems were also reflected with cotton yields, with the sequential tank mix yielding at least three-times the amount in the other two systems. Other researchers have also documented the effectiveness of glufosinate plus 2,4-D on numerous weed species (Botha et al. 2012; Chahal and Johnson 2012; Shaw and Arnold 2002).

There were significant main effects of POST application intervals for Palmer amaranth control and seed cotton yield, but no interactions between treatment type and timing (Table 4.3). Palmer amaranth control was 15 to 27% greater at layby and harvest when the interval between

POST applications was 10 (58 to 74%) or 15 d (54 to 68%) as compared to 5 d (31 to 53%). It appeared that Palmer amaranth plants surviving the initial application did not recover enough with just a 5 d interval between applications in this dry environment. At the time of the second application, it is possible that the plant was too stressed to adequately be affected by the sequential application, while intervals of 10 to 15 d apart controlled Palmer amaranth more consistently (Carpenter and Boutin 2010). Palmer amaranth populations and cotton heights were not impacted by intervals between POST applications (data not shown), but cotton yield from the 10 d interval treatment was nearly double that with a 5 d interval.

Although the glufosinate plus 2,4-D system with an interval of 10 or 15 d between POST applications was the most effective program, Palmer amaranth control did not exceed 90% from the initial POST application through harvest at this dryland site (data not shown). Achieving Palmer amaranth control below 90% can cause lower yields and harvesting efficiency issues (Fast et al., 2009; Morgan et al. 2001; Price et al. 2011; Smith et al. 2000). However, this system may prevent total crop loss that would be observed with current standards (Craigmyle et al. 2012; Robinson et al 2012). Additionally, 90% control from a herbicide system in a salvage situation plus hand weeding or secondary tillage that is common today could salvage a cotton crop even in a stressful environment (Sosnoskie and Culpepper 2012).

Decatur County: At the irrigated field site, there were significant interactions among POST herbicide treatments and timing intervals for both Palmer amaranth and carpetweed control (Table 4.4). Control between 89 and 99% was noted with these weeds when sequential applications of glufosinate plus 2,4-D or when 2,4-D fb glufosinate were applied; the interval between POST applications did not affect control by these systems. In contrast, control of Palmer amaranth and carpetweed at layby from sequential 2,4-D applications was influenced by application intervals, with control of 53-76%, 71-94%, and 62-66% for 5, 10, and 15 d intervals, respectively. At the conclusion of the season following the layby, differences among all herbicide systems for carpetweed (99%) and differences among systems including glufosinate for Palmer amaranth (92 to 99%) were muted. However, the 2,4-D system was still more effective with a 10 d interval (97%) as compared to a 5 d interval (81%).

There was a main effect of herbicide treatment on control of Florida beggarweed, smallflower morningglory, and cotton yield, but there was no effect of application interval or an interaction between these factors (Table 4.5). Florida beggarweed was controlled more effectively with both systems containing glufosinate (≥94%) as compared to 2,4-D alone (68%), regardless of intervals between applications. After the layby application, Florida beggarweed control was 99% in all treatments. Smallflower morningglory control was 99% in all treatments at layby and at the conclusion of the season.

Cotton plant heights were at least 26% greater with herbicide systems, relative to the non-treated control, with no differences among herbicide systems (data not shown). Differences in cotton yield among treatments reflected the differences noted with late-season Palmer amaranth control, confirming previous observations (Smith et al. 2000). Cotton yield was 15% greater with the glufosinate plus 2,4-D (2,185 kg ha^{-1}) compared to the 2,4-D alone (1,850 kg ha^{-1}), while yields from the 2,4-D fb glufosinate were intermediate and comparable to the other systems (2,065 kg ha^{-1}).

In conclusion, when at-plant residual herbicides fail, cotton yield loss from Palmer amaranth interference and losses due to harvest inefficiency is likely to be extremely costly to growers with current cotton weed management programs. This technology offers growers an effective option to salvage a crop infested with large Palmer amaranth plants by applying glufosinate plus 2,4-D sequentially, with applications spaced 10 to 15 d apart and followed by diuron plus MSMA prior to surviving plants becoming erect. Success of this salvage system, however, will depend on Palmer amaranth size and environmental conditions.

Table 4.1. Weekly rainfall and irrigation totals for Macon and Decatur Counties during the first 17 wks after planting in 2011 and 2012.

	Rainfall (cm)			
Weeks after planting	Macon Co.		Decatur Co.	
	2011	2012	2011[a]	2012[a]
1	4.6	0.5	0.64	5.7
2	0	2.0	0	4.5
3	0.3	0.8	6.2	0.7
4	5.3	0.3	0.1	6.1
5	0	0	4.5	2.1
6	1.5	8.4	0.9	3.7
7	1.5	0	7.0	6.1
8	0	0	4.1	20.1
9	0	0.5	2.4	2.4
10	0	3.3	0.1	4.3
11	1.8	4.4	1.0	5.9

12	0	0	0.6	1.8
13	0	0.3	0	1.0
14	0	2.9	3.1	5.5
15	0	0.8	0	0
16	2.3	2.3	0.1	10.2
17	1.8	0	0	0.2

[a] Locations received weekly irrigation application of 2.5 cm

Table 4.2. Large Palmer amaranth response to 2,4-D and glufosinate at a dryland production site in Macon County, GA and its influence on cotton heights and yields.[a]

POST herbicide applications[b,c,d]	Palmer Amaranth control (%)		Palmer amaranth density at layby (plants m^{-2})	Cotton height at layby (cm)	Seed cotton yield ($kg\ ha^{-1}$)
	At layby	At harvest			
2,4-D fb 2,4-D	54 b	35 b	16.8 a	24 c	175 b
2,4-D fb glufosinate	54 b	36 b	15.7 a	26 b	325 b
2,4-D + glufosinate fb 2,4-D +glufosinate	86 a	72 a	3.9 b	33 a	1,390 a

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[b]Initial POST application made once Palmer amaranth reached 20 cm in height; sequential POST applications made either 5, 10, or 15 d after the initial application.

[C]2,4-D amine and glufosinate applied at 840 and 600 g ha^{-1}, respectively.

[d]Diuron at 1120 g ha^{-1} plus MSMA at 1680 g ha^{-1} applied at layby for all herbicide systems just prior to cotton canopy closure.

Table 4.3. Large Palmer amaranth response to intervals between POST herbicide applications at a dryland production site in Macon County, GA and its influence on cotton yield.[a]

Intervals between POST herbicide applications[b,c,d]	Palmer amaranth control (%)		Seed cotton yield (kg ha^{-1})
	At layby	At harvest	
5 d	53 b	31 b	420 b
10 d	74 a	58 a	835 a
15 d	68 a	54 a	635 ab

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[b]Initial POST application made once Palmer amaranth reached 20 cm in height; sequential POST applications made either 5, 10, or 15 d after the initial application.

[C]2,4-D amine and glufosinate applied at 840 and 600 g ha^{-1}, respectively.

[d]Diuron at 1120 g ha^{-1} plus MSMA at 1680 g ha^{-1} applied at layby for all herbicide systems just prior to cotton canopy closure.

Table 4.4. Large Palmer amaranth and carpetweed response to herbicide systems at an irrigated production site in Decatur County, GA. [a]

POST herbicide applications[b,c,d]	Interval between POST applications	Palmer amaranth control (%)		Carpetweed control (%)	
		At layby	At harvest	At layby	At harvest
2,4-D fb 2,4-D	5 d	76 bc	81 b	53 c	99
2,4-D fb glufosinate	5 d	89 ab	92 ab	99 a	99
2,4-D + glufosinate fb 2,4-D + glufosinate	5 d	99 a	99 a	99 a	99
2,4-D fb 2,4-D	10 d	94 ab	97 a	71 b	99
2,4-D fb glufosinate	10 d	93 ab	94 ab	99 a	99
2,4-D + glufosinate fb 2,4-D +	10 d	99 a	99 a	99 a	99

glufosinate					
2,4-D fb 2,4-D	15 d	66 c	87 ab	62 c	99
2,4-D fb glufosinate	15 d	89 ab	93 ab	98 a	99
2,4-D + glufosinate fb 2,4-D + glufosinate	15 d	99 a	98 a	99 a	99

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[b]Initial POST application made once Palmer amaranth reached 20 cm in height; sequential POST applications made either 5, 10, or 15 d after the initial application.

[C]2,4-D amine and glufosinate applied at 840 and 600 g ha^{-1}, respectively.

[d]Diuron at 1120 g ha^{-1} plus MSMA at 1680 g ha^{-1} applied at layby for all herbicide systems just prior to cotton canopy closure.

Table 4.5. Florida beggarweed and smallflower morningglory control and cotton yield as influenced by POST herbicide systems in an irrigated production site in Decatur County, GA. [a]

POST herbicide applications [b,c,d]	Florida beggarweed control (%)		Smallflower morningglory control (%)		Seed cotton yield (kg ha^{-1})
	At layby	At harvest	At layby	At harvest	
2,4-D fb 2,4-D	68 b	99	99	99	1,850 b
2,4-D fb glufosinate	94 a	99	99	99	2,065 ab
2,4-D + glufosinate fb 2,4-D + glufosinate	97 a	99	99	99	2,185 a

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$; means within a column without letters are not different.

[b]Initial POST application made once Palmer amaranth reached 20 cm in height; sequential POST applications made either 5, 10, or 15 d after the initial application.

[C]2,4-D amine and glufosinate applied at 840 and 600 g ha^{-1}, respectively.

[d]Diuron at 1120 g ha^{-1} plus MSMA at 1680 g ha^{-1} applied at layby for all herbicide systems just prior to cotton canopy closure.

CHAPTER 5

APPLICATION TIME OF DAY INFLUENCES WEED CONTROL BY GLUFOSINATE AND 2,4-D CHOLINE IN COTTON RESISTANT TO GLYPHOSATE, 2,4-D, AND GLUFOSINATE[1]

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[1] R.M. Merchant, A.S. Culpepper, P.M. Eure, J.S. Richburg, L.B. Braxton. To be submitted to *Weed Technology*.

ABSTRACT

Pesticide applications during night or early morning may be one approach to reduce spray drift by taking advantage of lower winds often observed during these times. An experiment conducted during 2011 and 2012 at four Georgia sites determined if application time of day influenced weed control by herbicides potentially used in these cotton systems. Sequential applications of 2,4-D choline or glufosinate were more effective applied at 1 or 7 PM as compared to 1 or 7 AM controlling 12 cm tall Palmer amaranth 53 to 84% at 7 AM, 85 to 99% at 1 PM, 82 to 99% at 7 PM, and 36 to 85% at 1 AM. Applying sequential applications of glufosinate plus 2,4-D choline resulted in more consistent and effective control as compared to applying either of these herbicides alone; Palmer amaranth control with the mixture was at least 92% at 7 AM, 99% at 1 PM, 99% at 7 PM and 74% at 1 AM. Mixing glyphosate with 2,4-D choline had little effect on glyphosate-resistant Palmer amaranth but the mixture controlled glyphosate-sensitive Palmer amaranth 99%, regardless of application time of day. Carpetweed, Florida beggarweed, or smallflower morningglory control was not influenced by herbicide application time of day. Cotton heights and seed yields were among their highest and most consistent when sequential POST applications of glufosinate plus 2,4-D were applied at 7 AM, 1 PM, or 7 PM and when sequential glufosinate applications were made at 1 or 7 PM. Although environmental conditions less favorable for drift often occur at night and early in the morning, reduced control of Palmer amaranth by glufosinate or 2,4-D choline is expected at these times. Mixtures of glufosinate plus 2,4-D choline can overcome the loss in Palmer amaranth control observed with early morning applications by these herbicides individually, but the mixture cannot adequately overcome the loss in control observed at night.

INTRODUCTION

Cotton technology with resistance to glufosinate, glyphosate, and 2,4-D choline will offer growers more effective management options for the control of glyphosate-resistant Palmer amaranth and other troublesome weeds as compared to current programs (Braxton et al. 2010; Richburg et al. 2012). Other possible benefits with this technology include a reduction in herbicide inputs, less herbicide carryover risks, less at-plant herbicide injury, and lower hand weeding costs (Chahal and Johnson 2012; Robinson et al. 2012; Vink et al. 2012). Additionally, the this cotton system may allow growers that were forced into tillage by glyphosate-resistant Palmer amaranth to return back to a more environmentally favorable conservation tillage production practice (Sosnoskie and Culpepper 2012).

Although the effectiveness of the glyphosate, 2,4-D, and glufosinate weed management program is well understood (Braxton et al. 2010; Richburg et al. 2012) adoption of the technology will result in 2,4-D use on resistant cotton in areas also producing non-2,4-D resistant cotton, soybean, and peanut (Edwards et al. 2012; Smith et al. 2012). Previous research has shown all three of these non-2,4-D resistant crops to have varying levels of injury and yield loss from drift rates of auxin herbicides (Everitt and Keeling 2009; Johnson et al. 2012; Marple et al. 2008). Additionally, more than 40 different vegetable crops and over a dozen fruit, tree, and vining crops are also grown throughout Georgia and will add to the importance of mitigating drift of auxin herbicides (Grover et al. 1972; Hemphill and Montgomery 1981; USDA-NASS 2012). The most current farm gate value for these specialty crops grown in Georgia exceeds $1.24 billion and is actually larger than the farm gate value of cotton at $1.18 billion (USDA-ERS 2010; USDA-NASS 2012). Specialty crops are extremely sensitive to 2,4-D and other auxin herbicides with maturity delays, yield loss, and/or crop death occurring at extremely low rates (Gilreath 1987; Hemphill and Montgomery 1981; Merchant et al. 2012).

Although development of 2,4-D resistant cotton is being accompanied by new 2,4-D formulations that minimize off target movement (Edwards et al. 2012), other management approaches will be needed. One of the primary mechanisms of off-target movement of pesticides is the result of particle drift from wind (Carlson et al. 2006; Costa et al. 2007). Applications during certain environmental conditions, such as higher winds, increase the potential risk for damage to sensitive crops nearby (Behrens and Lueschen 1979; Grover et al. 1972). Wind speeds are usually less during late evening, overnight, or early in the morning as compared to the middle of the day (Table 5.1). Growers who wish to mitigate the risk involved with applying pesticides during unfavorable environmental conditions may defer applications to these more desirable timings. However, research has shown some herbicides are sensitive to the time of day in which they are applied (Anderson et al. 1993; Coetzer et al. 2001; Sellers et al. 2003). Thus, a study was conducted to determine how time of day influenced weed control by potential herbicides used in a glyphosate, 2,4-D, and glufosinate resistant cotton weed management programs.

MATERIALS AND METHODS

The field experiment was conducted during 2011 and 2012 at four sites, two sites each in Macon and Decatur Counties, Georgia. These sites were chosen because they offered a unique opportunity to study both glyphosate-resistant and glyphosate-sensitive Palmer amaranth as well as to compare herbicide responses at a low yield dryland production site and a high yield intensely irrigated production site (Table 5.2). At both locations, two AAD-12:1910 cotton seed (Dow AgroScience; Indianapolis, IN), resistant to 2,4-D choline, were planted conventionally every 22 cm down the row using the hill-drop method with a row spacing of 91 cm. Plot size consisted of 1.8 m in width by 7.6 m in length with treatments replicated 4 times. Insect control, fertilization, and defoliation practices were standard for either dryland or irrigated production in Georgia (Collins and Whitaker 2012).

A factorial treatment arrangement including four sequentially applied POST herbicide options and four application time of day options was implemented. POST herbicide options included sequential applications of glufosinate at 540 g ae ha^{-1}, 2,4-D choline at 1065 g ae ha^{-1}, 2,4-D choline plus glufosinate, or a premix of 2,4-D choline plus glyphosate at 2185 g ae ha^{-1} (Enlist Duo; Dow AgroSciences, Indianapolis, IN). Application time of day options included herbicide applications at 7 AM, 1 PM, 7 PM, or 1 AM. The initial POST applications were made when Palmer amaranth reached a maximum of 12 cm in height with the subsequent POST application of the same herbicide(s) at the same assigned time 18 d later. All herbicide systems received a layby application of diuron at 1120 g ai ha^{-1} (Direx; DuPont Crop Protection, Wilmington, DE) plus MSMA at 1680 g ai ha^{-1} (MSMA 6 Plus; Drexel Chemical Company, Memphis, TN) plus crop oil at 2.3 L ha^{-1} (AGRI-DEX; Helena Chemical Company, Collierville, TN) directed to the base of the cotton plant just prior to cotton canopy closure. A non-treated control was included for comparison and no adjuvants were used with POST applications. All applications were made with a CO_2-pressurized backpack sprayer equipped with 11002 DG flat-fan nozzles during 2011 and 11002 AIXR nozzles during 2012 calibrated to deliver 140 L ha^{-1} at 165 kPa.

Macon County consisted of a Dothan loamy sand characterized as 80% sand, 12% silt, and 8% clay with 1.9-2.1% organic matter and a pH of 6.2-6.4. Cotton was planted on 16 June 2011 and 26 April 2012 and the initial POST application was made on 29 June 2011 and 31 May

2012. An intense (1,470,000 ha^{-1}) and highly resistant population of glyphosate-resistant Palmer amaranth was present at the site (Culpepper et al. 2006). The location was a dryland production site plagued with typical environmental conditions that are stressful during times in which herbicides are being applied (Table 5.2).

Decatur County was a Dothan loamy sand soil characterized as 86% sand, 6% silt, and 8% clay with 1.9-2.1% organic matter and a pH of 6.2-6.4. Cotton was planted on 24 May and 7 June 2012 and the initial POST application was made on 7 June, 2011 and 2 July, 2012. A glyphosate-sensitive Palmer amaranth population was present with 95,700 plant/ha. Carpetweed, Florida beggarweed and smallflower morningglory also infested the experiment with populations ranging from 23,900 to 95,700 plant ha^{-1} with weed sizes ranging 1 to 3 cm at time of the initial POST application. At this location, drought stress was avoided throughout the season (Table 5.2).

Cotton plant heights were taken prior to layby by measuring 20 consecutive plants in a row per plot. Cotton was harvested with a spindle picker modified for small-plot harvesting in November of each year. Visual estimates of weed control were made prior to each herbicide application, after layby, and at harvest using a visual scale of 0 (no control) to 100 (plant death) (Frans et al. 1986). Cotton seed planted in these studies were segregating populations and crop response is not indicative of the herbicide tolerance that will be present in commercial cultivars. Thus, cotton tolerance data is not reported. Palmer amaranth densities were quantified between the two center rows of each plot just prior to layby.

Data were analyzed using PROC Mixed (SAS 9.2; SAS Institute, Cary, NC), with herbicide treatments, timings, and locations as fixed effects, while random effects included replications, years, and their interactions with fixed effects. Prior to analysis, weed control ratings and Palmer amaranth counts were square-root transformed, but presented in original form in the tables. Treatment means were separated using Fisher's Protected LSD at $P \leq 0.05$. The non-treated control was not included in the statistical analysis in order to maintain the treatment factorial.

RESULTS AND DISCUSSION

Although cotton visual injury is not reported, final cotton stand did not differ among herbicide systems or when compared to the non-treated control at any location (data not shown). Additionally at each location, seed cotton yield differences followed closely with Palmer amaranth densities present and late-season Palmer amaranth control suggesting herbicide injury had little impact on cotton yields (Tables 5.3 and 5.4).

Macon County: Application time of day influenced control by POST herbicides (Table 5.3). Sequential glufosinate or 2,4-D choline applications controlled Palmer amaranth 36 to 57% when applied at 1 or 7 AM and 82 to 99% when applied at 1 or 7 PM. Research has shown that glufosinate is sensitive to the time of day in which it is applied on weeds such as velvetleaf (*Abutilon theophrasti* Medicus), common ragweed (*Ambrosia artemisifolia* L.), common lambsquarter (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), barnyardgrass (*Echinocloa crus-galli* [L.] Beauv.), Pennsylvania smartweed (*Polygonum pennsylvanicum* L.), yellow foxtail (*Setaria pumila* [Poir.] Roem & Schult.), green foxtail (*Setaria viridis* [L.] Beauv.), and wild mustard (*Sinapsis arvensis* L.) (Anderson et al. 2008; Martinson et al. 2005). Although leaf angle and dew likely contribute to this time of day affect, it is not the sole reason for reduced efficacy with glufosinate. Sellers et al. (2004) also suggests that this response is influenced by a physiological process that occurs, at least within velvetleaf. Mixtures of glufosinate plus 2,4-D choline were more consistent and effective across application times of day with control of at least 92% when applied at 7 AM, 1PM or 7 PM. Although the mixture was also more effective than either herbicide applied alone at 1 AM (74% vs. 36 to 56%), control was still unacceptable. Mixing glyphosate with 2,4-D choline did not significantly improve control compared to 2,4-D choline applied alone and is to be expected with highly glyphosate-resistant populations (Culpepper et al. 2006; Norsworthy et al. 2008; Steckel et al. 2008). Following the layby and at harvest, greater than 92% control was observed by glufosinate plus 2,4-D choline systems with applications made at 7 AM, 1 PM, or 7 PM and with the glufosinate system with applications made at 1 or 7 PM.

Palmer amaranth populations were measured after sequential POST applications were made but prior to the layby (Table 5.3). Results showed that at least 33% of the Palmer amaranth plants present or at least 475,000 plants ha^{-1} were not killed with sequential 2,4-D choline systems; although many of the plants responded by laying prostrate on the surface of the soil. Glufosinate systems were usually more effective than 2,4-D choline systems in killing plants with populations ranging from 1460 to 201,000 plants ha^{-1}. Mixtures of glufosinate plus 2,4-D choline were more consistent with populations ranging from 1460 to 12,400 plant ha^{-1} across application times of day.

Cotton heights prior to layby were similar and ranged from 39 to 44 cm when sequential glufosinate plus 2,4-D choline applications were made during day or night (Table 5.3). Sequential glufosinate systems had similar heights to those of the glufosinate plus 2,4-D choline systems but cotton from 2,4-D choline or glyphosate plus 2,4-D choline systems were shorter (30 to 34 cm). Cotton heights followed densities of Palmer amaranth present and results suggest Palmer amaranth plants damaged from 2,4-D choline, even when laying prostrate on the soil surface, may be competing with cotton for resources such as moisture.

As expected, systems providing greater Palmer amaranth control and lower densities generated the highest cotton yields (Table 5.3). Palmer amaranth not only reduces cotton yield through competition for resources but can also reduce harvesting efficiency (Fast et al. 2009; Morgan et al. 2001; Price et al. 2011; Smith et al. 2000). Seed cotton yields were maximized and ranged from 2035 to 2140 kg ha^{-1} with the glufosinate system when applications were made at 1 or 7 PM and with the glufosinate plus 2,4-D system when applications were made at 7 AM, 1 PM or 7 PM. Yields less than 440 kg ha^{-1} were recorded with the glufosinate system when applications were made at 1 or 7 AM and yield of 1430 kg ha^{-1} was observed with the glufosinate plus 2,4-D choline system when applications were made at 1 AM. Among the 2,4-D and glyphosate plus 2,4-D systems, highest yields occurred with 1 or 7 PM applications (1595 to 1715 kg ha^{-1}) and lower yields (< 425 kg ha^{-1}) were noted with 1 or 7 AM applications.

Decatur County: Glyphosate plus 2,4-D choline controlled glyphosate-sensitive Palmer amaranth at least 96% (Table 5.4), regardless of application time of day. Although research has shown that diurnal fluctuations negatively impact control of velvetleaf with glyphosate, this effect was not seen in glyphosate-susceptible Palmer amaranth populations when glyphosate was tank-mixed with 2,4-D (Martinson et al. 2005; Mohr et al. 2007; Waltz et al. 2004). Similar to Macon County, the influence of application time of day on glufosinate and 2,4-D choline was observed with Palmer amaranth in Decatur County. However, the overall control of Palmer amaranth by these herbicides in Decatur County was greater than that in Macon County which would be expected when applying herbicides to weeds growing in an ideal environment (Stewart et al. 2010; Stewart et al. 2012). Sequential glufosinate applications controlled Palmer amaranth 99% when applied at 1 or 7 PM but control was only 49 to 68% when applied 1 or 7 AM. Sequential 2,4-D choline applications also were 14 to 15% more effective when applied at 1 or 7

PM as compared to 1 or 7 AM. Diuron plus MSMA at layby killed most plants escaping previous 2,4-D choline applications but was not effective in controlling plants escaping glufosinate applications. Palmer amaranth surviving the glufosinate application were erect while those surviving the 2,4-D choline application were prostrate laying on the soil surface at time of layby. Herbicide coverage was enhanced by the prostrate plant structure thereby improving control. The length of time Palmer amaranth remained prostrate was at least one week longer in Decatur county as compared to Macon county and this may have been a result of the ideal growing environment improving control by POST 2,4-D choline applications.

In contrast to Palmer amaranth, carpetweed, smallflower morningglory and Florida beggarweed control was not influenced by application time of day of any herbicide system (Table 5.4). All herbicide systems controlled smallflower morningglory 99% but glufosinate or glyphosate systems (> 91%) were more effective than the 2,4-D choline alone system in controlling carpetweed (77 to 84%) and Florida beggarweed (81 to 83%) at layby. Once the layby was applied, these weeds were controlled 99% by all systems.

Cotton plant heights were similar among treatments except shorter plants were noted with the glufosinate only system when applications were made at 1 AM, due to poor Palmer amaranth control (53%) at time of cotton height measurements (Table 5.4). Seed cotton yields also noted the lack of Palmer amaranth control by the glufosinate only system when applications were made at 1 or 7 AM as yields from these systems ranged from 1810 to 1960 kg ha^{-1} compared to yields exceeding 2240 kg ha^{-1} with all other systems.

Although environmental conditions less favorable for off target particle drift may occur at night and early in the morning, reduced control of Palmer amaranth with glufosinate or 2,4-D was observed at these times. Mixtures of glufosinate plus 2,4-D were able to overcome the loss in Palmer amaranth control observed with early morning applications by these herbicides applied individually, but the mixture did not adequately overcome the loss in control observed at night. In areas infested with Palmer amaranth, glufosinate plus 2,4-D choline applied in the morning may offer the most effective control of emerged plants while minimizing the potential for herbicide drift. However even in cotton resistant to glufosinate, glyphosate, and 2,4-D choline, grower sustainability will rely on weed management programs implementing diversified herbicide chemistry including residuals in addition to tillage, hand weeding and/or the use of cover crop residues.

Table 5.1. Percent of time windspeed <40 MPH during day[a]

Time of day	% time <40 MPH
12 AM – 4 AM	85
4 AM – 8 AM	79
8 AM – 12 PM	35
12 PM – 4 PM	19
4 PM – 8 PM	52
8 PM – 12 AM	73

[a] Based on maximum windspeed recorded every 15 minutes throughout each day. Data collected by the Georgia Weather Network. www.georgiaweather.net

Table 5.2. Weekly rainfall and irrigation totals for Macon and Decatur Counties during the first 17 wks after planting in 2011 and 2012.

Weeks after planting	Rainfall (cm)			
	Macon Co.		Decatur Co.	
	2011	2012	2011[a]	2012[a]
1	4.6	0.5	0.64	5.7
2	0	2.0	0	4.5
3	0.3	0.8	6.2	0.7
4	5.3	0.3	0.1	6.1
5	0	0	4.5	2.1
6	1.5	8.4	0.9	3.7
7	1.5	0	7.0	6.1
8	0	0	4.1	20.1
9	0	0.5	2.4	2.4
10	0	3.3	0.1	4.3
11	1.8	4.4	1.0	5.9
12	0	0	0.6	1.8
13	0	0.3	0	1.0
14	0	2.9	3.1	5.5
15	0	0.8	0	0
16	2.3	2.3	0.1	10.2
17	1.8	0	0	0.2

[a] Locations received weekly irrigation application of 2.5 cm.

Table 5.3. Effect of application time of day on glyphosate-resistant Palmer amaranth control, cotton height, and cotton yield by 2,4-D choline, glufosinate, and glyphosate in dryland cotton production.[a]

Sequential POST treatment[b,c,d]	Time of application	Glyphosate-resistant Palmer amaranth control (%)		Palmer amaranth population prior to layby (plants ha^{-1})	Cotton height prior to layby (cm)	Seed cotton yield (kg ha^{-1})
		At layby	At harvest			
2,4-D choline	7 AM	57 e	38 d	894,000 a	30 f	420 d
Glufosinate	7 AM	53 e	35 d	201,000 de	40 abc	435 d
Glufosinate + 2,4-D choline	7 AM	92 abc	94 a	12,400 e	41 ab	2035 ab
Glyphosate + 2,4-D choline	7 AM	59 e	40 d	678,900 abc	31 ef	395 d
2,4-D choline	1 PM	85 bcd	78 bc	558,000 bc	33 ef	1590 c
Glufosinate	1 PM	96 ab	98 a	4,200 e	42 a	2135 a
Glufosinate + 2,4-D choline	1 PM	99 a	99 a	2,200 e	39 abcd	2140 a
Glyphosate + 2,4-D choline	1 PM	91 abc	88 ab	475,000 cd	35 cdef	1595 c
2,4-D choline	7 PM	82 cd	75 bc	598,000 abc	31 ef	1655 bc
Glufosinate	7 PM	99 a	99 a	4,900 e	41 ab	2095 a
Glufosinate + 2,4-D choline	7 PM	99 a	99 a	1,460 e	44 a	2155 a
Glyphosate + 2,4-D choline	7 PM	91 abc	89 ab	507,000 c	34 def	1715 bc
2,4-D choline	1 AM	56 e	40 c	826,000 ab	31 ef	270 d
Glufosinate	1 AM	36 f	28 c	70,000 e	36 bcde	205 d
Glufosinate + 2,4-D choline	1 AM	74 d	69 c	9,700 e	40 abc	1430 c
Glyphosate + 2,4-D choline	1 AM	52 e	36 d	479,000 cd	31 ef	215 d

Non-treated control	1,470,000	20	0

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$. Data pooled over two locations in Macon County, Georgia during 2011 and 2012.

[b]Initial POST application made once Palmer amaranth reached 12 cm in height; sequential POST applications made 18 d after the initial application.

[C]2,4-D choline applied at 1065 g ha^{-1} when alone or mixed with glufosinate; glufosinate applied at 540 g ha^{-1} when alone or mixed with 2,4-D choline; glyphosate plus 2,4-D choline applied as a premix (Enlist Duo) at 2185 g ha^{-1}.

[d]Diuron at 1120 g ha^{-1} plus MSMA at 1680 g ha^{-1} applied at layby for all herbicide systems just prior to cotton canopy closure.

Table 5.4. Effect of application time of day on weed control, cotton height, and cotton yield by 2,4-D choline, glufosinate, and glyphosate in irrigated cotton production.[a]

Sequential POST treatment[b,c,d]	Time of application	Glyphosate-sensitive Palmer amaranth control (%)		Carpetweed control (%)		Florida beggarweed control (%)		Smallflower morningglory control (%)		Cotton height (cm)	Seed cotton yield (kg ha^{-1})
		At layby	At harvest	At layby	At harvest[e]	At layby	At harvest[e]	At layby[e]	At harvest[e]		
2,4-D choline	7am	84 b	98 a	79 b	99	83 b	99	99	99	35 b	2315 abc
Glufosinate	7am	68 c	54 b	96 a	99	99 a	99	99	99	37 ab	1960 bc
Glufosinate + 2,4-D choline	7am	99 a	99 a	97 a	99	99 a	99	99	99	39 a	2480 ab
Glyphosate + 2,4-D choline	7am	99 a	99 a	97 a	99	99 a	99	99	99	38 ab	2305 abc
2,4-D choline	1pm	99 a	99 a	84 b	99	81 b	99	99	99	36 ab	2640 a
Glufosinate	1pm	99 a	97 a	99 a	99	99 a	99	99	99	36 ab	2760 a
Glufosinate + 2,4-D choline	1pm	99 a	99 a	98 a	99	99 a	99	99	99	38 ab	2700 a
Glyphosate + 2,4-D choline	1pm	99 a	99 a	98 a	99	99 a	99	99	99	38 ab	2480 ab
2,4-D choline	7pm	99 a	99 a	81 b	99	81 b	99	99	99	38 ab	2685 a
Glufosinate	7pm	99 a	99 a	97 a	99	99 a	99	99	99	38 ab	2620 a
Glufosinate + 2,4-D choline	7pm	99 a	99 a	98 a	99	99 a	99	99	99	39 a	2550 a
Glyphosate + 2,4-D choline	7pm	99 a	99 a	98 a	99	99 a	99	99	99	38 ab	2340 abc
2,4-D choline	1am	85 b	99 a	77 b	99	81 b	99	99	99	36 ab	2415 ab
Glufosinate	1am	49 d	47 b	92 a	99	95 a	99	99	99	27 c	1810 c
Glufosinate + 2,4-D choline	1am	90 ab	97 a	94 a	99	99 a	99	99	99	38 ab	2340 abc

Glyphosate + 2,4-D choline	1am	96 a	99 a	94 a	99	99 a	99	99	99	38 ab	2245 abc
Non-treated control										28	0

[a]Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P $\leq$ 0.05. Data pooled over two locations in Decatur County, Georgia during 2011 and 2012.

[b]Initial POST application made once Palmer amaranth reached 12 cm in height; sequential POST applications made 18 d after the initial application.

[C]2,4-D choline applied at 1065 g ha^{-1} when alone or mixed with glufosinate; glufosinate applied at 540 g ha^{-1} when alone or mixed with 2,4-D choline; glyphosate plus 2,4-D choline applied as a premix (Enlist Duo) at 2185 g ha^{-1}.

[d]Diuron at 1120 g ha^{-1} plus MSMA at 1680 g ha^{-1} applied at layby for all herbicide systems just prior to cotton canopy closure.

[e]No significant differences among treatments noted.

CHAPTER 6

PEANUT YIELD RESPONSE TO 2,4-D

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[1] R.M. Merchant, E.P. Prostko, P.M. Eure, and T.M. Webster. To be submitted to *Peanut Science*.

ABSTRACT

Research was conducted at Ponder Research Farm and Attapulgus Research and Education Center in 2011 and 2012 to determine the response of peanuts to various rates of 2,4-D amine. 2,4-D amine was applied at 0, 105, 210, 420, 840, and 1680 g ai ha^{-1} at timings of 30, 60, and 90 days after planting (DAP). Visual crop injury ratings were collected through the growing season and yield data collected at maturity. After inversion, 100 pod weights and 100 seed weights were obtained. When pooled over rate, peanut yield losses were greater when 2,4-D was applied at 60 DAP when compared to 90 DAP. There was no difference in yield between 30 and 60 DAP or 30 and 90 DAP. When pooled over timing, peanut yield losses were 7, 7, 9, 14, and 24% when 2,4-D was applied at 105, 210, 420, 840, and 1680 g ai/ha. 2,4-D had no effect on peanut pod or seed weights. Growers can use this information to make more effective management decisions when peanut are inadvertently damaged by 2,4-D through drift, volatilization, spray-tank contamination, or accidental spraying.

INTRODUCTION

Peanut were planted on over 293,000 ha^{-1} in 2012 (NASS, 2012). Peanut in Southern states are often grown in close proximity to corn, cotton, and soybean. Weed management systems used in these crops varies greatly from those used in peanut (Massinger et al. 2001; Webster and Sosnoskie 2010; Whitaker et al. 2010). With the advent of glyphosate-resistant crops, increase in use of glyphosate resulted in in the increased occurrence of off-target damage to peanut (Grey and Prostko 2010; Lassiter et al. 2009), this same trend was seen with the increased use of glufosinate (Culpepper et al. 2009; Grichar and Dotray 2007; Johnson et al. 2011).

Palmer amaranth remains the most troublesome broadleaf weed in Southern crop production (Nandula et al. 2012; Price et al. 2011; Sosnoskie et al. 2011; Ward et al. 2012). In an effort to control this and other broadleaf weeds, corn, cotton, and soybean that are resistant to topical applications of synthetic auxin herbicides are being developed (Braxton et al. 2010; Green 2012; Mortensen et al. 2012). If the trend of increased off-target damage to peanut from registered herbicides continues with synthetic auxins, there could be serious implications for peanut grown in close proximity.

Synthetic auxins were one of the first families of selective herbicides to be widely used and decades of research have documented their effectiveness, limitations, and risks (Aberg and Eliasson 1978; Bovey 1971; Marple et al. 2009; van Overbeek 1962). Although efforts are being made to mitigate the risk of off-target movement through formulation and application improvements, it will be impossible to completely guarantee off-target movement through drift, volatilization, tank-contamination, or inadvertent application (Henry et al. 2004; Hilz 2013; Robinson and Johnson 2012).

The response of peanut to simulated drift rates of dicamba has already been documented (Prostko et al. 2011). In this research peanut yield losses were as high as 29% to 100% when treated with 40 to 560 g ai/ha. The objective of this research was to determine peanut yield response to various rates of 2,4-D amine so that growers can make an informed decision about managing a peanut crop after an off-target or sprayer contamination problem has occurred.

MATERIALS AND METHODS

The experiment was conducted over 2011 and 2012 at Ponder Research Farm in Ty Ty, GA, and at Attapulgus Research and Education Center in Attapulgus, GA for a total of four site-years. 'GA-06G' peanut (Branch 2007) were planted on twin rows (90 x 8 cm) at a depth of 5 cm. Soil was prepared through conventional tillage and plots were 2 m wide by 8 m in length. Soil at the Ponder Research Farm site was Tifton loamy sand characterized as 82% sand, 14% silt and 4% clay with 2% organic matter and a pH of 6.1. Soil at the Attapulgus Research and Education Center was Dothan loamy sand characterized as 84-86% sand, 4-8% silt, 8-10% clay with 1-1.3% organic matter and a pH of 6.0.

Treatments included a factorial arrangement of 2,4-D amine rate (Weedar 64 380 g/l; Nufarm, Burr Ridge, IL) and three application timings. 2,4-D rates were 0, 105, 210, 420, 840, or 1680 g ai/ha. The labeled use rate of 2,4-D amine is 840 g ai/ha. Application timings included 30, 60, or 90 days after planting (DAP). All treatments were replicated four times. Treatments at the Ponder location at 30, 60, and 90 DAP corresponded to the beginning bloom (R1), beginning pod (R3), and full seed (R6) maturity stages respectively (Boote 1982). Treatments at the Attapulgus location at 30, 60, and 90 DAP corresponded to the beginning bloom (R1), full pod (R4), and full seed (R6) maturity stages, respectively. Herbicides were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 l/ha at 165 kPa with 11002 XR flat-fan nozzle tips (Teejet Technologies; Wheaton, IL). Plots were maintained weed-free throughout the year using a combination of the commonly used PRE and POST herbicides (pendimethalin, flumioxazin, diclosulam, and imazapic) and hand-weeding.

Yield data were collected and transformed to percent yield loss. After inversion 100 pod weight and 100 seed weights were obtained. Data were analyzed as a factorial using PROC Mixed of SAS (SAS 9.2; SAS Institute, Cary, NC). Site and replication were considered fixed effects and treatments considered random effects. Means were separated using Fisher's Protected LSD (α=0.05) and regressions made using percent yield loss as a function of herbicide rate. Data were pooled over location and year as there were no significant interactions between location and treatment. There were no significant differences in 100 pod weights or 100 seed weights as a function of treatment, so these variables are not reported.

RESULTS AND DISCUSSION

Data are presented as main effects of time or rate since there was no significant interaction between time, rate, or location. When data were pooled over time of application, there was a weak linear relationship (R^2=0.26) between rate and yield loss (Figure 6.1). Yield losses were 7, 7, 9, 14, and 24% when treated with 105, 210, 420, 840, and 1680 g ai/ha respectively. These yield losses are similar to what was seen in a Virginia-type peanut treated with similar rates at an earlier timing of 21 days after emergence (Johnson et al. 2011).

When pooled over herbicide rate, peanut injury was greater when 2,4-D amine was applied 30 or 60 DAP, 10 and 13% respectively (Table 6.1). Peanut yield losses were only 7% when 2,4-D amine was applied 90 DAP. This could be due to a number of factors, ranging from the density of peanut vine to the stage of maturity (Prostko et al. 2012). Other susceptible broadleaf crops have shown greater injury to growth regulator herbicides early in maturity as well and at key reproductive stages (Everitt and Keeling 2009; Johnson et al. 2011; Marple et al. 2009).

The purpose of this study was to create a model that could predict potential injury to peanut from off-target movement of 2,4-D amine, whether through drift, volatilization, or spay tank-contamination. The new 2,4-D choline formulation to be released for use in transgenic crops will greatly reduce drift and volatility risk, so the most likely event of off-target movement will be tank-contamination (Braxton et al. 2010; Richburg et al. 2012). In this situation, the application rate is unlikely to be as high as 1680 g ai/ha, twice the labeled recommended rate of 2,4-D amine, however significant yield losses (5-10%) were recorded when peanuts were treated with rates as low as 105 g ai/ha, or 1/8th the labeled rate. More concerning is the potential that increased use of synthetic auxin herbicides will increase the occurrence of applicators mistaking 2,4-D for the commonly used peanut herbicide 2,4-DB. This problem has already occurred, and the possibility of peanut being treated with the full use rate of 2,4-D, 840 g ai/ha, is likely, which can result in yield losses as high as 11-16%.

It is imperative that growers and applicators communicate effectively to reduce the likelihood of any off-target movement, through drift, volatilization, tank-contamination, or inadvertent application. In the situations this does occur, growers can use this information to determine potential yield loss and make more informed management decisions concerning inputs through the remainder of the growing season when damage has occurred.

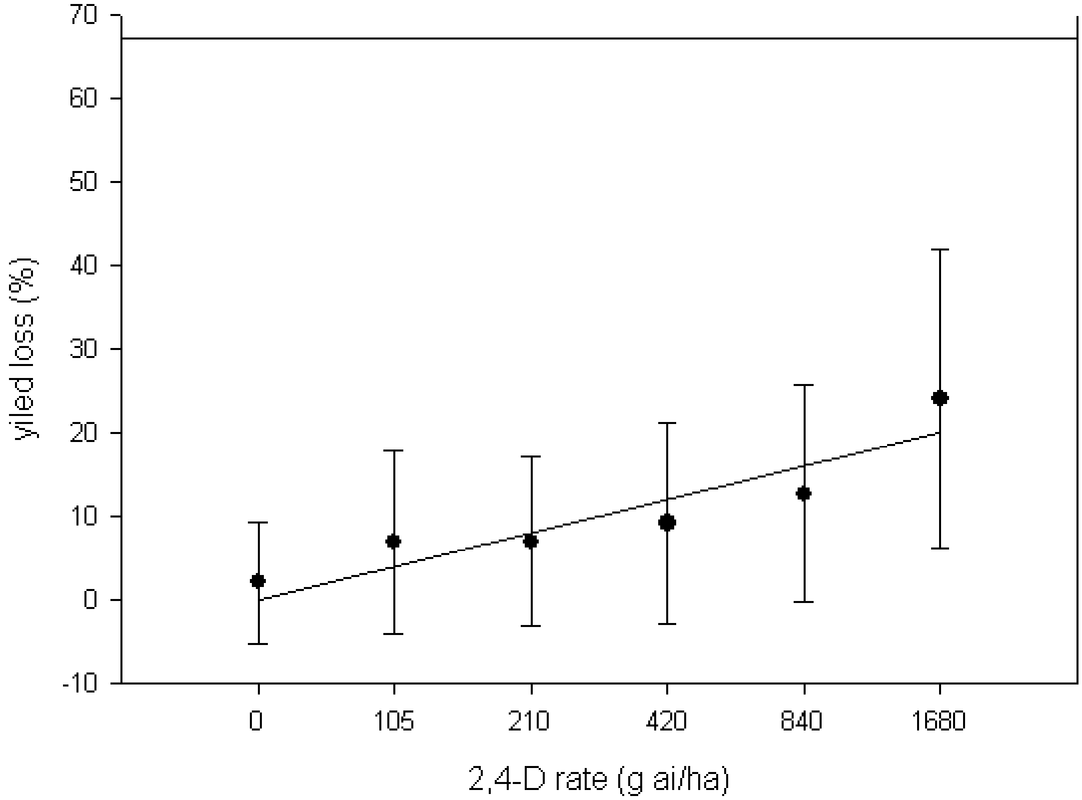

Figure 6.1. Peanut yield loss as influenced by 2,4-D rate when pooled over three application timings y=0.06+2.9, r^2=0.26.

Table 6.1. Peanut yield losses as influenced by 2,4-D time of application.[a]

Time	Yield Loss (%)
30 DAP[b]	10
60 DAP	13
90 DAP	7
LSD (α=0.05)	4

[a]Pooled over 6 rates of 2,4-D.

[b]DAP = days after planting.

CHAPTER 7

CONCLUSIONS

Glyphosate, 2,4-D, and glufosinate-resistant cotton can positively impact growers by allowing for broader POST weed management options. In order for this technology to have a longer effective life it is important that growers continue to use other management practices in conjunction with POST herbicides. Greatest control of glyphosate-resistant Palmer amaranth can be achieved by using an at-plant PRE herbicide with sequential POST applications of 2,4-D tank-mixed with glyphosate or glufosinate applied at least 10 days apart, followed by a layby application just prior to canopy closure. In an effort to reduce the possibility of particle drift, growers may choose to apply POST 2,4-D tank-mixtures early morning when wind-speeds are lower and the reduced efficacy of glufosinate is compensated by the addition of 2,4-D. If off-target movement does occur, peanut and specialty crops will most likely be damaged, therefore extreme diligence on the part of applicators is required.

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