Control, Assessment and Glyphosate Resistance of Palmer Amaranth (*Amaranthus palmeri* S. Wats) in Virginia

by

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ABSTRACT

Glyphosate resistant crops were rapidly adopted by farmers since their introduction in 1996 and currently, greater than 90% of cotton and soybean crops are glyphosate resistant. Glyphosate has been an effective mean for controlling Palmer amaranth, however overreliance on glyphosate based systems resulted in weeds that can no longer be controlled with glyphosate. Palmer amaranth resistance to glyphosate has been confirmed in ten US states including Virginia's bordering neighbor North Carolina. The objectives of this study were to i) determine the spread of Palmer amaranth and evaluate awareness among farmers and agribusinesses of herbicide resistant weeds in Virginia; ii) determine the efficacy of commonly used cotton and soybean herbicides programs for Palmer amaranth control; and iii) conduct greenhouse experiments to quantify the level of glyphosate resistance in a Greensville County, Virginia population. Using a communication network of Virginia county extension agents and crop advisers, Palmer amaranth was found in 15 Virginia counties. A survey was conducted to evaluate awareness of herbicide resistance and management of weeds in Virginia. Ninety percent of producers had fields planted to Roundup Ready® crops for each of the last 3 years. One hundred percent of the responders claimed awareness of the potential for weeds to develop resistance to glyphosate, but when asked about how serious they consider weed resistance to herbicides, the responders average rating was of 7.9 (on a scale of 1 to 10 where 1 is "not at all serious" and 10 is "very serious"). Eighteen percent of the responder population claimed no awareness of glyphosate resistant weeds documented in Virginia. Herbicide efficacy experiments were established in soybean and cotton fields infested with Palmer amaranth. In soybean, experiments were established in a field where Palmer amaranth was not adequately controlled with glyphosate in the previous year. Glyphosate applied at 0.87 + 0.87 + 1.74 kg ae ha^{-1} at 1, 3, and 5 weeks after planting (WAP) provided 82 to 85% control in 2009, but only 23 to 30% control in 2010, a hot and dry year. Glyphosate applied after preemergence (PRE) herbicides improved control to 90 percent. Programs that included s-metolachlor + metribuzin applied preemergence and followed by glyphosate + fomesafen applied postemergence provided the best control (93%) at 8 WAP. Glufosinate based herbicide programs provided greater than 85% control when applied alone, and control increased to 95% when preceded by PRE herbicides. Many conventional control systems integrating different modes of action provided more than 80% control at final evaluation of Palmer amaranth in 2009 and 2010. In soybean, the most consistent and effective program was flumioxazin applied PRE followed by chlorimuron + thifensulfuron, which provided 99 and 82% control at final evaluation in 2009 and 2010, respectively. Cotton fields were heavily infested with Palmer amaranth, but control with glyphosate had historically been good. Glyphosate applied early postemergence, late postemergence, and late post-directed provided more than 95 percent control at final evaluation of Palmer amaranth. Preemergence applications of fomesafen, fluometuron, or pendimethalin + fomesafen provided 77 to 99 percent early-season control and control was complete with an additional postemergence glyphosate application. Glufosinate applied at 0.45 kg ha^{-1} at 1 and 3 WAP or applied at 0.45 kg ha^{-1} following a preemergence herbicide provided greater than 95% control. Greenhouse experiments confirmed Palmer amaranth resistance in a population collected from Greensville County, Virginia. In the first experiment, the resistant biotype's I_{50} value (rate necessary for 50% inhibition) for dry weight was 1.47 kg ae ha^{-1}, which is 4.6 times greater than

the susceptible biotype and 1.7 times the recommended use rate of glyphosate. For fresh weight, the I_{50} value of the resistant biotype was 1.60 kg ae ha^{-1}, 4.7 times that of the susceptible biotype of 0.34 kg ae ha^{-1}. In the second experiment, the I_{50} value for the susceptible population could not be determined because all glyphosate rates resulted in complete control. However, the resistant population required 1.01 and 1.30 kg ae ha^{-1} of glyphosate to reduce the fresh and dry weight by 50%.

DEDICATION

This effort is dedicated to my parents, Mohamed Aly Tawfic and Azza Abdelwahed. Even if one is not amongst us today, their love, guidance and support had made this and everything else that I have accomplished or shall accomplish possible.

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CHAPTER I

INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* S. Wats.), also known as careless weed and Palmer pigweed, is an erect branched summer annual broadleaf weed that is native to the southwest United States (Bryson and DeFelice 2009). It is one of approximately 60 *Amaranthus* species native to the Americas, and one of 9 species of amaranth that is considered an invasive and noxious weed (USDA Plant Profile 2009). Palmer amaranth can reduce corn (*Zea mays* L.) grain yield by up to 74%, corn silage yield by up to 44% (Massinga et al. 2003), soybean (*Glycine max* (L.) Merr.) yield by up to 78% (Klingman and Oliver 1994, Bensch et al. 2003), cotton (*Gossypium hirsutum* L.) lint yield by up to 92% (Rowland et al. 1999), and peanut (*Arachis hypogaea* L.) yield up to 28% (Burke et al. 2007).

Palmer amaranth is difficult-to-control due to its extended emergence period (Jha et al. 2006), rapid erect growth (Klingaman and Oliver 1994; Norsworthy et al. 2008), large number of seed produced (Keeley et al. 1987), and confirmed resistance to acetolactate synthase (ALS)-inhibiting herbicides (Wise et al. 2009) and glyphosate in the southern U.S (Culpepper et al. 2006). Palmer amaranth has a rapid growth rate of 0.18 to 0.21cm GDD^{-1} (growing degree days) (Horak and Loughin, 2000), which is 30 to 160% greater than that of common waterhemp (*Amaranthus rudis*) and redroot pigweed (*Amaranthus retroflexus*), respectively. Palmer amaranth can reach heights of over two meters and produce 600,000 seeds per female inflorescence, which can remain dormant in the soil for years (Keeley et al. 1987). At the density of 5.2 plants m^{-2}, Burke et al. (2007) found that. 1.2 billion seed ha^{-1} were produced by Palmer amaranth. Furthermore, Palmer amaranth has possible allelopathic properties. Menges (1987) concluded that when Palmer amaranth residues were incorporated into the soil, growth of carrot and onion were reduced by 49 to 68%, which was attributed to allelotoxins.

Glyphosate resistance has been confirmed in biotypes of 21 weed species around the world. (Heap 2011). The first confirmed Palmer amaranth resistance was in South Carolina in 1989 to dinitroanilines (Gossett et al. 1992), but the first case of glyphosate resistance was not confirmed until 2004 in Georgia (Culpepper 2005). Further research confirmed Palmer amaranth resistance to four herbicide modes of action (dinitroanilines, ALS-inhibitors, photosystem II inhibitors and glycines) with glyphosate resistance confirmed in North Carolina, Arkansas, Tennessee, New Mexico, Mississippi, Alabama, Missouri, Louisiana and Illinois (Heap 2011). In Georgia, glyphosate applied to 5- to 13-cm-tall Palmer amaranth at three times the normal use rate of 0.87 kg ae ha^{-1} resulted in only 17% control. The biotype was controlled 82% by glyphosate at 12 times the normal use rate (Culpeper et al. 2006). Research conducted in Arkansas concluded that glyphosate resistant biotypes were effectively controlled with post-emergence herbicides where 2,4-D , glufosinate, paraquat, MSMA and atrazine provided 93 to 100% control while herbicides such as pyrithiobac, trifloxysulfuron, and imazethapyr only provided 63 to 82% at 28 d after treatment (Norsworthy et al. 2008).

In Virginia, Palmer amaranth has been reported in several counties and will likely enlarge its territory. Its spread can be rapid because of custom harvesting, failing to clean vehicles and equipment after exiting infested fields, and failing to hand remove escapes. There are currently populations of ALS-inhibitor resistant Palmer amaranth in Virginia and another population that was not controlled with three applications of glyphosate, totaling 3.36 kg ae ha^{-1} in Greensville County (Holshouser et al. 2009). Information is limited on the efficacy of glyphosate, glufosinate, and conventional herbicides for control of Palmer amaranth in cotton and soybean.

A recent survey of farmers from six states (Indiana, Illinois, Iowa, Nebraska, Mississippi, and North Carolina) was conducted to assess farmers' views on glyphosate-resistant (GR) weeds and tactics used to prevent or manage GR weed populations in genetically engineered GR crops. Only 30% of farmers thought GR weeds were a serious issue. Few farmers thought field tillage and/or using a non-GR crop in rotation with GR crops would be an effective strategy. Most farmers did not recognize the role that the recurrent use of an herbicide plays in the development of resistance. A substantial number of farmers underestimated the potential for GR weed populations to develop in an agroecosystem dominated by glyphosate as the weed control tactic (Johnson et al. 2009). An earlier survey by Johnson of corn and soybean growers across Indiana during winter 2003/2004 showed that even though a relatively low percentage of growers were highly concerned about resistance (36%), they still expressed a willingness to use field scouting, tank-mixes with glyphosate for burn-down and postemergence weed control, and soil-applied residual herbicides as resistance management strategies (Johnson and Gibson 2006). A survey of this type has not been conducted in Virginia.

Objectives

1. Determine the spread of Palmer amaranth and evaluate awareness among farmers and agribusinesses of herbicide resistance of weeds in Virginia.
2. Determine the efficacy of commonly used cotton and soybean herbicide programs for Palmer amaranth control.
3. Conduct greenhouse experiments to quantify the level of glyphosate resistance in a Greensville County, Virginia Palmer amaranth population.

Expected outcomes

1. Establish geographical distribution of Palmer amaranth and awareness among farmers and agribusinesses of herbicide resistant weeds in Virginia.
2. Identify effective herbicide control strategies and offer recommendations for control of Palmer amaranth in cotton and soybean.
3. Confirm that the Greensville County population of Palmer amaranth is resistant to glyphosate.

The overall goal of this research is to minimize the spread of Palmer amaranth in Virginia and reduce the likelihood that it will develop resistance to herbicides. The spread of glyphosate and ALS-inhibitor resistant Palmer amaranth is closely linked to the effectiveness of weed management programs in the field where a resistant population is first detected. Minimizing the impact of GR or herbicide resistant Palmer amaranth can be achieved through increasing the awareness of the farmers of the current status of Palmer amaranth resistance and implementing better resistance management strategies. This research provides the information and knowledge needed for controlling and reducing further spread of Palmer amaranth.

In conclusion, the research results will act as a tool for extension organizations to increase farmers' awareness of the current herbicide resistance status and the best resistance management regime. Thus, it will provide growers with better information and knowledge on controlling Palmer amaranth resulting in preventing further spread of Palmer amaranth.

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CHAPTER II

Assessement of Palmer Amaranth (*Amaranthus palmeri* S. Wats) Spread and Evaluation of Farmer and Agribusinesses Awareness of Herbicide Resistance in Virginia

ABSTRACT

A survey was conducted to assess the spread of Palmer amaranth in Virginia via a communication network of Virginia county extension agents and crop advisers. The survey indicated that Palmer amaranth is present in 15 counties. Palmer amaranth biotypes were not being controlled with glyphosate in one county, or with ALS-inhibiting herbicides in two other counties. A second survey was conducted to evaluate farmer awareness of herbicide resistance management in Virginia. Three hundred and eighteen surveys were sent using regular mail and one hundred were sent by email. Ninety nine Virginia crop producers or advisors responded. Ninety percent of those surveyed confirmed having fields planted to Roundup Ready crops for each of the last 3 years. All responders claimed awareness of the potential for weeds to develop resistance to the glyphosate; however, when asked about how serious they consider herbicide resistance, the responders' average rating was 7.9 (on a scale of 1 to 10 where 1 is "not at all serious" and 10 is "very serious"). Eighteen percent of the responder population claimed no awareness of glyphosate resistant weeds documented in Virginia, but 44% claimed the presence of herbicide resistant weeds on their farm. Herbicides were ranked the most useful of 12 weed management tactics with an average ranking of 1.7, followed by crop rotation (2.8) and narrow row spacing (4.6). Producers rated using more than one herbicide mode of action in a given year, using different herbicide modes of action from one year to the next, and using herbicides with soil residual as the most effective resistance management strategies (all receiving a rating of

greater than 9 out of 10) (on a scale of 1 to 10 where 1 is “not at all effective” and 10 is “very effective”); tillage was rated as the least effective.

INTRODUCTION

Glyphosate-resistant Palmer amaranth is a major problem in the southeastern United States. A single Palmer amaranth per 9.1 m of row in cotton or 3 m of row in soybean (*Glycine max* L. Merr.) reduced yield 13 and 17%, respectively (Morgan et al. 2001; Klingaman and Oliver 1994). It is a common weed in southeastern Virginia, especially in the cotton and peanut growing regions. However, it is unknown as to how far from southeastern Virginia that Palmer amaranth has spread. Growers continue to express concerns with Palmer amaranth and often request information about the best programs for control. Although herbicides are extremely effective weed management tools, overreliance on a single herbicide mode of action is likely to result in weed populations that are resistant to that herbicide family. Herbicide resistant weeds are a constraint to weed management in many cropping regions around the world.

Several herbicide resistant weed species have been reported in Virginia. The first to be identified was smooth pigweed (*Amaranthus hybridus*) to atrazine, a photosystem II inhibiting herbicide, in 1976 (Heap 2011). In 2002, common lambsquarters plants from Westmoreland County, VA, exhibited differential response among lines with respect to glyphosate susceptibility after not being controlled with a postemergence glyphosate application in glyphosate-resistant soybean. (Hite et al. 2008). Several smooth pigweed (*Amaranthus hybridus*) biotypes were reported to be resistant to ALS-inhibiting herbicides (Trader et al. 2009; Whaley et al. 2006). Most recently, chickweed (*Stellaria media*) collections have been confirmed to be resistant to ALS-inhibiting herbicides in Virginia (Hagood et al. 2009).

The first confirmed Palmer amaranth herbicide resistance was in South Carolina 1989 to dinitroanilines (Gossett et al. 1992), but the first case of glyphosate resistance (GR) was not confirmed until 2004 in Georgia (Culpepper 2005). Further research confirmed Palmer amaranth resistance to four herbicide modes of action (dinitroanilines, ALS-inhibitors, photosystem II inhibitors, and glycines) with GR confirmed in Georgia, North Carolina, Arkansas, Tennessee, New Mexico, Mississippi, Alabama, Missouri, Louisiana and Illinois (Heap 2011).

U.S. farmers account for approximately 50% of the genetically modified crops grown in the world (James 2008). A recent survey of farmers from six states (Indiana, Illinois, Iowa, Nebraska, Mississippi, and North Carolina) was conducted to assess the farmers' views on GR weeds and tactics used to prevent or manage GR weed populations in genetically engineered crops. Only 30% of farmers thought GR weeds were a serious issue. Few farmers thought field tillage and/or using a non-GR crop in rotation with GR crops would be an effective strategy. Most farmers did not recognize the role that the recurrent use of an herbicide plays in the development of resistance. A substantial number of farmers underestimated the potential for GR weed populations to develop in an agroecosystem dominated by glyphosate as the weed control tactic. (Johnson et al. 2009). An earlier survey by Johnson of corn and soybean growers across Indiana during winter 2003/2004 showed that even though a relatively low percentage of growers were highly concerned about resistance (36%), they still expressed a willingness to use field scouting, tank-mixes with glyphosate for burn-down and postemergence weed control, and soil-applied residual herbicides as resistance management strategies (Johnson and Gibson 2006).

The distribution of Palmer amaranth in Virginia is unknown. A survey of the presence of Palmer amaranth was needed to identify areas where research is needed and extension programming directed. Furthermore, knowledge of farmer and agribusinesses awareness and attitudes towards weed resistance to herbicides can also help identify priority areas for research and extension programming efforts. Therefore, the objectives are 1) to determine the spread of Palmer amaranth in Virginia; and 2) evaluate the level of awareness among farmers and agribusinesses of herbicide resistance.

MATERIALS AND METHODS

Spread of Palmer amaranth in Virginia.

A communication network was established with Virginia county extension agents and crop advisers via email, phone, production meetings, and field days to increase awareness of Palmer amaranth in Virginia. Participants in the network were asked to report fields with Palmer amaranth observations. Reported fields were visited and confirmed to be Palmer amaranth. In some instances, Palmer amaranth plants were either brought or mailed to the Tidewater AREC and confirmed there. In addition, fields with Palmer amaranth observations were noted as part of the Virginia soybean rust and aphid survey. If Palmer amaranth plants were reported as not being controlled with herbicides, fields were revisited after additional herbicide application to confirm the reports. Several of these fields were used for subsequent herbicide efficacy trials. Surveying was carried out in the growing seasons of 2008 through 2010.

Farmer awareness of herbicide resistance

A list of growers was obtained from cotton, grain, and peanut, and soybean grower associations. Three hundred and eighteen farmers and crop advisors were mailed the table appended at the end of this chapter (Table 2.1). In addition, the survey was sent to the Virginia Crop Production Association email listserve, which consists of crop advisors and others in the agribusinesses industry. The survey assessed the respondent’s profession, number of acres under their management, and background information on crop and herbicide management practices. Respondents were asked about their perception of issues related to herbicide resistance, their opinion of management practices that reduce or prevent resistance, and their main sources of information about herbicide resistance.

RESULTS AND DISCUSSION

Spread of Palmer amaranth in Virginia

Palmer amaranth was found in 15 Virginia counties/cities (Figure 2.1). Counties or cities confirmed to have Palmer amaranth were Chesapeake, Dinwiddie, Greensville, Hanover, Isle of Wight, King and Queen, King William, Mecklenburg, New Kent, Prince George, Southampton, Suffolk, Surry, Sussex, and Virginia Beach. Palmer amaranth was fairly ubiquitous in the southeastern counties of Greensville, Isle of Wight, and Southampton, and the City of Suffolk. There were also a large number of farms with Palmer amaranth detected in Dinwiddie and Prince George counties. In Hanover County, Palmer amaranth was detected largely in areas containing small tomato farms. The King William observation was on a farm that was in organic grain and soybean production at the time of confirmation. Palmer amaranth was only confirmed in one location in Virginia Beach, which was near a country grain elevator. In many instances, what was reported as Palmer amaranth was actually another pigweed species. Palmer amaranth was not being controlled with ALS-inhibiting herbicides in the City of Suffolk and Isle of Wight County. Glyphosate resistant Palmer amaranth was confirmed in Greensville County (Chapter 4).

Farmer awareness of herbicide resistance

Ninety nine mail surveys were returned, representing a 31 percent response rate. Only five surveys were returned from the Virginia Crop Production Association listserve. Data for each question of the survey were summarized and are presented in Table 2.2 Out of the 99 respondents, 86 identified themselves as producers, five as crop advisors, four as county agents and four as chemical/ fertilizer dealers. Total acreage under the producers' management was 151,705 acres with an average of 1785 acres per producer. The breakdown of the number of acres under producer management shows that 50% of the producers manage less than 1200 acres, and 75% of the producers manage less than 2250 acres (Figure 2.2). Only 2 producers were managing 10,000 acres or more. Total acreage under crop advisors, chemical/fertilizer dealers, and County Agents management was 701,837 acres (some overlap between county agents and crop advisors may exist). Producers used a number of different crop rotations of which corn followed by small grain followed by soybean was the most common.

Ninety-seven percent of respondents indicated planting Roundup Ready crops, 41% Liberty Link, 33% conventional and 26% sulfonylurea tolerant soybean (STS). It should be noted that many Roundup Ready soybean have the STS trait; therefore, some overlap exists in this instance. Ninety percent of respondents confirmed having fields that have been planted in Roundup Ready crops for each of the last 3 years. Moreover, 96% of the responders reported that they tank-mix and rotate herbicides with different modes of action. Additionally, 94% scout their fields during the growing season after herbicide application to check for suspected herbicide resistant weeds. Other suggested management strategies used included crop rotation, tillage, nonselective control of vegetation existing at planting and mowing.

Moreover, respondents were also asked to rank 12 practices according to usefulness for weed management, with a 1 = “most useful”. It was not a surprise that herbicides were ranked as number one, with an average ranking of 1.7. This was followed by crop rotation (2.8), narrow row spacing (4.6), cover crops (5.3), seeding rates (5.3), planting date (5.6), cleaning equipment (6.2) and competitive crops (6.6). The least ranked practices were tillage (8.4), hand rouging (8.4), and mowing weed patches (8.6). All responders claimed awareness of the potential for weeds to develop resistance to glyphosate. When asked about how serious they consider weed resistance to herbicides, on a scale of 1 to 10 a scale where 1 is “not at all serious” and 10 is “very serious”; respondents’ average rating was of 7.9. Eighteen percent of the responder population claimed no awareness of glyphosate resistant weeds documented in Virginia.

The participants reported their channels of learning about weed resistance to glyphosate and the responses were categorized to extension, farm magazines, internet and hands on experience. Forty-four percent claimed the presence of herbicide resistant weeds on their farm. The most commonly reported were horseweed and pigweed resistance to glyphosate and ALS-inhibitors. On a scale of 1 to 10 a scale where 1 is “not at all effective” and 10 is “very effective”, responding producers rated using more than one herbicide mode of action in a given year at 9.3 as a way to manage potential weed resistance to glyphosate, followed by rotating herbicide modes of action from one year to the next at 9.1. Using herbicides with soil residual was rated at 9.0 and using the correct label recommendations and rotating crops rated 8.7 and 8.4, respectively. The lowest rating was for tillage at 5.9.

The final question asked the responding producers to convey the problems and objections they may have with herbicide resistant weed management approaches. Some objections conveyed by a large number of producers were soil erosion, time and cost when tillage is practiced (Table 2.3). Another example is cost and compatibility when using herbicide tank mixes.

In conclusion, Palmer amaranth was found in 15 counties in Virginia's crop production region. However, it is not widespread except for the traditional cotton and peanut growing region of southeastern Virginia. Producers need to be educated on the difficulty of control of Palmer amaranth once a population has been established in a field. The results from the grower awareness survey indicated that 100% of the sampled producers are aware of glyphosate resistance in weeds. However, when asked about the importance of glyphosate resistance, the average rating was only 7.9. The survey shows that although tillage could be of benefit in herbicide resistant weed management, producers understand the benefits of conservation tillage and are unlikely to consider tillage. It also suggests that farmers expect best results for weed control from herbicide use and genetically modified crops.

These surveys helped identify the spread of Palmer amaranth and the current level of awareness among farmers of resistance management. Knowledge of the distribution of glyphosate and ALS resistant Palmer amaranth will alert farmers to the severity of the problem and hopefully encourage them to adopt resistance management programs. Finally, results from these surveys can be utilized to better direct research efforts and to help educate and advise producers about the importance of weed resistance management.

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Table 2.1. Virginia weed resistance management grower survey, 2011.

1. Profession:

   __ Producer __ County Agent __ Crop Advisor __ Chemical/Fertilizer Sales

2. Number of acres responsible for: _____
3. Crop rotation: ____

4. Do you plant :
   ___ Round up Ready ___ Liberty Link ___ Conventional ___ Other (eg. STS)

5. Do you have fields that have been planted in Roundup Ready crops for each of the last 3 years? __Yes __No
6. To delay the development of resistant weeds, do you: (Please circle Y for Yes and N for No)

   Y N Tank-mix herbicides from different modes of action or groups?

   Y N Rotate herbicide modes of action?

   Y N Scout your fields during the growing season after herbicide application to check for suspected resistant weed patches?

   Y N Use other management strategies? Which strategies?

____

7. Rank the following practices as to their usefulness for weed management on your farm. (Rank from 1 – 12, 1 = “most useful”)

_____ Competitive crops	_____ Cover crops	_____ Narrow row spacing
_____ Seeding rate	_____ Planting date	_____ Clean equipment
_____ Herbicides	_____ Mow weed patches	______ Hand rouging
_____ Crop rotation	_____ Tillage/Cultivation	______ Other (please state)

8. Are you aware of the potential for weeds to develop resistance to the glyphosate herbicides? __Yes __No
9. Using a scale of 1 to 10 where 1 is “not at all serious” and 10 is “very serious”, how serious of a problem do you consider weed resistance? ____ To glyphosate herbicides? ____
10. Are you aware of any specific weeds in Virginia that have been documented to be resistant to glyphosate? __ Yes __ No

    Which weeds? ____

11. Where did you learn about weed resistance to glyphosate herbicides?_____________________________________

Table 2.1 (continued).

12. Do you have resistant weeds on you farm? __ Yes __ No
    What weeds? Which herbicides?
    ____
13. What are you doing to minimize the potential for weeds developing resistance on your farm?
    ____
    ____
14. As a way to manage potential glyphosate weed resistance, how effective do you consider each of the following: (Using a scale of 1 to 10 where 1 is "not at all effective" and 10 is "very effective")
    — Rotating herbicide modes of action from one year to the next
    — Tillage
    — Rotating crops
    — Using correct label rates of herbicides at the proper timing for the size and types of weeds present
    — Using more than one herbicide mode of action in a given year
    — Using herbicides with soil residual
15. In terms of your farming operation, what are your major objections, if any, of the each of the following as a resistance management approach?
    a. Tillage____
       ____
    b. Rotating crops____
       ____
    c. Using correct label rates of herbicides at the proper timing for the size and types of weeds present____
       ____
    d. Using more than one herbicide chemistry in a given year, such as glyphosate and a residual herbicide____
       ____
    e. Using more than one herbicide chemistry in a given year, such as glyphosate and another post-applied herbicide____
       ____

Table 2.2 Grower responses to Virginia weed resistance management grower survey, 2011.

Q #	Question	Choices	Response
1	Profession:	Producer	86 (number of Producers)
		County Agent	4 (number of County Agents)
		Crop Advisor	5 (number of Crop Advisers)
		Chemical/ Fertilizer Sales	4 (number working in Chemical/ Fertilizer Sales)
2	Number of acres responsible for:		• Total Producer = 151,705. • Average Producer = 1784. • Total Country Agent = 455, 015. • Average Country Agent = 113, 754. • Total Crop Advisor = 177,015. • Average Crop Advisor = 43,753. • Total Chemical/Fertilizer Sales = 69, 820. • Average Chemical/Fertilizer Sales = 16,606. • Refer to Figure 2.2 for more details.
3	Crop rotation:		Small grain followed by soybean was the most common.
4	Do you plant :	Round-up Ready	97 % of responders
		Liberty-Link	41 % of responders
		Conventional	33 % of responders
		Other (eg. STS)	26 % of responders
5	Do you have fields that have been planted in Roundup Ready crops for each of the last 3 years? (Y or N)		90 % of responders
6	To delay the development of resistant weeds, do you: (Please circle Y for Yes and N for No)	Tank-mix herbicides from different modes of action or groups?	96 % of responders
		Rotate herbicide modes of action?	96 % of responders
		Scout your fields during the growing season after herbicide application to check for suspected	94 % of responders
		Use other management strategies? Which strategies?	Crop rotation, tillage, nonselective control of vegetation existing at planting and mowing

Table 2.2 (continued).

Q #	Question	Choices	Response
7	Rank the following practices as to their usefulness for weed management on your farm.(Rank from 1 to 12) (Average rank is listed)	Herbicides	1.7
		Crop rotation	2.8
		Narrow row spacing	4.6
		Seeding rate	5.3
		Cover crops	5.3
		Planting date	5.6
		Clean equipment	6.2
		Competitive crops	6.6
		Hand rouging	8.4
		Tillage/ Cultivation	8.4
		Mow weed patches	8.6
		Other (please state)	10.7
8	Are you aware of the potentials for weeds to develop resistance to the glyphosate herbicides?		100% of responders answered with "Yes"
9	Using a scale of 1 to 10 where 1 is “not at all serious” and 10 is “very serious”, how serious of a problem do you consider weed resistance?		7.9 (average rating)
	To glyphosate herbicides?		7.7 (average rating)
10	Are you aware of any specific weeds in Virginia that have been documented to be resistant to glyphosate?		80 % of responders answered with "Yes"
	Which weeds?		Palmer, Pigweed, Horsetail
11	Where did you learn about weed resistance to glyphosate herbicides?		Extension, farm magazines, internet and hands on experience

Table 2.2 (continued).

Q #	Question	Choices	Response
12	Do you have resistant weeds on you farm?		44% of responders answered with "Yes"
	What weeds?		Mostly horseweed and pigweed
	Which herbicides?		Mostly glyphosate and ALS-inhibitors
13	What are you doing to minimize the potential for weeds developing resistance on your farm?		Rotating chemicals and crops/ heavy cover crop/narrow rows
14	As a way to manage potential glyphosate weed resistance, how effective do you consider each of the following: (Using a scale of 1 to 10 where 1 is “not at all effective” and 10 is “very effective”)	Rotating herbicide modes of action from one year to the next	9.3
		Tillage	5.9
		Rotating crops	8.4
		Using correct label rates of herbicides at the proper timing for the size and types of weeds present	8.7
		Using more than one herbicide mode of action in a given year	9.3
		Using herbicides with soil residual	9
15	In terms of your farming operation, what are your major objections, if any, of the each of the following	Tillage	Soil erosion, time and cost when tillage is practiced. Cost and compatibility when using herbicide tank mixes.
		Rotating crops	
		Using correct label rates of herbicides at the proper timing for the size and types of weeds present	
		Using more than one herbicide chemistry in a given year, such as glyphosate and a residual herbicide	
		Using more than one herbicide chemistry in a given year, such as glyphosate and another post-applied herbicide	

Table 2.3 Producer objections to tillage as presented through responses to survey question 15a.

Producer Number	Objections
1	Cost
2	Cost (Use more fuel)
3	Cost / Erosion
4	Cost/ Time /Erosion / Compaction
5	Time consuming / Lack of Labor/Cost
6	light disking eliminates pre-plant herbicides
7	Erosion/ Organic matter oxidation
8	Loss of organic matter , moisture
9	No till
10	No till - Only for potatoes- Erosion
11	No till - Only in Tobacco Rotation

Figure 2.1. Distribution of susceptible and resistant Palmer amaranth in Virginia 2011.

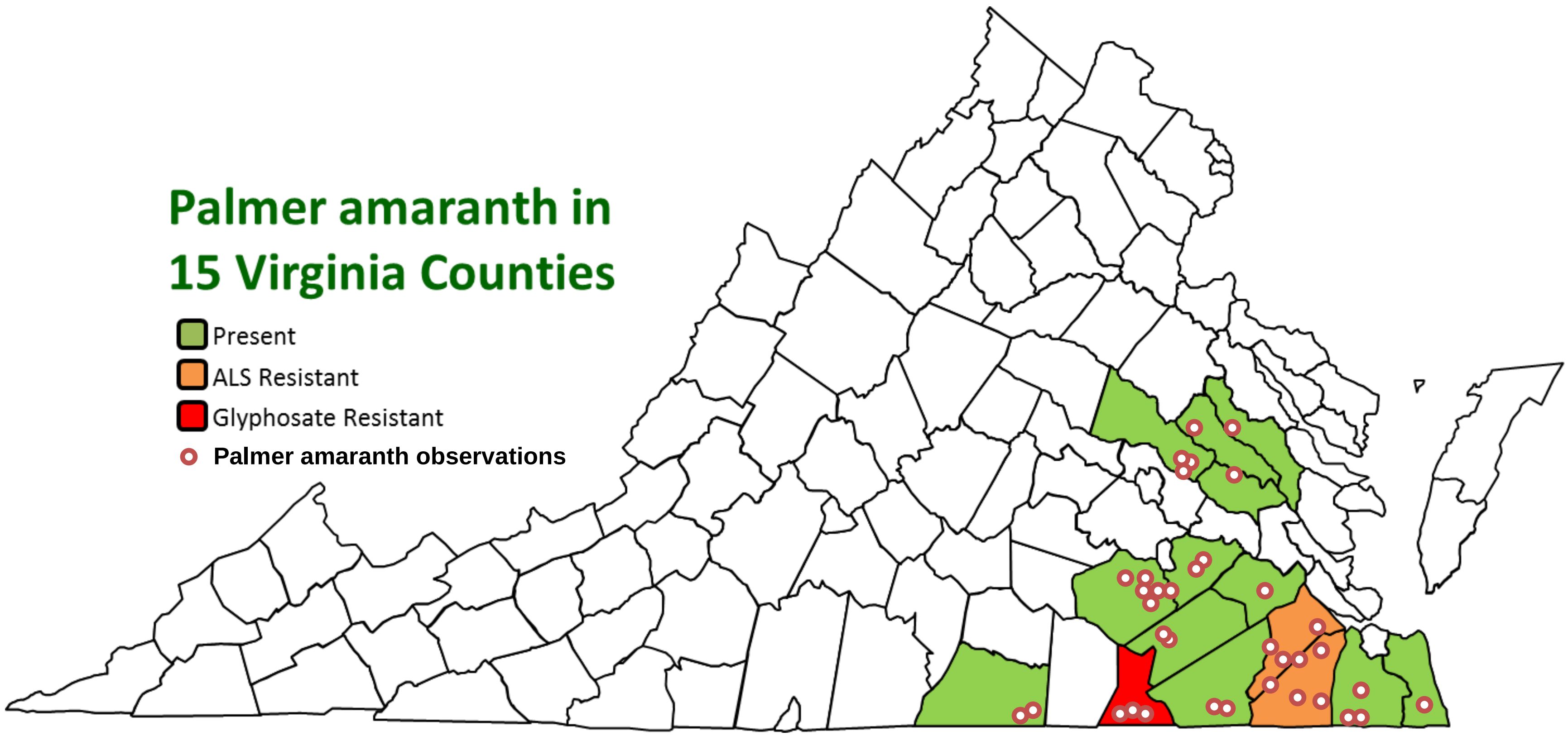
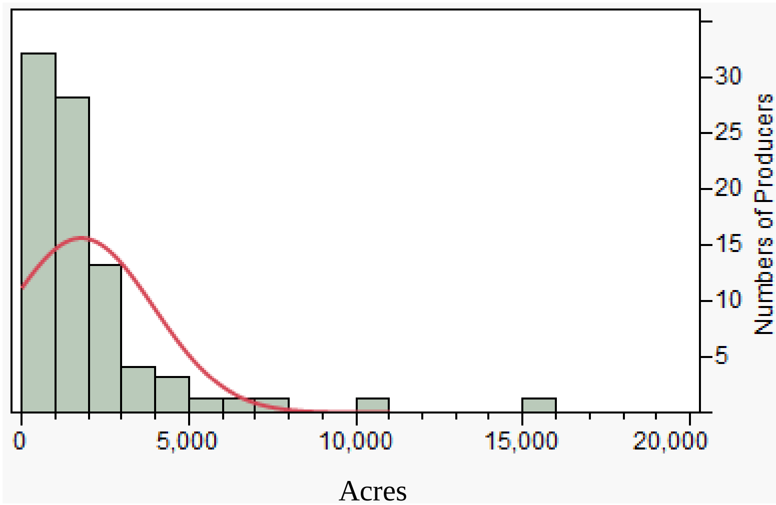


Figure 2.2. Breakdown of producer response to number of acres under their management in question 1.



Quantiles

100.0%	maximum	15000
99.5%		15000
97.5%		9550
90.0%		3850
75.0%	quartile	2250
50.0%	median	1200
25.0%	quartile	635
10.0%		280
2.5%		61.75
0.5%		30
0.0%	minimum	30

CHAPTER III

Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri* S. Wats) Control in Soybean (*Glycine max*)

ABSTRACT

Glyphosate-resistant (GR) Palmer amaranth is a major problem in the southeastern U.S. Herbicide efficacy experiments were established in 2009 and 2010 in a field heavily infested with Palmer amaranth to evaluate the use of glyphosate-based herbicide programs, glufosinate-based herbicide programs and conventional herbicide programs in soybean (*Glycine max* L. Merr.). In 2009, glyphosate applied at 0.87 + 0.87 + 1.74 kg ae ha^{-1} at 1, 3, and 5 weeks after planting (WAP), provided 82 to 85% control at final evaluation. In 2010, a hot and dry year, control was reduced to 23 to 30%. Glyphosate applied at 3 WAP following preemergence (PRE) applications of flumioxazin or fomesafen provided greater than 90% control in 2009, but only flumioxazin followed by glyphosate gave greater than 75% control in 2010. Glyphosate tank mixed with imazethapyr or imazethapyr applied alone at 2 WAP provided greater than 90% control in 2009. But in 2010, only s-metolachlor + metribuzin applied PRE followed by glyphosate tank mixed with fomesafen 4 WAP conferred greater than 90% control at final evaluation. Although PRE herbicides before glyphosate application or tank mixing postemergence (POST) herbicides with glyphosate could improve glyphosate-resistant Palmer amaranth control, hot and dry conditions may greatly reduce control. In 2009, glufosinate applied at 0.45 kg ha^{-1} at 1 and 3 WAP or applied at 0.45 kg ha^{-1} following a preemergence herbicide provided greater than 95% control. Glufosinate applied at 0.74 kg ai ha^{-1} three WAP provided greater than 85 and 95% control in 2009 and 2010, respectively. Glufosinate weed control programs offer an effective alternative for Palmer amaranth control, especially where glyphosate resistant weeds are present. Many conventional control systems that include different modes of action provided more than 80% at the final evaluation of Palmer amaranth in 2009 and 2010. A POST application of the ALS-inhibiting herbicides chlorimuron + thifensulfuron following a PRE application of flumioxazin provided 99% and 82% season-long in 2009 and 2010, respectively.

Nomenclature: Acifluorfen; bentazon; chlorimuron; cloransulam; fenoxaprop; fluazifop; flumioxazin; fomesafen; glufosinate; glyphosate; imazethapyr; linuron; metribuzin;; MSMA; paraquat; pendimethalin; saflufenacil; s-metolachlor; sulfentrazone; thifensulfuron; Palmer amaranth, *Amaranthus palmeri* S. Wats; cotton, *Gossypium hirsutum* L.; soybean, *Glycine max* (L.) Merr.

Key words: Weed control, resistant weeds, herbicide resistance.

Abbreviations: ALS, acetolactate synthase; GR, glyphosate-resistant; PRE, preemergence; POST, postemergence; PPO, protoporphyrinogen oxidase; WAP, weeks after planting.

INTRODUCTION

Palmer amaranth (*Amaranthus Palmeri* S. Wats.), also known as carelessweed and Palmer pigweed, is an erect branched summer annual broadleaf that is native to the southwest United States (Bryson and DeFelice 2009). Palmer amaranth is difficult-to-control due to its extended emergence period (Jha et al. 2006), rapid erect growth (up to 5 cm/d under full light) (Klingaman and Oliver 1994; Horak and Loughin 2000; Norsworthy et al. 2008), and large number of seed produced (Keeley et al. 1987). Also, Palmer amaranth was found to have the highest photosynthetic rate (81 µmol m^{-2} s^{-1}) among C_4 plants (Ehleringer 1983). This rate is 3 to 4 times the rate of crops such as soybean and cotton (*Gossypium hirsutum* L.) ith which it competes (Gibson 1998).

Numerous pigweed species have become resistant to several herbicide families (Heap 2011; Sprague et al. 1997; Horak and Peterson 1995). Common waterhemp and palmer amaranth are the most competitive and the most troublesome weeds of the *Amaranthus* species (Steckel et al. 2003). Common waterhemp (*Amaranthus rudis* Sauer*)* was proven resistant to four herbicide families (Patzoldt et. al 2005; Heap 2011). The most recent was the resistance to glyphosate in 2010. The first confirmed herbicide resistant Palmer amaranth was in South Carolina in 1989 to dinitroanilines (Gossett et al. 1992), followed by resistance to acetolactate synthase (ALS)-inhibiting herbicides in 1991 where resistant biotypes of Palmer amaranth and common waterhemp demonstrated greater than 2800- and 130-fold resistance, respectively, to phytotoxicity by imazethapyr compared to susceptible biotypes (Horak et al. 1995; Sprague et al 1997). The first case of glyphosate resistance (GR) was not confirmed until 2004 in Georgia (Culpepper et al. 2006). In addition, Palmer amaranth biotypes with multiple resistances to glyphosate and ALS-inhibiting herbicides exist in Georgia and North Carolina (Sosnoskie et al.

2009; Whitaker 2009). Moreover, it has been found that palmer amaranth biotypes susceptible to ALS-inhibiting herbicide can cross pollinate with common waterhemp biotypes resistant to ALS-inhibiting herbicide to produce a ALS-inhibiting herbicide resistant hybrid (Tranel and Wright 2002; Trucco et al. 2005). To date, Palmer amaranth has become resistant to four herbicide modes of action - dinitroanilines, ALS-inhibitors, photosystem II inhibitors and glycines - with GR confirmed in Georgia, North Carolina, Arkansas, Tennessee, New Mexico, Mississippi, Alabama, Missouri, Louisiana and Illinois (Heap 2011).

In Georgia, glyphosate applied to 5 to 13 cm tall Palmer amaranth at three times the normal use rate of 0.87 kg ae ha^{-1} resulted in only 17% control (Culpeper et al. 2006). At 12 times the normal use rate, glyphosate only provided 82% control. Other research in Tennessee reported reduced biomass sensitivity to glyphosate when 1.5 to 5 times the normal rate was needed to control the weed (Steckel et al. 2008). Research conducted in Arkansas concluded that GR biotypes were effectively controlled with postemergence (POST) herbicides, where 2,4-D, glufosinate, paraquat, MSMA, or atrazine provided 93 to 100% control and herbicides such as pyrithiobac, trifloxysulfuron, or imazethapyr only provided 63 to 82% at 28 d after treatment. (Norsworthy et al. 2008).

An alternative to the glyphosate-based weed control system is glufosinate. Glufosinate is a non-selective herbicide which can be applied POST on glufosinate resistant soybean cultivars. This genetically modified soybean was created by the insertion and expression of a bialaphos resistance (*bar*) gene isolated from the soil bacterium *Streptomycyes hygroscopius* which encodes for the phosphinothricin acetyl transferase enzyme. This enzyme detoxifies the L-isomer of glufosinate into an inactive form (Devine et al. 1993; Tsaftaris 1996). Glufosinate is typically less effective than glyphosate on Palmer amaranth (Corbett et al. 2004). However, with timely application, glufosinate can effectively control Palmer amaranth (Culpepper et al. 2000; Gardner et al. 2006; Norsworthy et al. 2008). Glufosinate offers an alternative to glyphosate for glyohsate resistant weed control with herbicide resistant crops (Culpepper et al. 2008; MacRae et al. 2008; Whitaker et al.2009).

To control weeds before the introduction of glyphosate resistance crops, growers used herbicide programs that did not depend on crop resistance. These programs are referred to today as conventional control systems. Reliance on control using glyphosate has led to a rapid decrease in use of conventional control systems, but as the glyphosate resistance incidence increase in weeds, conventional control is in demand once again and thus is tested in this experiment.

Glyphosate resistant crops, especially cotton and soybean, have been readily adopted by most farmers. Currently, greater than 90% of these crops are glyphosate-resistant. That is more reason that our study focuses on soybean as glyphosate resistance threatens it more than most other crops. Glyphosate resistant palmer amaranth threatens the Commonwealth’s crop production systems. To prevent or delay GR, information is needed on efficacy of glyphosate-based herbicide programs in soybean that include preemergence (PRE) and/or POST herbicides of differing modes of action. Even when Palmer amaranth has become resistant to glyphosate, a glyphosate-based weed control program still offers many advantages over other systems for control of other weeds, such as broad spectrum weed control and the flexibility in application timing. However, with continued reliance on glyphosate alone and the rapid increase in GR weeds reported, glyphosate may cease to be an effective option for weed control. Therefore, information is also needed on GR Palmer amaranth control with programs that include PRE herbicides and/or POST tank mixtures and/or alternative non selective herbicide programs such as glufosinate. The following experiments were conducted to evaluate glyphosate-based herbicide programs, glufosinate-based herbicide programs and conventional herbicide programs using PRE and POST herbicides for control of GR Palmer amaranth in soybean.

MATERIALS AND METHODS

Experiments were established during 2009 and 2010 in Greensville County, VA in a field heavily infested with Palmer amaranth (36.59^{o}N, 77.64^{o}W) where control with glyphosate was poor in 2008. In 2009, the field was no-till planted on May 27 and received a preplant application of glyphosate at 0.87 kg ae ha^{-1} two weeks before planting. In 2010, the seedbed was prepared by tillage and planting was delayed until June 11 due to dry soil conditions. Many weeds had emerged when tillage was performed; therefore tillage provided considerable control of early emerging Palmer amaranth. Soil types were Fluvanna and Mattaponi sandy loams (clayey, mixed, thermic typic Hapludults).

Experimental design was a randomized complete block with three replications. Plot area was of 3 by 9 m. Herbicides were applied with a CO_2 unicycle sprayer traveling at 4.8 kilometers hour^{-1} and using 80015 flat fan spray tips at 140 liters ha^{-1}and 220 kpa of operating pressure. Plots were rated according to visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control . Data were subjected to analysis of variance using SAS PROC GLM (SAS 2003). Data were transformed using arcsine square root transformation prior to analysis (Ahrens et al., 2009). Transformed means were separated using Fisher's protected LSD test at $P \leq 0.05$. Non transformed means are reported with interpretation based on transformed data.

Glyphosate-based herbicide programs

The experiment was planted with Southern States (Southern States Cooperative, Richmond, VA) cultivar RT 5760N in 19 cm rows. The first experiment evaluated control of Palmer amaranth with PRE herbicides in combination with one POST glyphosate application. Preemergence herbicides were applied within 2 days after planting. Paraquat at 0.7 kg ai ha^{-1} was tank mixed with all preemergence treatments and to the untreated control to kill emerged weeds in 2009. Glyphosate was applied three or four weeks after planting (WAP) in 2009 or 2010, respectively, and before Palmer amaranth reached 10 cm in height. In addition to PRE followed by glyphosate treatments, glyphosate was applied at 0.87, 0.87 and 1.74 kg ae ha^{-1} at 1, 3, and 5 WAP, respectively in 2009. In 2010, the glyphosate applications were delayed until 2, 4, and 6 WAP due to slow weed emergence and growth. An untreated control was also included. Herbicide treatments, rates, and timing are presented in Tables 3.1 and 3.2.

The second glyphosate-based herbicide experiment evaluated POST herbicides tank-mixed with glyphosate. The focus of the POST experiment was to determine additional control of emerged weeds and residual control of unemerged weeds by the herbicides in the tank mixture. No preemergence non-selective herbicides to kill present vegetation were applied; therefore applications were made 1 WAP to Palmer amaranth ranging in size from 2 to 10 cm. Treatments, rates, and timing are presented in Tables 3.3 and 3.4.

Glufosinate-based herbicide programs

Southern States soybean variety LL499N was planted in 19 cm rows on the same dates as the previously described experiments. Treatments consisted of 13 herbicide programs including glufosinate applied alone, glufosinate following selected preemergence herbicides, and an untreated control. Treatments rates and timing are presented in Tables 3.5 and 3.6. In 2010, glufosinate treatments were postponed 1 week due to dry conditions that delayed emergence and stressed emerged Palmer amaranth.

Conventional herbicide systems

This experiment was established to evaluate a variety of total POST, total PRE and combined PRE and POST approaches. Treatments consisted of combinations of PRE and POST herbicides from different herbicide families and modes of action. Within herbicide programs, repetition of more than one herbicide mode of action was kept at minimum. Preemergence treatments included photosystem II inhibitors metribuzin and linuron; protoporphyrinogen oxidase (PPO) inhibitors flumioxazin and sulfentrazone; ALS inhibitor cloransulam; cell growth inhibitor pendimethalin; and long chain fatty acids inhibitor s-metolachlor. Postemergence treatments included PPO inhibitors fomesafen and acifluorfen; ALS-inhibitors chlorimuron and thifensulfuron; photosystem II inhibitor bentazon and long chain fatty acids inhibitor s-metolachlor. Treatments rates and timing are presented in Tables 3.7 and 3.8.

RESULTS AND DISCUSSION

Glyphosate-based herbicide programs

Preemergence herbicide programs. Activating rainfall of 13.5 mm occurred during the 2 days after preemergence herbicides were applied in 2009. In 2010, there was a dry period where only 2.1 mm of rainfall occurred 2 days after preemergence herbicides were applied, after which only 0.3 mm of rainfall was received for 20 days (Figure 3.1). In general, optimal conditions existed for crop and weed growth in 2009, but drought persisted throughout most of 2010; therefore, Palmer amaranth control was evaluated in two very different growing seasons.

In 2009, treatments containing the PPO-inhibiting herbicides flumioxazin or fomesafen provided greater than 90% control at 2 WAP. The only treatment containing sulfentrazone, another PPO-inhibiting herbicide, to provide greater than 90% control was sulfentrazone + imazethapyr. The photosynthesis-inhibiting herbicides, metribuzin and linuron, provided only 42 and 63% control. The addition of s-metolachlor improved the control with metribuzin to 75%. Both rates of metribuzin + chlorimuron provided greater than 90% control at 2 WAP. Pendimethalin or s-metolachlor alone provided only 7 or 38% control, respectively. This was expected since previous research indicated little control of Palmer amaranth using pendimethalin, with a threshold period (threshold was 1 plant per m^{-2}) of only 3 days (Dobrow 2010; Whitaker and York 2009; Grichar 2008).

In 2010, control with preemergence herbicides was similar to 2009, but greater for most treatments at 2 WAP (Table 3.1). Treatments containing the PPO-inhibiting herbicides flumioxazin or fomesafen provided greater than 93% control. Other treatments that provided greater than 90% control were s-metolachlor + metribuzin (93%), the higher rate of metribuzin + chlorimuron (95%), and the photosynthesis-inhibiting herbicide linuron (92%). The other photosynthesis-inhibiting herbicide, metribuzin provided 60% control at 2 WAP. Pendimethalin or s-metolachlor alone provided only 40 or 75% control, respectively. Better early-season control in 2010 may be because of the dry weather conditions in late June and the beginning of July in 2010 which resulted in unfavorable conditions for palmer amaranth emergence and growth. By 3 WAP, when the glyphosate was originally scheduled to be applied, soybean and weeds were wilting and not growing; therefore application was delayed one week. Approximately 20 mm of rain fell in the second week of July, stimulating weed growth and emergence. With the addition of newly emerged weeds, control ratings for most treatments declined by 4 WAP. The only treatments maintaining greater than 75% control were flumioxazin (77%), fomesafen (83%), s-metolachlor + fomesafen (82%), s-metolachlor + metribuzin (82%), the higher rate of metribuzin + chlorimuron (83%), and chlorimuron + flumioxazin + thifensulfuron (83%). With the exception of pendimethalin, where control was maintained at 43%, control with other treatments was 10 to 45% less than at 2 WAP.

In 2009, glyphosate applied 1 WAP at 0.87 kg ae ha $^{-1}$ provided 85 % initial control (Table 3.1), but many Palmer amaranth plants survived the application. Some of the surviving plants appeared stunted and were yellowing while others were completely unharmed. Another cohort of Palmer amaranth emerged after the first application, but results with a second application of glyphosate were similar to the first, resulting in only 80% control at 4 WAP. At 5 WAP, 1.74 kg ae ha^{-1} of glyphosate was applied to these same plots, but only 82% control at final evaluation could be obtained. In 2010, results were very different. Glyphosate applied 2 WAP at 0.87 kg ae ha $^{-1}$ provided 58% control (Table 3.2), with more Palmer amaranth plants surviving than in 2009. A second application of 0.87 kg ae ha^{-1} two weeks after the first increased control to 50% at 6 WAP but not before it had dropped to 33% at 5 WAP. A third application of 1.74 kg ae ha^{-1} of glyphosate at 6 WAP did not improve control.

Although glyphosate did not control all Palmer amaranth plants in 2009, preemergence applications of flumioxazin or fomesafen, followed by one application of glyphosate at 0.87 kg ae ha^{-1} provided 95 and 91% control at final evaluation, respectively (Table 1). S-metolachlor + fomesafen, chlorimuron + flumioxazin + thifensulfuron, sulfentrazone + imazethapyr, and both rates of metribuzin + chlorimuron provided slightly less, but statistically equal control. Control at final evaluation with the other treatments ranged from 27 to 62%. The highly prolific characteristics of Palmer amaranth allows it to completely dominate a field under less than optimum management. Therefore, there is no economic threshold for Palmer amaranth management. Near zero tolerance is required each year.

In 2010, preemergence applications of flumioxazin or fomesafen, followed by one application of glyphosate at 0.87 kg ae ha^{-1} provided 88 or 67% control at final evaluation, respectively (Table 2). Glyphosate following s-metolachlor + fomesafen or chlorimuron + flumioxazin + thifensulfuron provided 75 or 70% control, respectively. Control at final evaluation with the other treatments was unacceptable, ranging from 10 to 62%. It is worth noting that glyphosate following metribuzin + chlorimuron at 0.28 and 0.04 kg ai ha^{-1}, respectively, provided 30 percent better control than when metribuzin + chlorimuron was applied at 0.18 + 0.03 kg ai ha^{-1}.

Postemergence herbicide tank mixtures. In 2009, glyphosate at 0.87 kg ae ha^{-1} provided only 73% control one week after application (Table 3.3). Control did not improve after a second application at the same rate, but did improve to 92% after a third application of glyphosate at 1.74 kg ae ha^{-1}. Still, there were many Palmer amaranth plants unaffected by these applications and control dropped to 85% by 8 WAP. Regardless of the herbicide used, tank mixtures improved Palmer amaranth control over glyphosate alone at 2 WAP. However, at 4 WAP, only tank mixtures with fomesafen, imazethapyr, or chlorimuron + thifensulfuron provided 90% or greater control. Imazethapyr alone provided 98 and 94% control at 2 and 4 WAP, respectively, indicating that Palmer amaranth in this field was susceptible to ALS-inhibiting herbicides. In addition to the tank mixtures applied at 1 WAP, glyphosate + fomesafen, when applied after a PRE application of s-metolachlor + metribuzin or after a POST application of glyphosate + s-metolachlor, provided 98 and 96% control at 4 WAP. Control after 4 WAP began to decrease with several treatments, and only glyphosate + imazethapyr or imazethapyr alone provided 90% or greater control at final evaluation. Interestingly, by 6 WAP, control with glyphosate +

pendimethalin or s-metolachlor actually improved, relative to the other treatments. Although initial control was not as good as other treatments, both herbicides suppressed further emergence of Palmer amaranth through 6 WAP.

Due to poor and uneven weed emergence at 1 WAP in the 2010 experiment, herbicides were not applied until 2 WAP. Glyphosate applied at 0.87 kg ae ha^{-1} provided only 20% control 4 WAP (Table 4). Control did not improve after a second or third application of glyphosate at 1.74 kg ae ha^{-1} providing only 23% control at 8 WAP. Many Palmer amaranth plants appeared unaffected by these applications. All herbicide control ratings were lower in 2010 as a result of dry conditions at the time of POST herbicide application and to the lack of activation rain needed for effective residual control with the tank-mix partners. Tank mixtures improved Palmer amaranth control over glyphosate alone at 4 WAP. However, at 6 WAP, only tank mixtures with acifluorfen or with s-metolachlor followed by a 4 WAP application of glyphosate + fomesafen provided greater than 80% control. In striking contrast to 2009, imazethapyr only provided 42 and 35% control at 4 and 6 WAP, respectively. The best control at final evaluation which did not include a PRE herbicide was glyphosate + s-metolachlor followed by glyphosate + fomesafen resulting in an overall season control of 55%. By 8 WAP, control by other solely POST treatments had fallen to 42% or less. Moreover, glyphosate + fomesafen, when applied after a PRE application of s-metolachlor + metribuzin, provided 93% control at 8 WAP. This demonstrates the importance of maintaining one or more herbicides with residual activity in the soil from planting until canopy closure in a field infested with GR Palmer amaranth.

A significant decline in control ratings was noticeable between the years 2009 and 2010. This could be attributed to elevated temperature and dry weather in 2010 (Figure 3.1). Rainfall moves herbicides into weed seed germination zone, thus it is needed for effective PRE herbicide uptake and activation. Also as soil moisture decreases, herbicide molecules tend to bind more tightly with soil particles reducing the effectiveness of most soil-applied herbicides. Moreover, drought stressed weeds are more difficult to control with POST herbicides because of reduced herbicide absorption and low physiological activity (Menalled et al. 2001). Although glyphosate application was delayed in 2010 until 2, 4, and 6 WAP compared to 1, 3 and 5 WAP in 2009 in order to allow weed emergence and germination, herbicides were applied before Palmer amaranth reached 10 cm in height; therefore, the timing of application should not have greatly affected control.

With glyphosate-based weed control programs, three applications of glyphosate provided poor to fair control of Palmer amaranth. This population was later confirmed in 2011 as resistant to glyphosate (Chapter 5). Under elevated temperatures and dry weather, all herbicide treatments were challenged and most herbicide programs were rendered less effective. Residual control with combinations of PRE or POST herbicides was better than by glyphosate alone, but few treatments provided good control at final evaluation during the hot and dry year. Of all preemergence herbicide programs, only flumioxazin followed by glyphosate provided greater than 75% control when rainfall was limited. Under those conditions, the best and most consistent control of Palmer amaranth occurred when s-metolachlor + metribuzin was applied PRE and was followed by glyphosate + fomesafen POST. In that case, two PRE herbicides with differing modes of action were followed by a tank mixture of glyphosate and a herbicide with both postemergence and residual activity on Palmer pigweed. This provided for a residual herbicide in the soil throughout the growing season plus an effective postemergence tank-mix partner with glyphosate. Such a program may be necessary for consistent control of high populations of GR weeds over varying environments. Although glyphosate-resistant Palmer amaranth control is possible in glyphosate-resistant soybean, one or more preemergence herbicides followed by a tank mixture of glyphosate with a herbicide that has both postemergence and residual activity may pose less risk and greater return on investment.

Glufosinate-based herbicide programs

As previously stated, weather conditions were very different in 2009 and 2010 (Figure 3.1). Rainfall was adequate and cooler temperatures prevailed in 2009 and 2010 was very hot and dry. Still, with the exception of saflufenacil in 2009, control of Palmer amaranth was very good with all preemergence herbicides at 2 WAP (Tables 3.5 and 3.6). The addition of a POST application of glufosinate resulted in control at final evaluation with all treatments containing a PRE herbicide. Since the glufosinate application was delayed in 2010 due to dry weather, further evaluation of preemergence control was possible. By 4 WAP, control was less with most treatments and much less with flumioxazin + chlorimuron and metribuzin + chlorimuron. Control ratings for these two treatments were reduced significantly from 85 and 90% at 2 WAP to 30 and 40% at 4 WAP, respectively. This is difficult to explain, especially with flumioxazin + chlorimuron, since the flumioxazin + chlorimuron + thifensulfuron provided 96% control. This might be due to variation in soil seed bank population within the field. Regardless, the addition of a postemergence application of glufosinate at 4 WAP improved control only slightly at 5 WAP. This could be attributed to dry weather in 2010 that delayed weed response to the herbicide (Figure 3.1). However, by 6 WAP, over 90% of the weeds present were controlled regardless of herbicide program (Tables 1 and 2).

In 2009, when applied alone without preemergence herbicides, glufosinate at 0.45 kg ha^{-1} at 1 and 3 WAP or at 0.74 kg ha^{-1} provided 99 or 87% control at 8 WAP, respectively. In 2010, control with glufosinate applied at 0.45 kg ha^{-1} was excellent (94%) through 5 WAP, but control was poor (20%) from the 0.74 kg ha^{-1} application made just one week earlier. However, by 6 WAP control was complete (99%) and was 95% by 8 WAP. Again, dry weather likely affected herbicide efficacy.

In summary, the glufosinate herbicide programs tested in this study provided excellent control at final evaluation. Using either a preemergence herbicide followed by glufosinate or two postemergence applications of glufosinate were usually required for control at final evaluation. A glufosinate-based herbicide program offers a very good alternative to glyphosate-based programs when Palmer amaranth has developed resistance to glyphosate.

Conventional herbicide systems

In 2009, PRE treatment of flumioxazin alone provided 87% control of Palmer amaranth at 3 WAP, providing greater control than pendimethalin (73%) and s-metolachlor (43 % to 68% control) (Table 3.7). Tank mixing s-metolachlor with photosystem II inhibitors linuron, or metribuzin provided 58 and 80% control, respectively. Moreover, mixing s-metolachlor with sulfentrazone and cloransulam or sulfentrazone and metribuzin increased control to 73 to 87%. Also, sulfentrazone and metribuzin provided 82% control at 2 WAP. At 4 WAP, with no POST herbicide, control with s-metolachlor + sulfentrazone and cloransulam or s-metolachlor + metribuzin and sulfentrazone declined to 65% or 62% (Table 3.7).

All treatments including a POST herbicide resulted in more than 83% control of Palmer amaranth at 4 WAP. The total POST approach of fomesafen + bentazon + fluazifop and fenoxaprop initially provided 98% control, but control declined to 68% by 8 WAP. Treatments including fomesafen POST provided control at final evaluation of 83 to 96%. Even when fomesafen was used at the lower rate of 0.28 kg ha^{-1} applied and tank-mixed with bentazon, the control at final evaluation result was equal to fomesafen alone at a higher rate of 0.42 kg ha^{-1}

(93%). When POST treatment of fomesafen followed a treatment of s-metolachlor + metribuzin and sulfentrazone, control at final evaluation increased from 62 to 96%, compared to control at final evaluation of the same PRE treatment without fomesafen. Flumioxazin PRE followed by a POST application of chlorimuron and thifensulfuron + fluazifop and fenoxaprop or sulfentrazone and metribuzin PRE followed by fomesafen + fluazifop and fenoxaprop provided the best control at final evaluation of Palmer amaranth at 96%. Although acifluorfen does not provide residual control of Palmer amaranth, acifluorfen provided 91 season-long control. However, when the rate of acifluorfen was reduced and combined with bentazon, control was only 72%. Treatments that did not include a post treatment provided only 47 and 65% control.

In 2010, Palmer amaranth populations were less (probably due to tillage burying some of the seed) and more variable. PRE treatment of flumioxazin provided 93% control of Palmer amaranth at 3 WAP, proving greater control than pendimethalin (70%) and s-metolachlor (15 to 65% control). Tank mixing s-metolachlor with photosystem II inhibitors linuron or metribuzin increased control to 89 or 96% control, respectively. Moreover, mixing s-metolachlor + sulfentrazone and cloransulam or metribuzin and sulfentrazone increased control to 96% and 95 to 99%, respectively (Table 3.8).

POST application was delayed in 2010 to 4 WAP to allow for additional weed emergence and for rainfall to relieve stressed plants. Still, Palmer amaranth did not exceed 10 cm when POST treatments were applied. At 5 WAP, control with treatments containing no POST herbicides such as PRE applications of s-metolachlor + sulfentrazone and cloransulam or s-metolachlor + metribuzin and sulfentrazone declined to 80 or 82%. Chlorimuron and thifensulfuron following a PRE flumioxazin application provided 75% control at 5 WAP compared to 65% control provided by fomesafen + bentazon. Unlike 2009, POST fomesafen treatments did not provide control at final evaluation in 2010. When POST treatment of fomesafen followed s-metolachlor + metribuzin and sulfentrazone, control at final evaluation increased to 70% compared to control at final evaluation of the same PRE treatment without fomesafen (47%). Chlorimuron and thifensulfuron following a PRE application of flumioxazin provided the best control at final evaluation of 82%.

The decline in control ratings in 2010 could be explained by elevated temperature and dry weather conditions (Figure 3.1). Rainfall is essential for effective PRE herbicide uptake and activation. Rainfall moves the herbicides into seed germination zone and releases soil bound herbicides into soil available water rending herbicide molecules available for plant uptake. Moreover, drought stressed weeds are more difficult to control with POST herbicides because of reduced herbicide absorption and low physiological activity (Menalled. 2001). It is worth mentioning that although POST applications were delayed until rainfall relieved the severe stress that weeds were experiencing at 3 WAP, weeds were still growing with little soil moisture at 4 WAP.

Many conventional herbicide programs provided good to excellent control of Palmer amaranth. Acetolactase synthase and PPO inhibitors provided the best control at final evaluation. ALS-based POST treatment chlorimuron plus thifensulfuron following flumioxazin PRE provided the best control for both years. Herbicides with ALS-inhibiting mode of action provide a valuable alternative for resistance management. However if Palmer amaranth also develops resistance to ALS-inhibitors, difficulties may ensue. Conventional herbicide programs provide an alternative to glyphosate to manage GR Palmer amaranth. But, success with conventional systems will require PRE and POST combinations and will depend on environmental conditions.

Moreover, PRE and POST herbicides used in conventional control methods can be used with glyphosate to achieve better control and reduce selection pressure for resistant biotypes.

This chapter provides a contrast of information on GR Palmer amaranth control in soybean between three herbicide management programs. Overall, glufosinate-based management systems provided the best results with control at final evaluation of up to 99%. Results observed in the conventional herbicide systems varied according to the treatment used, ranging from 30 to 99% control at final evaluation. Certain conventional programs offer a viable option for effective Palmer amaranth control. Moreover, glyphosate-based management systems achieved adequate control of the GR weed only when combined with effective PRE and/or POST herbicides of a differing mode of action, thus keeping a residual herbicide in place throughout the season. Finally, it is worthwhile to observe the effect of dry weather conditions on herbicide activation and efficiency. The effect of dry weather can most easily be noticed in the success of PRE herbicides during the wetter year which failed to activate under dry weather condition leading to a drastic decrease in control rates.

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Table 3.1. Glyphosate-resistant Palmer amaranth control with preemergence (PRE) herbicides followed by glyphosate applied at 3 weeks after planting (WAP), Greensville County, VA, 2009.

Herbicide applications[a]		AMAPA Control[de]							
PRE herbicide treatments[b]	Application rate	2 WAP		4 WAP		6 WAP		8 WAP	
	(kg ai ha $^{-1}$)	------------------- % Visual control[f] --------------------							
Untreated		7	f	7	g	7	d	8	f
None[c]		85	abc	80	b-e	83	ab	82	abc
Pendimethalin	0.80	7	f	50	f	20	cd	27	ef
S-metolachlor	1.34	38	e	68	ef	33	c	47	de
Flumioxazin	0.09	95	ab	98	a	91	a	95	a
Fomesafen	0.21	96	a	94	ab	85	ab	91	a
Metribuzin	0.28	42	de	65	ef	30	c	62	bcd
Linuron	0.56	63	cd	73	def	53	bc	53	cd
S-metolachlor + fomesafen	1.22 + 0.28	95	ab	91	abc	93	a	87	ab
S-metolachlor + metribuzin	1.11 + 0.26	75	bc	73	de	42	c	62	bcd
Sulfentrazone + cloransulam	0.14 + 0.02	77	bc	73	def	43	c	62	bcd
Sulfentrazone + metribuzin	0.10 + 0.15	75	abc	75	cde	42	c	60	bcd
Sulfentrazone + imazethapyr	0.12 + 0.02	95	ab	91	ab	88	a	82	abc
Metribuzin + chlorimuron	0.18 + 0.03	92	ab	90	a-d	86	a	80	abc
Metribuzin + chlorimuron	0.27 + 0.04	95	ab	96	a	83	ab	82	abc
Chlorimuron + flumioxazin + thifensulfuron	0.03 + 0.08 + 0.01	96	a	98	a	85	ab	87	ab

[a] Glyphosate was applied postemergence (POST) at 0.87 kg ae ha $^{-1}$ 3 WAP to all treatments except for the untreated control.

[b] All treatments except for glyphosate applied alone, indicated by "None", received paraquat PRE at 0.70 kg ai ha^{-1}.

[c] Glyphosate applied POST at 0.87, 0.87, 1.74 kg ae ha^{-1} respectively at 1, 3, and 5 WAP.

[d] Abbreviations: AMAPA, palmer amaranth; PRE, preemergence; WAP, weeks after planting.

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

[f] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 3.2. Glyphosate-resistant Palmer amaranth control with preemergence (PRE) herbicides followed by glyphosate applied at 4 weeks after planting (WAP), Greensville County, VA, 2010.

Herbicide applications[a]		AMAPA Control[de]									
PRE herbicide treatments[b]	Application rate	2 WAP		4 WAP		5 WAP		6 WAP		8 WAP	
	(kg ai ha^{-1})	-------------- % Visual control[f] ---------------									
Untreated		7	g	0	f	0	f	0	h	0	g
None[c]		23	f	58	cde	33	e	50	fg	30	def
Pendimethalin	0.80	40	f	43	de	37	de	43	g	20	ef
S-metolachlor	1.34	75	de	37	e	37	de	65	d-g	10	fg
Flumioxazin	0.09	96	ab	77	abc	72	abc	80	a-d	88	a
Fomesafen	0.21	95	ab	83	a	73	abc	82	a-d	67	abc
Metribuzin	0.28	60	e	50	de	47	cde	52	fg	30	def
Linuron	0.56	92	abc	47	de	57	cde	58	efg	37	cde
S-metolachlor + fomesafen	1.22 + 0.28	98	a	82	ab	85	ab	88	ab	75	ab
S-metolachlor + metribuzin	1.11 + 0.26	93	abc	82	abc	70	abc	88	ab	60	a-d
Sulfentrazone + cloransulam	0.14 + 0.02	80	cd	65	a-d	62	bcd	80	a-d	53	a-d
Sulfentrazone + metribuzin	0.10 + 0.15	88	abc	62	a-e	55	cde	73	b-e	47	b-e
Sulfentrazone + imazethapyr	0.12 + 0.02	87	bcd	60	a-e	62	bcd	68	def	33	def
Metribuzin + chlorimuron	0.18 + 0.03	88	bcd	60	b-e	65	a-d	73	cde	30	def
Metribuzin + chlorimuron	0.27 + 0.04	95	ab	83	ab	72	abc	88	abc	62	a-d
Chlorimuron + flumioxazin + thifensulfuron	0.03 + 0.08 + 0.01	96	ab	83	a	88	a	92	a	70	ab

[a] Glyphosate was applied postemergence (POST) at 0.87 kg ae ha^{-1} 4 WAP to all treatments except for the untreated control.

[b] All treatments except for glyphosate applied alone, indicated by "None", received paraquat PRE at 0.70 kg ai ha^{-1}.

[c] Glyphosate applied POST at 0.87, 0.87, 1.74 kg ae ha^{-1} respectively at 1, 3, and 5 WAP.

[d] Abbreviations: AMAPA, palmer amaranth PRE, preemergence; WAP, weeks after planting.

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

[f] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 3.3. Glyphosate-resistant Palmer amaranth control with glyphosate tank mixtures applied 1, 3, or 5weeks after planting (WAP), Greensville County, VA, 2009.

	Application timing and rates			AMAPA Control[c]							
POST herbicide treatments[a]	1 WAP	3 WAP	5 WAP	2 WAP		4 WAP		6 WAP		8 WAP	
	(kg ae or ai ha^{-1})			-------- % Visual control[d] ---------							
Untreated				8	d	7	e	7	d	7	d
Glyph	0.87	0.87	1.74	73	bc	72	abc	92	a	85	abc
Glyph + pendimethalin	0.87 + 1.07			95	ab	75	abc	93	a	70	bc
Glyph + s-metolachlor	0.87 + 1.34			83	ab	55	bcd	70	ab	78	abc
Glyph + fomesafen	0.87 + 0.21			96	a	83	ab	88	a	85	abc
Glyph + acifluorfen	0.87 + 0.28			96	a	13	de	23	cd	60	c
Glyph + s-metolachlor fb glyphosate + fomesafen	0.87 + 1.34	0.87 + 0.21		95	ab	96	a	85	a	87	abc
Glyph + fomesafen[b]		0.87 + 0.21		50	c	98	a	82	ab	80	abc
Glyph + imazethapyr	0.87 + 0.07			99	a	96	a	92	a	90	ab
Imazethapyr	0.07			98	a	94	a	93	a	96	a
Glyph + chlorimuron + thifensulfuron	0.87 + 0.006 + 0.002			99	a	90	a	73	ab	82	abc
Glyph + thifensulfuron-methyl	0.87 + 0.004			99	a	42	cd	45	bc	75	abc

[a] Abbreviations: AMAPA, Palmer amaranth; fb, followed by; glyph, glyphosate; POST, postemergence; WAP, weeks after planting.

[b] Paraquat, s-metolachlor, and metribuzin applied preemergence (PRE) at 0.70, 1.10 and 0.26 kg ai ha^{-1}.

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

[d] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 3.4. Glyphosate-resistant Palmer amaranth control with glyphosate tank mixtures applied 2, 4, or 6weeks after planting (WAP), Greensville County, VA, 2010

POST herbicide treatments[a]	Application timing and rates: 1 WAP	3 WAP	5 WAP	AMAPA Control[d]: 4 WAP		5 WAP		6 WAP		8 WAP	
	(kg ae or ai ha^{-1})			------------ % Visual control[d] --------------							
Untreated				0	e	3	f	0	d	0	d
Glyph	0.87	0.87	1.74	20	d	20	e	30	c	23	bc
Glyph + pendimethalin	0.87 + 1.07			43	cd	20	e	23	c	17	c
Glyph + s-metolachlor	0.87 + 1.34			53	bcd	27	e	30	c	17	c
Glyph + fomesafen	0.87 + 0.21			78	ab	63	bc	50	bc	42	bc
Glyph + acifluorfen	0.87 + 0.28			90	a	91	a	83	ab	37	bc
Glyph + s-metolachlor fb glyphosate + fomesafen	0.87 + 1.34	0.87 + 0.21		85	ab	93	ab	80	ab	55	b
Glyph + fomesafen[b]		0.87 + 0.21		78	ab	93	a	95	a	93	a
Glyph + imazethapyr	0.87 + 0.07			37	cd	37	de	27	c	33	bc
Imazethapyr	0.07			43	cd	37	de	30	c	40	bc
Glyph + chlorimuron + thifensulfuron	0.87 + 0.006 + 0.002			57	bc	27	e	23	c	20	c
Glyph + thifensulfuron-methyl	0.87 + 0.004			60	bc	55	cd	37	c	17	c

[a] Abbreviations: AMAPA, palmer amaranth; fb, followed by; glyph, glyphosate; POST, postemergence; WAP, weeks after planting.

[b] Paraquat, s-metolachlor, and metribuzin applied PRE at 0.70, 1.10 and 0.26 kg ai ha^{-1}.

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

[d] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 3.5. Glyphosate-resistant Palmer amaranth control with preemergence (PRE) herbicides and glufosinate, Greensville County, VA, 2009

Treatment		Glufosinate		AMAPA Control[ab]							
PRE	Rate	Rate	Application timing	2 WAP		4 WAP		6 WAP		8 WAP	
	(kg ai ha^{-1})	(kg ai ha^{-1})		--------------- % Visual control[c] ----------------							
Untreated control				3	d	3	c	0	b	0	c
None		0.74	3 WAP	13	d	93	ab	93	bc	87	b
None		0.45 + 0.45	1 WAP + 5 WAP	99	a	83	b	99	a	99	a
Flumioxazin	0.07	0.74	3 WAP	92	ab	98	a	90	c	83	b
Flumioxazin	0.07	0.45 + 0.45	3 WAP + 5 WAP	96	ab	99	a	98	ab	96	a
Flumioxazin + chlorimuron	0.06 + 0.02	0.45 + 0.45	3 WAP + 5 WAP	96	ab	99	a	99	a	96	a
Flumioxazin + chlorimuron + thifensulfuron	0.06 + 0.02 + 0.01	0.45 + 0.45	3 WAP + 5 WAP	91	ab	94	a	99	a	99	a
Saflufenacil	0.02	0.45 + 0.45	3 WAP + 5 WAP	68	c	96	a	99	a	98	a
Saflufenacil + imazethapyr	0.02 + 0.07	0.45 + 0.45	3 WAP + 5 WAP	93	ab	99	a	99	a	99	a
Sulfentrazone + cloransulam	0.17 + 0.02	0.74	3 WAP	83	bc	96	ab	96	abc	90	b
Sulfentrazone + cloransulam	0.17 + 0.03	0.45 + 0.45	3 WAP + 5 WAP	87	abc	98	a	98	ab	99	a
S-metolachlor + fomesafen	1.22 + 0.28	0.45 + 0.45	3 WAP + 5 WAP	92	ab	99	a	99	a	99	a
Metribuzin + chlorimuron	0.18 + 0.03	0.45 + 0.45	3 WAP + 5 WAP	93	ab	99	a	99	a	99	a

[a] Abbreviations: AMAPA, palmer amaranth; PRE, preemergence; WAP, weeks after planting.

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

[c] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 3.6. Glyphosate-resistant Palmer amaranth control with preemergence (PRE) herbicides and glufosinate, Greensville County, VA, 2010.

Treatment		Glufosinate		AMAPA Control[ab]									
PRE	Rate	Rate	Application timing	2 WAP		4 WAP		5 WAP		6 WAP		8 WAP	
	(kg ai ha^{-1})	(kg ai ha^{-1})		--------------- % Visual control[c] ----------------									
Untreated control				0	b	0	f	10	d	0	c	0	d
None		0.74	4 WAP	0	b	15	ef	20	d	99	a	95	bc
None		0.45 + 0.45	2 WAP + 6 WAP	7	b	99	a	94	a	56	b	99	a
Flumioxazin	0.07	0.74	4 WAP	98	a	78	a-d	93	a	99	a	98	ab
Flumioxazin	0.07	0.45 + 0.45	4 WAP + 6 WAP	99	a	90	ab	96	a	99	a	99	a
Flumioxazin + chlorimuron	0.06 + 0.02	0.45 + 0.45	4 WAP + 6 WAP	85	a	30	de	40	cd	96	a	99	a
Flumioxazin + chlorimuron + thifensulfuron	0.06 + 0.02 + 0.01	0.45 + 0.45	4 WAP + 6 WAP	99	a	96	ab	95	a	98	a	99	a
Saflufenacil	0.02	0.45 + 0.45	4 WAP + 6 WAP	99	a	93	ab	88	a	99	a	99	a
Saflufenacil + imazethapyr	0.02 + 0.07	0.45 + 0.45	4 WAP + 6 WAP	93	a	85	ab	78	abc	99	a	99	a
Sulfentrazone + cloransulam	0.17 + 0.02	0.74	4 WAP	99	a	75	abc	85	ab	99	a	98	ab
Sulfentrazone + cloransulam	0.17 + 0.03	0.45 + 0.45	4 WAP + 6 WAP	96	a	70	bcd	80	abc	99	a	99	a
S-metolachlor + fomesafen	1.22 + 0.28	0.45 + 0.45	4 WAP + 6 WAP	99	a	91	ab	77	abc	99	a	99	a
Metribuzin + chlorimuron	0.18 + 0.03	0.45 + 0.45	4 WAP + 6 WAP	95	a	40	cde	45	bcd	98	a	96	c

[a] Abbreviations: AMAPA, palmer amaranth; PRE, preemergence; WAP, weeks after planting.

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

[c] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 3.7. Glyphosate-resistant Palmer amaranth control with conventional herbicide programs 3, 4, 6, 8 and 10 weeks after planting (WAP), Greensville County, VA, 2009.

Appl. time	Herbicide treatments	Application rate	AMAPA Control[cd]									
			3 WAP		4 WAP		6 WAP		8 WAP		10 WAP	
		(kg ai ha^{-1})	% Visual control[e]									
	Untreated		0	f	0	e	0	e	0	f	0	f
PRE	None		11	ef	98	a	90	bc	68	abc	88	abc
POST	Fomesafen + bentazon[f]	0.42 + 0.56										
PRE	S-metolachlor + sulfentrazone + cloransulam	1.34 + 0.28 + 0.04	88	ab	65	bcd	75	cd	47	e	57	e
POST	None											
PRE	S-metolachlor + metribuzin + sulfentrazone	1.34 + 0.15 + 0.10	87	a	62	d	72	d	62	de	65	de
POST	None											
PRE	S-metolachlor + metribuzin + sulfentrazone	1.34 + 0.15 + 0.10	73	abc	98	a	93	ab	96	abc	96	ab
POST	Fomesafen	0.42										
PRE	S-metolachlor + metribuzin	1.34 + 0.28	80	bcd	90	cd	92	ab	85	bcd	85	bcd
POST	Fomesafen	0.42										
PRE	Sulfentrazone + metribuzin	0.15 + 0.23	82	abc	99	a	99	ab	96	a	92	ab
POST	Fomesafen[f]	0.42										
PRE	S-metolachlor + linuron	1.34 + 1.12	58	bcd	90	ab	93	ab	88	abc	87	bc
POST	Fomesafen	0.42										
PRE	S-metolachlor	1.34	43	cde	83	abc	93	ab	91	abc	85	bc
POST	Acifluorfen	0.42										
PRE	S-metolachlor	1.34	62	de	87	ab	88	bc	72	cd	72	cde
POST	Acifluorfen + bentazon	0.28 + 0.56										
PRE	S-metolachlor	1.34	59	a-d	96	a	95	ab	93	a	95	ab
POST	Fomesafen	0.42										
PRE	S-metolachlor	1.34	68	abc	98	a	96	ab	93	ab	88	abc
POST	Fomesafen + bentazon	0.28 + 0.56										
PRE	Pendimethalin	0.80	73	a-d	96	a	95	ab	83	cd	90	abc
POST	S-metolachlor + fomesafen	1.34 + 0.42										

Table 3.7 (continued).

Herbicide treatments		Application rate	AMAPA Control[cd]									
			3 WAP		4 WAP		6 WAP		8 WAP		10 WAP	
		(kg ai ha^{-1})	--------------------- % Visual control[e] ----------------------									
PRE	Flumioxazin	0.09	87	a	90	ab	96	ab	96	a	99	a
POST	Chlorimuron + thifensulfuron [f]	0.01 + 0.004										

[a] Paraquat applied PRE at 0.70 kg ai ha^{-1}.

[b] All POST treatments were applied at 3 WAP.

[c] Abbreviations: AMAPA, palmer amaranth; POST, postemergence; PRE, preemergence; WAP, weeks after planting.

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

[e] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

[f] Fluazifop + fenoxaprop was included for grass weed control.

Table 3.8. Glyphosate-resistant Palmer amaranth control 3, 4, 6, 8 and 10 weeks after planting (WAP), Greensville County, VA, 2010

Appl. time	Herbicide treatments[ab]	Application rate	AMAPA Control[cd]									
			3 WAP		4 WAP		5 WAP		6 WAP		8 WAP	
		(kg ai ha^{-1})	% Visual control[e]									
Untreated	Untreated		25	de	25	f	10	b	0	c	0	e
PRE	None		25		17	ef	65	a	62	b	28	cde
POST	Fomesafen + bentazon[f]	0.42 + 0.56										
PRE	S-metolachlor + sulfentrazone + cloransulam	1.34 + 0.28 + 0.04	96	ab	86	ab	80	a	83	ab	72	ab
POST	None											
PRE	S-metolachlor + metribuzin + sulfentrazone	1.34 + 0.15 + 0.10	95	ab	90	a	82	a	83	ab	47	a-d
POST	None											
PRE	S-metolachlor + metribuzin + sulfentrazone	1.34 + 0.15 + 0.10	99	a	57	bcd	80	a	85	ab	70	ab
POST	Fomesafen	0.42										
PRE	S-metolachlor + metribuzin	1.34 + 0.28	93	ab	77	ab	85	a	90	ab	80	a
POST	Fomesafen	0.42										
PRE	Sulfentrazone + metribuzin	0.15 + 0.23	96	a	75	abc	82	a	85	ab	68	abc
POST	Fomesafen[f]	0.42										
PRE	S-metolachlor + linuron	1.34 + 1.12	89	ab	72	abc	78	a	80	ab	57	a-d
POST	Fomesafen	0.42										
PRE	S-metolachlor	1.34	65	bc	27	def	72	a	62	b	33	b-e
POST	Acifluorfen	0.42										
PRE	S-metolachlor	1.34	48	cd	40	cde	63	a	63	b	37	a-d
POST	Acifluorfen + bentazon	0.28 + 0.56										
PRE	S-metolachlor	1.34	47	c	20	ef	68	a	62	b	27	b-e
POST	Fomesafen	0.42										
PRE	S-metolachlor	1.34	15	cde	20	ef	57	a	73	ab	20	de
POST	Fomesafen + bentazon	0.28 + 0.56										
PRE	Pendimethalin	0.80	70	abc	66	abc	72	a	95	a	63	a-d
POST	S-metolachlor + fomesafen	1.34 + 0.42										
PRE	Flumioxazin	0.09	93	ab	80	ab	75	a	88	ab	82	a
POST	Chlorimuron + thifensulfuron [f]	0.01 + 0.004										

Table 3.8 (continued).

[a] Paraquat applied PRE at 0.70 kg ai ha^{-1}.

[b] All POST treatments were applied at 3 WAP.

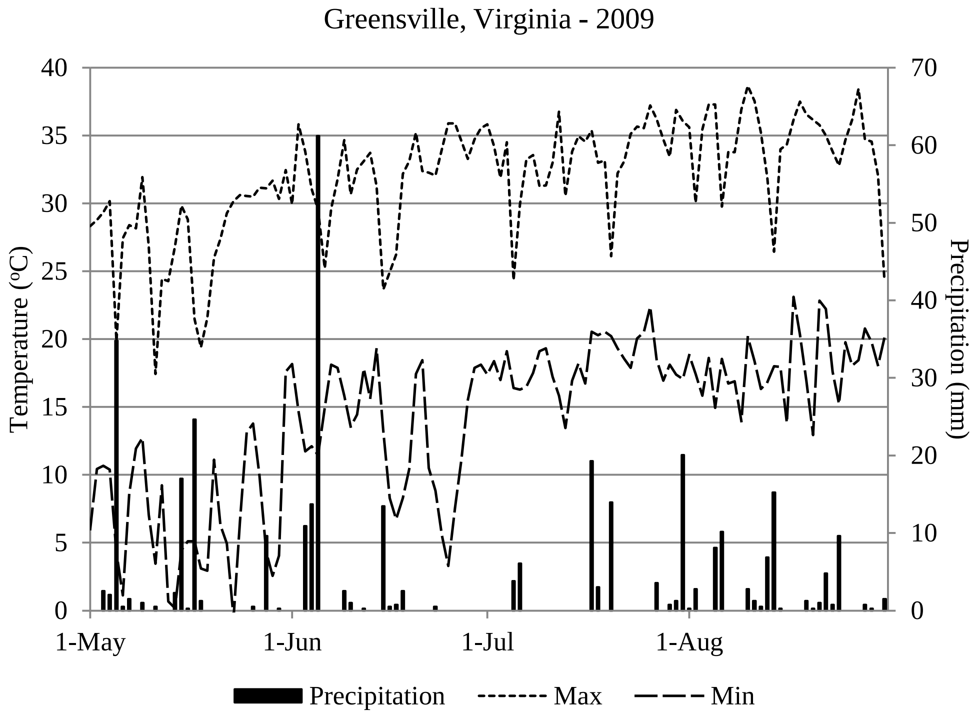
[c] Abbreviations: AMAPA, palmer amaranth; POST, postemergence; PRE, preemergence; WAP, weeks after planting.

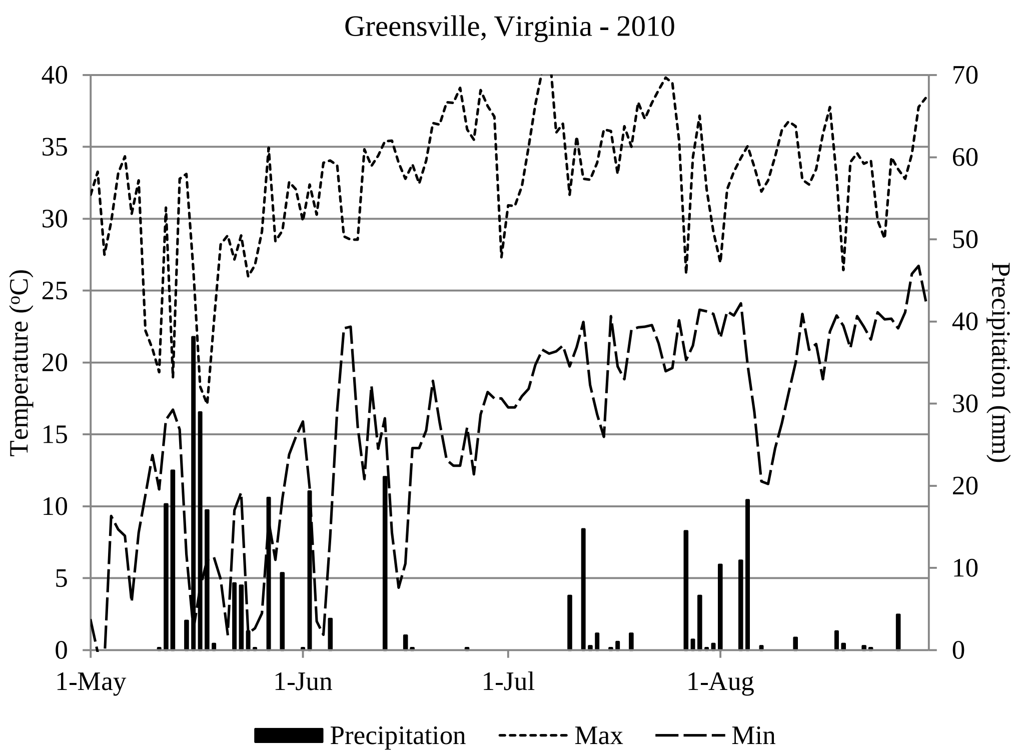
[d] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P \leq 0.05$.

[e] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

[f] Fluazifop + fenoxaprop was included for grass weed control.

Figure 3.1. Temperature and precipitation in Greensville County, Virginia in 2009 and 2010.





CHAPTER IV

Palmer Amaranth (*Amaranthus palmeri* S. Wats) Control in Cotton (*Gossypium hirsutum*)

ABSTRACT

Herbicide efficacy experiments were established in 2008 and 2009 in a field infested with Palmer amaranth to determine the efficacy of glyphosate- and glufosinate-based control programs in cotton (*Gossypium* L.). Preemergence (PRE) applications of fomesafen, fluometuron, and pendimethalin + fomesafen provided 91 to 99 percent control of Palmer amaranth. When followed with glyphosate, control ratings increased, providing a control at final evaluation of 97% to 99%. In both years, glyphosate applied early postemergence (EPOST), late postemergence (LPOST), and late postemergence directed (LPDIR) provided greater than 95 percent control at final evaluation. Glufosinate applied 0.45 kg ha^{-1} at 1 and 3 WAP or applied at 0.45 kg ha^{-1} following a preemergence herbicide provided greater than 95% control. Glyphosate remained effective for Palmer amaranth control in cotton in these experiments. In addition, glufosinate weed control programs offered effective alternatives to glyphosate for Palmer amaranth control.

Nomenclature: Diuron; flumioxazin; fluometuron; fomesafen; glufosinate; glyphosate; linuron; MSMA; oxyfluorfen; paraquat; pendimethalin; prometryn; S-metolachlor; trifloxysulfuron; Palmer amaranth, *Amaranthus palmeri* S. Wats; cotton, *Gossypium hirsutum* L..

Key words: Weed control, resistant weeds**,** herbicide tolerance, herbicide resistance.

Abbreviations: GR, glyphosate-resistant; PRE, preemergence; EPOST, early postemergence; LPOST, late postemergence; WAP, weeks after planting; LPDIR, late post directed; EPDIR, early post directed; AMAPA, Palmer amaranth.

INTRODUCTION

Palmer amaranth is one of the most common, prolific, and competitive weeds of crops in the southern United States (Klingaman and Oliver 1994). It grows rapidly and can reach 2 m or more in height (Horak and Loughin 2000). It has a high photosynthetic capacity and utilizes the C_4 photosynthetic pathway (Ehleringer 1983). Along with rapid growth, Palmer amaranth has effective drought tolerance mechanisms that allow it to survive and grow during dry conditions (Ehleringer 1983), and it readily adapts to shading (Jha et al. 2008), which allows it to compete under light-limited environments such as dense crop canopies. These characteristics allow Palmer amaranth to establish a competitive dominance for light and space with crops (Monks and Oliver 1988). Once established in fields, Palmer amaranth can be difficult to control due to its rapid growth, competitive ability, and prolific seed production (Keeley et al. 1987). Continued emergence throughout the season, coupled with prolific seed production, allows Palmer amaranth to quickly replenish seed banks if control at final evaluation is not achieved (Keeley et al. 1987; Sellers et al. 2003; Whitaker et al. 2010).

Glyphosate resistant (GR) technology offers an effective weed management tool for crop production in the US. However, the extensive, unprecedented adoption of this technology and associated use of glyphosate has resulted in development of resistant biotypes (Heap 2011). The first confirmed herbicide-resistant Palmer amaranth was in South Carolina in 1989 to dinitroanilines (Gossett et al. 1992) and the first case of GR was confirmed in 2004 in Georgia (Culpepper et al. 2006). To date, Palmer amaranth has become resistant to four herbicide modes of action commonly used in cotton production - dinitroanilines, ALS-inhibitors, photosystem II inhibitors and glycines - with glyphosate resistance confirmed in Georgia, North Carolina, Arkansas, Tennessee, New Mexico, Mississippi, Alabama, Missouri, Louisiana and Illinois (Heap 2011).

A single plant of Palmer amaranth per 9.1 m of row can decrease cotton yield by 13% (Morgan et al. 2001). Glyphosate resistant cotton, released in 1997, allowed for over-the-top application of glyphosate to that crop (Jones and Snipes 1999; Welch et al. 1997). Glyphosate management programs have effectively controlled Palmer amaranth and other weeds in cotton (Culpepper and York 1999; Culpepper et al. 2000; Scott et al. 2002). This effectiveness caused an increase in percentage of cotton planted with glyphosate resistant cultivars to 86% of US hectarage in 2006 (Johnson 2008). However, extensive reliance on glyphosate has led to selection for glyphosate resistant biotypes (Heap 2011).

Preemergence herbicides reduce early season weed interference with cotton growth and often improve season long control of Palmer amaranth (Culpepper and York 1998; Whitaker et al. 2008; Whitaker et al. 2011). Herbicides such as diuron, fluometuron, fomesafen, linuron and pendimethalin can be applied PRE to cotton for residual control of Palmer amaranth. Metolachlor or s-metolachlor may be mixed with glyphosate and applied postermergence to cotton (York and Culpepper, 2009). These herbicides do not have postemergence activity on Palmer amaranth, but the residual activity of metolachlor and *s*-metolachlor have been documented to increase effectiveness of glyphosate applied postemergence to Palmer amaranth in cotton (Clewis et al., 2006). Diuron, flumioxazin, linuron, linuron + diuron, prometryn, or prometryn + trifloxysulfuron can be applied postemergence directed to cotton (Whitaker et al. 2011). These herbicides control small weeds and provide residual control (Askew et al. 2002; Price et al. 2008).

To delay glyphosate or other herbicide resistance in this weed, a proactive and integrated approach to weed management must be pursued. Incorporating different herbicide modes of action into a glyphosate weed control program is part of such an approach. Moreover, genetically modified crops that include glufosinate resistance genes offer a viable alternative for glyphosate resistant crops for broad spectrum weed control, most importantly GR resistant weeds. Therefore, herbicide efficacy experiments were established in 2008 and 2009 in a field heavily infested with Palmer amaranth to determine the efficacy of glyphosate-based herbicide programs that integrate other modes of action and the efficacy of glufosinate based control programs in cotton.

MATERIALS AND METHODS

The experiments were established during 2008 and 2009 in Suffolk, VA in Palmer amaranth infested fields. The two fields were located within 1 km of each other. The field used in 2008 was in continuous cotton production and a cover crop of rye and vetch was established in the fall of 2007. Glyphosate was sprayed in April to kill the cover crop. Rye was killed, but vetch was not adequately controlled. Additional postemergence glyphosate applications eventually killed the vetch, but more rapid control of vetch was obtained with paraquat, which was applied with all preemergence herbicide treatments or with the first glufosinate application. Wheat and double-cropped soybean preceded the cotton crop in 2009. No cover crop was present, but the wheat-soybean residue provided good soil cover. In April 2009, the field was sprayed with glyphosate, 2,4-D, and flumioxazin herbicides to kill existing vegetation. In both years, part of the field was planted to glyphosate-resistant cotton cultivars DP143B2RF in 2008 and

PHY315RF in 2009; and part was planted to glufosinate-resistant cotton cultivars FM1735LLB2 in 2008 and FM958LL in 2009.

Experimental design was a randomized complete block with four replications. Plot area was 3 by 9 m. Herbicides were applied with a CO_2 unicycle sprayer traveling at 4.8 kilometers hour^{-1} and using 80015 flat fan spray tips at 140 liters ha^{-1}and 220 kpa of operating pressure. Plots were rated according to visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing complete control at 2, 4, 5, 7 and 9 WAP in 2008 and 4, 6, 8, and 12 WAP in 2009. Data were subjected to analysis of variance using SAS PROC GLM procedure (SAS 2003). Data were transformed using arcsine square root transformation prior to analysis (Ahrens et al., 2009). Transformed means were separated using Fisher's Protected LSD at $P \leq 0.05$. Non transformed means are reported with interpretation based on transformed data.

Glyphosate-based herbicide programs

Treatments consisted of glyphosate alone or used in combination with preemergence (PRE), postemergence over-the-top, and postemergence-directed herbicides of various modes of action (Tables 4.1 and 4.2). In addition to an untreated control, a single mode of action treatment containing only glyphosate applied early postemergence (EPOST) to 1- to 3-leaf cotton, late postemergence (LPOST) to 3- to 6-leaf cotton, and late post-directed (LPDIR) to 9- to 10-leaf cotton was included. A directed spray was used for the last application to obtain better coverage of weeds. A more integrated total postemergence treatment included an EPOST application of glyphosate tank mixed with s-metolachlor for residual control, followed by a LPOST application of glyphosate, and finally followed by a LPDIR tank mixture of glyphosate + flumioxazin for control of weeds that emerge after the LPOST application. The effect of the PRE herbicides pendimethalin, fomesafen or fluometuron on Palmer amaranth control with glyphosate applied

LPOST was also evaluated. Each of these treatments also included a LPDIR application of glyphosate or glyphosate + flumioxazin. As a way to further extend residual weed control and diversify herbicide modes of action, a PRE fomesafen application followed by glyphosate tank mixed with s-metolachlor LPOST followed by glyphosate + flumioxazin LPDIR was included in the treatment list. The most diverse glyphosate-based herbicide treatments in the experiment included pendimethalin + fomesafen PRE followed by a LPOST application of glyphosate, and then followed by a LPDIR application of fluometuron or prometryn and trifloxysulfuron or oxyfluorfen. Each of the LPDIR applications included MSMA for additional efficacy. Finally, a non-glyphosate program included pendimethalin + fomesafen PRE, an early post-directed (EPDIR) application of fluometuron + MSMA in place of glyphosate LPOST, and oxyfluorfen LPDIR. The EPDIR application was made to 3- to 6-leaf in 2008, but due to complete and extended weed control with pendimethalin + fomesafen in 2009, the application was delayed until 7- to 8-leaf cotton. The control plots received only the pre-plant herbicides described earlier and paraquat PRE. Rates and application timings are listed in Tables 4.1 and 4.2. All postemergence treatments not containing glyphosate included a non-ionic surfactant at 0.25% v/v.

Glufosinate-based herbicide programs

Treatments compared two applications of glufosinate to one glufosinate application following a PRE herbicide. The effectiveness of including s-metolachlor in a tank-mix with glufosinate was also evaluated. To plots not receiving a PRE herbicide, EPOST applications were made 2 WAP to 1- to 2-leaf cotton, and included glufosinate applied alone or tank mixed with *s*-metolachlor. Preemergence herbicides evaluated included pendimethalin, fomesafen and fluometuron applied 5 or 1 day after planting in 2008 or 2009, respectively. All PRE applications included paraquat to control emerged weeds. All treatments received a LPOST application of glufosinate at 3 or 4 WAP in 2008 or 2009, respectively, and made to 2- to 4-leaf cotton. In addition, a post-directed application of flumioxazin + MSMA or diuron and linuron + MSMA, was made in 2008 and 2009, respectively, was made when cotton was 38 to 43 cm tall to prevent additional weed emergence. The untreated control received only the pre-plant applications previously mentioned and paraquat PRE. All herbicide treatments and rates of application can be found in tables 4.3 and 4.4.

RESULTS AND DISCUSSION

Glyphosate-based herbicide systems

Palmer amaranth populations exceeded 50 plants m^{-2} in 2008. In 2009, less than 3 plants m^{-2} were present and most of the plants were within the tilled strip, reflecting the effect of wheat and soybean residue and the pre-plant flumioxazin application. In 2008, treatments that did not include a PRE herbicide provided 0 to 20% control due to variation in Palmer amaranth populations in 2008 (Table 4.1). This variation was largely due to patchy levels of the rye and vetch cover crop, which was observed to provide for some control of Palmer amaranth. In both years, glyphosate treatments controlled all emerged Palmer amaranth plants (Tables 4.1 and 4.2). A slight non-significant drop in control at 5 WAP was noticed in some plots for the glyphosate treatment in 2008 due to additional weed emergence, but was not observed for the glyphosate + s-metolachlor treatment. However, the additional LPDIR application of glyphosate or glyphosate + flumioxazin ensured complete control at final evaluation. Tank-mixtures of glyphosate with s-metolachlor EPOST or flumioxazin LPDIR did not improve control at final evaluation over the total glyphosate program.

All PRE treatments in 2008 provided excellent control, ranging from 92 to 99% at 2 WAP (Table 4.1). By 4 WAP, control with fomesafen fell to 79 to 88%, but control with pendimethalin or fluometuron remained above 90%. Palmer amaranth plants that emerged in plots with PRE pendimethalin or fomesafen treatments were less in number than plots containing fluometuron, but generally looked healthy. In contrast, slightly more escapes were noticed in plots treated with PRE fluometuron than with fomesafen, but plants were stunted and showed typical photosynthetic-inhibitor injury. In 2009, control with PRE fomesafen was complete through 6 WAP and control with fluometuron averaged 87% (Table 4.2). In contrast to 2008, pendimethalin gave virtually no control. Activating rainfall did not occur for over a week after PRE applications, therefore pendimethalin likely photodegraded and/or was lost to volatilization. The dry soils also prevented additional emergence after the PRE herbicide application, however, fomesafen and fluometuron were still present in sufficient levels to afford weed control when activating rainfall was reached. In both years, a LPOST application of glyphosate or glyphosate + s-metolachlor following these PRE herbicides resulted in complete control by 7 WAP.

In 2008, control with pendimethalin + fluometuron PRE was excellent at 2 WAP, but dropped to 71 to 79% by 5 WAP. Postemergence glyphosate followed by LPDIR applications to these treatments resulted in complete control at final evaluation; choice of LPDIR herbicides did not affect control. With this non-glyphosate control program, control at final evaluation was 88% 9 WAP. In 2009, all treatments provided complete control.

Glufosinate-based herbicide systems

Glufosinate applied EPOST at 0.45 kg ai ha^{-1} followed by a LPOST of the same rate provided 95 and 91% control at final evaluation in 2008 and 2009, respectively (Tables 4.3 and 4.4). The addition of s-metolachlor to glufosinate did not improve control over glufosinate alone in 2008, but provided numerically better control in 2009, especially at the 4 and 6 WAP ratings.

In 2008, PRE treatments provided excellent control of Palmer amaranth ranging from 92 to 99 percent at 2 WAP. At 3 WAP, control ratings were less for pendimethalin (73 to 74%) and fomesafen (76-77%). Control with fluometuron at 3 WAP was slightly greater and ranged from 81 to 90%. The combination of pendimethalin and fluometuron or pendimethalin and fomesafen resulted in 85 to 93% control at this time. After the LPOST application of glufosinate or glufosinate mixed with s-metolachlor, control ratings increased to 91 to 99% at 5 WAP. No differences were notable between glufosinate alone and glufosinate mixed with s-metolachlor when following a PRE herbicide. Finally, the LPDIR application of flumioxazin at a rate of 0.07 kg ai ha^{-1} maintained control at final evaluation with a range of 89 to 99 percent control.

In 2009, fomesafen provided better control (94%) than fluometuron (54 to 64%) and pendimethalin (32 to 50%). Under dry weather conditions in 2009 with no rainfall for 1 week after PRE application, pendimethalin had likely dissipated via photodecomposition and/or volatilization. Pendimethalin + fluometuron resulted in better control (72 to 78%) than pendimethalin + fluometuron, but pendimethalin + fomesafen (99%) provided little control advantage over fomesafen alone (94%). Late postemergence application of glufosinate increased control ratings of all plots at 6 WAP. Although control improved, treatments that had low ratings at 4 WAP remained lower than the rest of the treatments. For instance, control with fluometuron improved from 54 to 64 % control at 4 WAP to 72 to 81% control at 6 WAP when followed by the glufosinate application. This is in comparison to control with fomesafen which changed from 94% at 4 WAP to 99% at 6 WAP after the glufosinate application. Similar to 2008 results, tank mixing s-metolachlor with glufosinate did not result in better control. Finally, a late post application of diuron + linuron increased ratings at 10 WAP to an average of 96 percent control excluding fluometuron treatments which provided only 77 % control at 10 WAP.

To summarize the GR cotton results, PRE treatments provided early control of Palmer amaranth ranging from 77 to 99 percent control, excluding pendimethalin (4%) in 2009. Glyphosate treatments provided control at final evaluation of more than 95%. Other LPDIR treatments such as fluometuron, prometryn + trifloxysulfuron, or oxyfluorfen provided similar control to the LPDIR glyphosate treatments. Glyphosate alone provided excellent control of Palmer amaranth in this experiment; however, the use of residual herbicides is advised for prevention or delay of glyphosate resistance and consistent control of Palmer amaranth. Moreover, glufosinate based programs provided good to excellent control of Palmer amaranth, but there was notable variation in control rates between years. In 2008, two postemergence glufosinate applications without a PRE herbicide provided less control than a PRE + LPOST approach at 7 WAP. However, flumioxazin applied as a late post-directed spray minimized any treatment differences. In 2009, the total postemergence approach provided similar control at final evaluation levels to the PRE + LPOST treatments. Control with pendimethalin or fluometuron was not as good as in 2008. Differences were only recorded between treatments that included PRE herbicides and those which did not thus implying the importance of applying a PRE when weather conditions may not favor certain herbicide’s activation. It is important that volatile and photodegradation-prone herbicides such as pendimethalin receive an activating rainfall soon after planting, or control will suffer. Also, the long period between the PRE application of fluometuron and an activating rainfall resulted in less control than in the previous year when rain fell soon after application. Thus, early control of Palmer amaranth is important. Including a PRE herbicide with activity on Palmer amaranth in a glufosinate-based control program reduces risk and usually results in greater season long control.

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Table 4.1. Palmer amaranth control in cotton using glyphosate-based herbicide programs, Suffolk 2008.

Herbicides applied[a]	Rate[b]	Application timing[c]	AMAPA control[de] 2 WAP		4 WAP		5 WAP		7 WAP		9 WAP	
	(kg ae or ai ha^{-1})		% Visual control[f]									
Untreated			20	b	18	d	10	d	20	c	13	c
Glyphosate	0.87	EPOST	13	b	99	a	95	ab	99	a	99	a
Glyphosate	0.87	LPOST										
Glyphosate	0.87	LPDIR										
Glyphosate + s-metolachlor	0.87 + 1.07	EPOST	9	b	99	a	99	a	99	a	99	a
Glyphosate	0.87	LPOST										
Glyphosate + flumioxazin	0.87 + 0.07	PDIR										
Pendimethalin	1.07	PRE	99	a	96	ab	73	c	95	a	97	ab
Glyphosate	0.87	LPOST										
Glyphosate	0.87	LPDIR										
Pendimethalin	1.07	PRE	99	a	95	ab	79	bc	97	a	99	a
Glyphosate	0.87	LPOST										
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR										
Fomesafen	0.28	PRE	94	a	79	abc	60	c	95	a	97	ab
Glyphosate	0.87	LPOST										
Glyphosate	0.87	LPDIR										
Fomesafen	0.28	PRE	99	a	88	abc	76	c	99	a	99	a
Glyphosate	0.87	LPOST										
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR										
Fluometuron	1.12	PRE	99	a	93	ab	80	c	99	a	99	a
Glyphosate	0.87	LPOST										
Glyphosate	0.87	LPDIR										
Fluometuron	1.12	PRE	99	a	94	ab	78	c	99	a	99	a
Glyphosate	0.87	LPOST										
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR										

Table 4.1 (continued).

Herbicides applied[a]	Rate[b]	Application timing[c]	AMAPA control[de] 2 WAP		4 WAP		5 WAP		7 WAP		9 WAP	
	(kg ae or ai ha^{-1})		-------------- % Visual control[f] ----------------									
Fomesafen	0.28	PRE	92	a	79	bc	63	c	98	a	99	a
Glyphosate + s-metolachlor	0.87 + 1.07	LPOST										
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR										
Pendimethalin + fomesafen	1.07 + 0.28	PRE	95	a	92	abc	75	c	99	a	99	a
Glyphosate	0.87	LPOST										
Fluometron	2.24	LPDIR										
Pendimethalin + fomesafen	1.07 + 0.28	PRE	97	a	85	abc	71	c	99	a	99	a
Glyphosate	0.87	LPOST										
Prometryn + trifloxysulfuron	1.33 + 0.012	LPDIR										
Pendimethalin + fomesafen	1.07 + 0.28	PRE	96	a	88	abc	76	c	97	a	98	a
Glyphosate	0.87	LPOST										
Oxyfluorten	0.56	LPDIR										
Pendimethalin + fomesafen	1.07 + 0.28	PRE	99	a	69	c	79	bc	76	bc	88	b
Fluometron	2.24	EPDIR										
Oxyfluorten	0.56	LPDIR										

[a]All preemergence treatments included paraquat at 1.2 kg ai ha^{-1}. All postemergence treatments not containing glyphosate included a non-ionic surfactant at 0.25% (v/v).

[b] Glyphosate rates are listed as acid equivalent (ae). Other herbicide rates are listed as active ingredient (ai).

[c]Application timings: EPOST = 2 weeks after planting (WAP), 1 to 2 leaf cotton; LPOST = 5 WAP, 4 to 5 leaf cotton; EPDIR = 5 WAP, 4 to 5 leaf cotton; LPDIR = 7 WAP, 7 to 9 leaf cotton.

[d] Abbreviations: AMAPA, palmer amaranth.

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

[f] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 4.2. Palmer amaranth control in cotton using glyphosate-based herbicide programs, Suffolk 2009.

Herbicides applied[a]	Rate[b]	Application timing[c]	AMAPA control[de] 4 WAP		6 WAP		8 WAP		10 WAP	
	(kg ae or ai ha^{-1})		% Visual control[f]							
Untreated			0	b	0	c	0	b	0	b
Glyphosate	0.87	EPOST	0	b	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate	0.87	LPDIR								
Glyphosate + s-metolachlor	0.87 + 1.07	EPOST	0	b	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR								
Pendimethalin	1.07	PRE	3	b	10	b	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate	0.87	LPDIR								
Pendimethalin	1.07	PRE	4	b	10	b	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR								
Fomesafen	0.28	PRE	96	a	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate	0.87	LPDIR								
Fomesafen	0.28	PRE	91	a	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR								
Fluometuron	1.12	PRE	92	a	87	a	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate	0.87	LPDIR								
Fluometuron	1.12	PRE	94	a	87	a	99	a	99	a
Glyphosate	0.87	LPOST								
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR								

Table 4.2 (continued).

Herbicides applied[a]	Rate[b]	Application. timing[c]	AMAPA control[de] 4 WAP		6 WAP		8 WAP		10 WAP	
	(kg ae or ai ha^{-1})		------------------ % Visual control[f] --------------------							
Fomesafen	0.28	PRE	91	a	99	a	99	a	99	a
Glyphosate + s-metolachlor	0.87 + 1.07	LPOST								
Glyphosate + flumioxazin	0.87 + 0.07	LPDIR								
Pendimethalin + fomesafen	1.07 + 0.28	PRE	98	a	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Fluometron	2.24	LPDIR								
Pendimethalin + fomesafen	1.07 + 0.28	PRE	98	a	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Prometryn + trifloxysulfuron	1.33 + 0.012	LPDIR								
Pendimethalin + fomesafen	1.07 + 0.28	PRE	96	a	99	a	99	a	99	a
Glyphosate	0.87	LPOST								
Oxyfluorten	0.56	LPDIR								
Pendimethalin + fomesafen	1.07 + 0.28	PRE	98	a	99	a	99	a	99	a
Fluometron	2.24	EPDIR								
Oxyfluorten	0.56	LPDIR								

[a]All preemergence treatments included paraquat at 1.2 kg ai ha^{-1}. All postemergence treatments not containing glyphosate included a non-ionic surfactant at 0.25% (v/v).

[b] Glyphosate rates are listed as acid equivalent (ae). Other herbicide rates are listed as active ingredient (ai).

[c]Application timings: EPOST = 2 weeks after planting (WAP), 1 to 2 leaf cotton; LPOST = 6 WAP, 4 to 5 leaf cotton; EPDIR = 6 WAP, 4 to 5 leaf cotton; LPDIR = 8 WAP, 7 to 9 leaf cotton.

[d] Abbreviations: AMAPA, palmer amaranth.

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

[f] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 4.3. Palmer amaranth control in cotton using glufosinate-based herbicide programs, Suffolk, VA 2008.

Herbicide applied[a]	Rate	Application timing[b]	AMAPA control[cd]									
			2 WAP		3 WAP		5 WAP		7 WAP		9 WAP	
	(kg ai ha^{-1})		--------------------- % Visual control[e] ----------------------									
Untreated			23	b	18	e	10	b	6	e	0	c
Glufosinate	0.45	EPOST	3	c	69	cd	94	a	78	cd	95	ab
Glufosinate	0.45	LPOST										
Glufosinate + s-metolachlor	0.45 + 1.07	EPOST	14	bc	58	d	91	a	73	d	89	b
Glufosinate	0.45	LPOST										
Pendimethalin	1.07	PRE	96	a	74	bcd	98	a	90	abc	99	a
Glufosinate	0.45	LPOST										
Pendimethalin	1.07	PRE	96	a	73	bcd	97	a	85	bcd	99	a
Glufosinate + s-metolachlor	0.45 + 1.07	LPOST										
Fluometuron	1.12	PRE	95	a	81	a-d	99	a	98	a	99	a
Glufosinate	0.45	LPOST										
Fluometuron	1.12	PRE	97	a	90	ab	99	a	97	a	99	a
Glufosinate + s-metolachlor	0.45 + 1.07	LPOST										
Pendimethalin + fluometuron	1.07 + 1.12	PRE	99	a	92	ab	99	a	92	ab	99	a
Glufosinate	0.45	LPOST										
Pendimethalin + fluometuron	1.07 + 1.12	PRE	96	a	87	abc	99	a	98	a	99	a
Glufosinate + s-metolachlor	0.45 + 1.07	LPOST										
Fomesafen	0.28	PRE	98	a	76	a-d	99	a	99	a	99	a
Glufosinate	0.45	LPOST										
Fomesafen	0.28	PRE	97	a	77	a-d	97	a	96	a	99	a
Glufosinate + s-metolachlor	0.45 + 1.07	LPOST										
Pendimethalin + fomesafen	1.07 + 0.28	PRE	99	a	93	a	99	a	98	a	99	a
Glufosinate	0.45	LPOST										
Pendimethalin + fomesafen	1.07 + 0.28	PRE	94	a	85	abc	92	a	89	ab	93	ab
Glufosinate + s-metolachlor	0.45 + 1.07	LPOST										

Table 4.3 (continued).

[a] All PRE treatments included paraquat at 1.2 kg ai ha^{-1}. Flumioxazin at a 0.07 kg ai ha^{-1} was applied to all treatments as a post-directed spray on 2 July to prevent additional weed emergence.

[b] Application timings: EPOST = 2 weeks after planting (WAP), 1 to 2 leaf cotton; LPOST = 3 WAP, 2 to 3 leaf cotton.

[c] Abbreviations: AMAPA, palmer amaranth.

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

[e] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

Table 4.4. Palmer amaranth control in cotton using glufosinate-based herbicide programs, Suffolk, VA 2009.

Herbicide applied[a]	Rate	Application timing[b]	AMAPA Control[cd] 4 WAP		6 WAP		10 WAP	
	(kg ai ha^{-1})		------------------ % Visual control[e] --------------------					
Untreated			0	d	0	e	10	d
Glufosinate Glufosinate	0.45 0.45	EPOST LPOST	84	abc	82	bcd	91	abc
Glufosinate + s-metolachlor Glufosinate	0.45 + 1.07 0.45	EPOST LPOST	95	ab	96	ab	98	a
Pendimethalin Glufosinate	1.07 0.45	PRE LPOST	50	c	99	a	99	a
Pendimethalin Glufosinate + s-metolachlor	1.07 0.45 + 1.07	PRE LPOST	32	d	85	cd	86	c
Fluometuron Glufosinate	1.12 0.45	PRE LPOST	54	c	81	cd	77	c
Fluometuron Glufosinate + s-metolachlor	1.12 0.45 + 1.07	PRE LPOST	64	bc	72	d	78	bc
Pendimethalin + fluometuron Glufosinate	1.07 + 1.12 0.45	PRE LPOST	78	abc	90	a-d	92	abc
Pendimethalin + fluometuron Glufosinate + s-metolachlor	1.07 + 1.12 0.45 + 1.07	PRE LPOST	72	abc	92	abc	96	abc
Fomesafen Glufosinate	0.28 0.45	PRE LPOST	94	ab	99	a	99	a
Fomesafen Glufosinate + s-metolachlor	0.28 0.45 + 1.07	PRE LPOST	94	ab	99	a	97	ab
Pendimethalin + fomesafen Glufosinate	1.07 + 0.28 0.45	PRE LPOST	99	a	99	a	97	ab
Pendimethalin + fomesafen Glufosinate + s-metolachlor	1.07 + 0.28 0.45 + 1.07	PRE LPOST	99	a	99	a	99	a

Table 4.4 (continued).

[a] All PRE treatments included paraquat at 1.2 kg ai ha^{-1}. Diuron + linuron 0.56 + 0.56 kg ai ha^{-1}, respectively, was applied to all treatments as a post-directed spray on 2 July to prevent additional weed emergence.

[b] Application timings: EPOST = 2 weeks after planting (WAP), 1 to 2 leaf cotton; LPOST = 4 WAP, 2 to 3 leaf cotton.

[c] Abbreviations: AMAPA, palmer amaranth.

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

[e] Visual evaluation of total biomass on a scale of 0 to 100 with 0 representing no control and 100 representing the complete control .

CHAPTER V

Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri* S. Wats) Confirmed in Virginia

ABSTRACT

Palmer amaranth resistance to glyphosate has been confirmed in ten states including Virginia's bordering neighbor North Carolina. In Greensville County, VA, glyphosate applications of 0.87, 0.87, and 1.74 kg ae ha^{-1} at 1, 3, and 5 weeks after planting provided only 80% season-long control. Plants grown from seed obtained from a Palmer amaranth infested field were compared to a biotype known to be susceptible to glyphosate in two greenhouse experiments. In the first experiment, the susceptible biotype's I_{50} value for fresh weight was 0.34 kg ae ha^{-1} of glyphosate while the resistant biotype's I_{50} value was 1.60 kg ae ha^{-1}, which is 4.7 times greater than the susceptible biotype and 1.6 times the recommended use rate of glyphosate. In the second experiment, the I_{50} value for the susceptible population could not be determined because all glyphosate rates resulted in complete control. However, the resistant population required 1.01 and 1.30 kg ae $ha^{-1}$of glyphosate to reduce the fresh and dry weight by 50%, respectively. Visual rating, height, and dry weight data reflected similar I_{50} values to fresh weight. This research confirms that a Palmer amaranth biotype from Greensville County, VA is resistant to glyphosate.

Nomenclature: Glyphosate; Palmer amaranth, *Amaranthus palmeri* S. Wats.

Key words: Weed control, resistant weeds**,** herbicide tolerance, herbicide resistant.

Abbreviations: GR, glyphosate-resistant; WAT, weeks after treatment; I_{50} value, rate necessary for 50% inhibition**.**

INTRODUCTION

Glyphosate resistance has been confirmed in 21 weed species around the world (Heap 2011). The first instance of Palmer amaranth resistance to glyphosate was confirmed in 2004 in Georgia (Culpepper 2006). Glyphosate resistance was later confirmed with this weed in North Carolina, Arkansas, Tennessee, New Mexico, Mississippi, Alabama, Missouri, Louisiana and Illinois (Heap 2011). Previous research confirmed Palmer amaranth resistance to three other herbicide modes of action (dinitroanalinines, ALS-inhibitors, and photosystem II inhibitors) (Gosset et al. 1992; Sprague et al.1997; Horak et al. 1995). In Virginia, Palmer amaranth has been documented in 15 counties (Chapter 2), but will likely enlarge its territory. Its spread can be rapid because of custom harvesting; failing to clean vehicles and equipment after exiting infested fields and failing to hand remove escapes. There are currently populations of ALS resistant Palmer amaranth in Virginia and it was not controlled with three applications of glyphosate, totaling 3.36 kg ae ha^{-1} in Greensville County in 2009 (Chapter 3).

In Georgia, glyphosate applied to 5- to 13-cm-tall Palmer amaranth at three times the normal use rate of 0.87 kg ae ha^{-1} resulted in only 17% control. The biotype was controlled 82% by glyphosate at 12 times the normal use rate (Culpeper et al. 2006). In Arkansas, LD_{50} values were similar among three susceptible Palmer amaranth accessions, ranging from 0.24 to 0.36 kg ae ha^{-1} glyphosate, but a resistant biotype had an LD_{50} of 2.82 kg ha^{-1} of glyphosate, which was 79- to 115-fold greater than that of the susceptible biotypes and 3.4 times a normal glyphosate-use rate of 0.87 kg ha^{-1} (Norsworthy et al. 2008).

Because Palmer amaranth is considered to be one of the most problematic weeds in agronomic crops in southern US states, the lack of control with economic rates of glyphosate and continued spread of glyphosate resistance will negatively affect crop production in Virginia.

Therefore, greenhouse studies were conducted to confirm our field observations that suggested the presence of a resistant Palmer amaranth population in Greensville County, Virginia, and to specifically quantify the level of glyphosate resistance of this population.

MATERIALS AND METHODS

Mature seed were collected from a herbicide efficacy experiment planted to soybean in Greensville County, VA (Chapter 3). Seed were collected before soybean harvest in 2009 from the control plot that received no glyphosate and a plot in which glyphosate failed to control Palmer amaranth. In the glyphosate-treated plot, glyphosate was applied at 0.87 kg ae ha^{-1} one week after planting soybean and was supplemented with an additional 0.87 kg ae ha^{-1} of glyphosate at three weeks after planting. Because these treatments did not control all Palmer amaranth plants in the plot, another application of 1.66 kg ae ha^{-1} of glyphosate was applied at five weeks after planting.

In April 2010, the two seed collections were cleaned and planted in separate 52 by 27 by 6 cm flats containing commercial potting soil (Metro-mix®, Bellevue, WA). The flats were placed in a greenhouse at the Glade Road Research Center of Virginia Tech for a preliminary study to assess glyphosate resistance levels. When seedlings were approximately 4 cm tall (2 to 3 leaves), 18 plants from each flat were transplanted into 11 cm pots with one plant per pot. Seedlings were grown under a 12-h photoperiod with supplemental lighting of approximately 450 µmol m^{-2} s^{-1} and were maintained at 22 to 27 ^{o}C. Palmer amaranth plants were allowed to acclimate from transplanting and watered as needed. Glyphosate was applied at 0, 0.21, 0.43, 0.87, 1.74, and 3.48 kg ae ha^{-1} to 7.5 to 9 cm tall (5 to 7 leaves) to Palmer amaranth plants with a stationary track sprayer containing a single even-edge nozzle tip that delivered 230 L ha^{-1} of spray solution at 270 kPa. The plants were not irrigated for 24 h after herbicide application to prevent herbicide washoff. The experiment was arranged in a randomized complete block design with three replicates. Palmer amaranth vigor reduction was visually rated on a scale of 0 (no effect) to 10 (death of plant) at 7, 12, and 19 days after treatment (DAT), and plant height was determined at the same intervals. Plants were harvested 30 DAT, and fresh weights were collected.

Two additional greenhouse experiments were established at the Tidewater Agricultural and Extension Research Center, in Suffolk, VA in February and March 2011. Seed collected from the glyphosate treated plots in Greensville County were used in this experiment, and will hereafter be referred to as the Greensville biotype. Glyphosate-susceptible Palmer amaranth seed were purchased from a known seed source (Azlin Seed Service, Leland, MS). Plants derived from these seed will hereafter be referred to as the susceptible biotype. Seeds were planted separately in flats of 52 by 27 by 6 cm containing commercial potting soil (Miracle Grow®, Marysville, OH) and transplanted into 15 cm pots at the 3 to 4 leaf stage (4 to 5 cm tall). Palmer amaranth plants were allowed to acclimate from transplanting and watered as needed.

The experiment was a completely randomized design with four replications of six glyphosate rates at 0, 0.21, 0.43, 0.87, 1.74, 3.48 and 6.96 kg ae ha^{-1}. The 0.21 rate corresponded to one-fourth of the recommended glyphosate rate of 0.87 kg ai ha^{-1} and the greatest rate corresponded to 8 times the recommended rate. Palmer amaranth plants were carried outside the greenhouse to a designated spray area, where glyphosate was applied to five- to seven-leaf stage (7- to 10-cm tall) Palmer amaranth using a CO_2 unicycle sprayer traveling at 4.8 km $hour^{-1}$ and using 80015 flat fan spray tips at 140 L ha^{-1} and 220 kpa operating pressure. Spraying was applied when wind speed was less than 3 mph. Plants were not irrigated for 24 h after herbicide application to prevent herbicide washoff. After treatment, plants were returned to the greenhouse with 30/15 C day/night temperatures for the first experiment and 35/15 C day/night for the second experiment. The plants were provided 16-h photoperiod using supplemental florescent lighting and water for an additional 28 days. Plants were visually rated for weed control at 1, 2, 3, and 4 weeks after treatment (WAT) on a scale of 0 to 100, with 0 representing no control and 100 representing complete control. Height measurements were also recorded. At 4 weeks the plants were clipped to record fresh weight, and then dried for dry weight measurement. Height, fresh weight, and dry weight measurements were converted to percent of control for statistical analysis.

For each biotype in each experiment, all data were fit to a two-parameter log-logistic model of the form:

$$y = 100 / [1 + (r / I_{50})^{\beta}] = 100 / \{1 + \exp [\beta * (\log r - \log I_{50})] \} [1]$$

where y is the parameter % of control at rate r; β is the slope at the I_{50} value; and I_{50} is the glyphosate application rate necessary for 50% inhibition. This is a special case of the four-parameter log-logistic model, recommended by Seefeldt et al. (1995) and used by Hite et. al (2008), and was fit with the SAS PROC NLIN procedure. The model provides an estimation of the parameter I_{50} and slope (β) at the I_{50} value. In addition to parameter estimates, standard errors and 95% confidence intervals are provided by the nonlinear regression procedure.

RESULTS AND DISCUSSION

In the preliminary experiment, differences were observed between the plants grown from the seed collected from the control plot and those collected from the glyphosate treated plot (Table 5.1). Glyphosate applications failed to completely control either population even at the 3.3 kg ae ha^{-1} rate. The I_{50} value for fresh weight at 4 WAT for the treated population was 5.9 kg ae ha^{-1}, while that of the check plot population was 3.13 kg ae ha^{-1}. Differences in I_{50} values likely occurred because the seed collected from the control plot represented a population which included more susceptible plants since it had not been sprayed whereas the seed collected from the treated plot represented a herbicide selected population of resistant plants after surviving glyphosate applications of 0.87, 0.87, and 1.74 kg ae ha^{-1} at 1, 3 and 5 weeks after planting. The seed collected from the treated plot were used in the following experiments since they better represent a resistant biotype.

In both experiments conducted in Suffolk, VA, the Greensville biotype was more resistant to glyphosate than the susceptible biotype (Tables 5.2 and 5.3). This can be better inferred from the I_{50} values generated by nonlinear regression of visual control, height, dry weight and fresh weight (Table 5.4, Fig. 5.1). In the first experiment, the I_{50} of the Greensville biotype for visual control was 2.87, 1.60, 2.32 and 2.09 kg ae ha^{-1} while the I_{50} for the susceptible biotype was 0.34, 0.32, 0.31 and 0.32 kg ae ha^{-1} at 1, 2, 3 and 4 WAT, respectively. Furthermore, there is only 1.76 to 3.66% increase in control for every kg ha^{-1} increase in glyphosate rate (represented by β or the slope of the equation) for the Greensville biotype at those I_{50} values. In comparison, there was 85% or greater increase in control for every kg ha^{-1} increase in glyphosate rate at the I_{50} value for the susceptible biotype. The I_{50} for plant height at 1, 2, 3 and 4 WAT was similar to the ratings; values for the resistant biotype were 3.25, 1.89, 2.48 and 2.51 kg ae ha^{-1}, respectively, compared to 0.39, 0.32, 0.33 and 0.34 kg ae ha^{-1}, respectively, for the susceptible biotype. Finally, the I_{50} values for fresh and dry weights were 1.60 and 1.47 kg ae ha^{-1}, respectively, for the resistant biotype and 0.32 and 0.32 kg ae ha^{-1}, respectively, for the susceptible one. At the I_{50} values, height and weight were declining 59 to 96% for every kg ha^{-1} increase in glyphosate rate for the susceptible biotype. This is a much greater rate of decline than for the Greenville biotype which ranged from 1.7 to 3.7%. Complete control of Palmer amaranth plants was not achieved at 8 times the recommended rate as some resistant plants survived. These results show that the rates needed for 50% inhibition of the resistant biotype ranged from 4.5 to 8 times the rate required for 50% inhibition of the susceptible biotype and 1.7 to 3.7 times the recommended glyphosate use rate of 0.87 kg ae ha^{-1} (Table 5.4).

In the second experiment, both biotypes showed more sensitivity to glyphosate and the susceptible biotype plants were killed by all tested glyphosate rates (Table 5.3). This increased sensitivity may be a result of elevated temperatures during the month of May. The greenhouse used did not have a cooling mechanism other than side and top air panels, thus allowing temperature maximum to reach 35 ^{o}C. As all glyphosate rates effectively killed the susceptible biotype in the second experiment, the I_{50} value could not be calculated, but evidently falls between zero and the lowest tested glyphosate rate of 0.21 kg ae ha^{-1}. Despite increased glyphosate sensitivity, I_{50} values for the Greensville biotype was similar to the values calculated for the Greensville biotype in the first experiment (Table 5.4). The I_{50} values for visual control of the resistant biotype were 1.25, 0.81. 0.87 and 0.96 kg ae ha^{-1} at 1, 2, 3, and 4 WAT, respectively, while I_{50} values for plant height were 0.48, 0.94, 1.20 and 1.17 kg ae ha^{-1} at 1, 2, 3, and 4 WAT, respectively. Moreover, the I_{50} value for fresh weight of the resistant biotype was 1.01 kg ae ha^{-1} and the I_{50} value for dry weight was 1.30 kg ae ha^{-1}. All I_{50} values at 4 WAT were higher than the recommended glyphosate use rate, ranging from 1.1 to 1.5 times the recommended rate. The rate of increase in control for every kg ha^{-1} increase in glyphosate rate for the Greensville biotype in this experiment at those I_{50} values ranged from 1.4% to 2.7%.

The level of resistance reported in these experiments is greater than to the level of resistance (I_{50} = 0.56 kg ae ha^{-1} for resistant biotype) reported for Palmer amaranth in Georgia (Culpepper et al. 2006) but much less than the levels reported in Arkansas (LD_{50}= 2.82 kg ae ha^{-1} for resistant biotype) (Norsworthy 2008). However, as Norsworthy concludes in his study, it is not necessarily appropriate to compare levels of resistance across populations when experiments are conducted under differing environmental conditions using different susceptible standards.

This research confirms that a Palmer amaranth biotype from Greensville County, VA, is resistant to glyphosate. Therefore, glyphosate is no longer a stand-alone option for control of this biotype. The greater rates required for Palmer amaranth control indicates that increasing herbicide rates will not be an economical option for control of this population. Instead, integrating preemergence and/or postemergence herbicides, cover crops, or tillage with a glyphosate-based weed control program may be more effective. One should also entertain other alternatives such as rotation to another crop and/or away from a glyphosate-based program.

LITERATURE CITED

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York, A. C., J. R. Whitaker, A. S. Culpepper, and C. L. Main. 2007. Glyphosate-resistant Palmer amaranth in the southeastern United States. p. 225. In Proc. South. Weed Science Soc., Nashville, TN. 22-24 Jan. 2007. Southern Weed Science Soc., Champaign, IL.

Table 5.1. Control ratings, height, fresh weight and dry weight measurements for Palmer amaranth grown from seed collected from Greensville County, VA in 2009.

	Glyphosate rate	Control rating (%)			Height (cm)			Fresh weight (g)	Dry weight (g)
	(kg ae ha^{-1})	1 WAT	2 WAT	3 WAT	1 WAT	2 WAT	3 WAT	3 WAT	3 WAT
Unsprayed population (Seed collected from experimental check plot that had no glyphosate applied to it, but was in the infested field)	0.0	0.0	0.3	1.0	11.3	23.0	26.7	13.4	2.3
	0.2	0.3	1.0	2.7	10.7	20.7	20.7	15.6	2.8
	0.4	3.7	2.3	5.7	6.3	17.0	17.2	12.4	1.9
	0.8	1.3	3.0	3.7	9.0	13.7	12.3	12.0	1.3
	1.7	7.0	8.3	8.0	3.2	3.0	0.0	0.0	0.0
	3.3	8.0	8.3	7.7	2.7	3.0	4.2	9.6	0.2
Sprayed population (Seed collected from plot with 3 applications of glyphosate at 0.87, 0.87 and 1.74 kg ae ha^{-1})	0.0	0.0	3.3	2.7	11.7	13.0	22.4	14.4	2.0
	0.2	0.3	3.7	1.7	12.0	14.5	24.1	15.1	2.2
	0.4	0.3	6.0	2.0	12.3	12.3	26.2	13.6	2.1
	0.8	2.0	4.3	3.3	10.3	12.5	14.4	11.5	1.2
	1.7	6.3	7.3	6.3	6.0	5.3	5.0	8.7	0.3
	3.3	9.3	6.3	6.7	2.0	4.8	8.0	11.5	0.8

[a] Abbreviation: WAT, weeks after treatment.

Table 5.2. Control of susceptible and Greensville Palmer amaranth biotypes. The greenhouse experiment was established in the Tidewater Agricultural and Extension Research Center, in Suffolk, VA in February 2011.

Biotype[a]	Glyphosate rate (kg ae ha^{-1})	Visual control (%)				Height (cm)				Fresh weight (g)	Dry weight (g)
		1 WAT[b]	2 WAT	3 WAT	4 WAT	1 WAT	2 WAT	3 WAT	4 WAT	4 WAT	
Susceptible	0	0	0	0	0	7.2	10.3	19.7	28.4	8.7	1.7
	0.2	0	0	0	0	8.6	13.4	26	37.5	9.5	2
	0.4	81.3	100	100	100	1.4	0	0	0	0	0
	0.8	85	100	100	100	1.6	0	0	0	0	0
	1.7	90	100	100	100	0.5	0	0	0	0	0
	3.3	91.3	100	100	100	0.8	0	0	0	0	0
	6.6	93.8	100	100	100	0	0	0	0	0	0
Greensville	0	0	0	0	0	8.1	12.1	16.8	21.3	6.6	1.5
	0.2	0	5	0	0	7.7	11.9	20.4	26.6	5.7	1.2
	0.4	0	12.5	7.5	0	6.4	11	19	24.5	6.7	1.5
	0.8	0	22.5	7.5	0	8	10.9	18.2	23.3	5.8	1.3
	1.7	25	48.8	22.5	40	6.9	7	13.3	16.8	3	0.6
	3.3	63.8	80	80	75	3	2.4	4.1	4.8	1.1	0.3
	6.6	76.3	96.3	95	96.3	2.2	1.2	0	1.4	0.1	0

[a] The seed for the susceptible biotype were obtained from Azlin Seed Service, Leland, MS. The seed for the Greensville biotype were collected from an experimental plot in Greensville County, VA with 3 applications of glyphosate at 0.87, 0.87 and 1.74 kg ae ha^{-1}.

[b] Abbreviations: WAT, weeks after treatment.

Table 5.3. Control of susceptible and Greensville Palmer amaranth biotypes. This greenhouse experiment was a repetition of the 1st experiment and was also established in the Tidewater Agricultural and Extension Research Center, in Suffolk, VA in March 2011.

Biotype[a]	Glyphosate rate (kg ae ha^{-1})	Visual control (%)				Height (cm)				Fresh weight (g)	Dry weight (g)
		1 WAT[b]	2 WAT	3 WAT	4 WAT	1 WAT	2 WAT	3 WAT	4 WAT	4 WAT	
Susceptible	0	0	0	0	0	19.3	23.8	29.3	35.6	15.2	8.3
	0.2	97.5	100	100	100	1.3	0	0	0	0	0
	0.4	100	100	100	100	0	0	0	0	0	0
	0.8	92.5	100	100	100	2	0	0	0	0	0
	1.7	100	100	100	100	0	0	0	0	0	0
	3.3	100	100	100	100	0	0	0	0	0	0
	6.6	100	100	100	100	0	0	0	0	0	0
Greensville	0	0	1.3	0	0	13	18	21.4	26.9	13.3	7.6
	0.2	23.8	25	25	25	14.1	19.1	26.9	33.3	12.1	6.4
	0.4	3.8	25	20	18.8	12.2	14.7	21	26.4	10.7	7.2
	0.8	38.8	42.5	40	32.5	7.8	9.2	15.5	19.3	8.4	5.3
	1.7	50	71.3	72.5	73.8	7.8	6.2	6.3	7.5	4.2	3.3
	3.3	93.8	98.8	100	100	1.8	0	0	0	0	0
	6.6	98.8	98.8	100	100	0	0	0	0	0	0

[a] The seed for the susceptible biotype were obtained from Azlin Seed Service, Leland, MS. The seed for the Greensville biotype were collected from an experimental plot in Greensville County, VA with 3 applications of glyphosate at 0.87, 0.87 and 1.74 kg ae ha $^{-1}$.

[b] Abbreviations: WAT, weeks after treatment.

Table 5.4. I_{50} and slope estimates at I_{50} value derived from nonlinear regression for Palmer amaranth measurements collected in response to glyphosate rate of application.

	Experiment 1				Experiment 2	
	Greensville biotype[a]		Susceptible biotype		Greensville biotype	
	I_{50}	Slope	I_{50}	Slope	I_{50}	Slope
Control 1 WAT[b]	2.87	2.04	0.34	9.03	1.25	1.66
Control 2 WAT	1.60	1.76	0.32	85.84	0.81	1.41
Control 3 WAT	2.32	3.66	0.31	88.72	0.87	1.59
Control 4 WAT	2.09	2.76	0.32	85.84	0.96	1.76
Height 1 WAT	3.25	-1.92	0.39	-59.47	0.48	-1.69
Height 2 WAT	1.89	-2.37	0.32	-76.94	0.94	-1.87
Height 3 WAT	2.48	-3.77	0.33	-86.44	1.20	-2.71
Height 4 WAT	2.51	-3.45	0.33	-88.56	1.17	-2.74
Fresh Weight 4 WAT	1.60	-2.88	0.34	-96.02	1.01	-1.78
Dry Weight 4 WAT	1.47	-3.55	0.32	-97.64	1.30	-2.10

[a] The seed for the susceptible biotype were obtained from Azlin Seed Service, Leland, MS. The seed for the Greensville biotype were collected from an experimental plot in Greensville County, VA with 3 applications of glyphosate at 0.87, 0.87 and 1.74 kg ae ha $^{-1}$.

[b] Abbreviations: WAT, weeks after treatment.

Figure 5.1. Log-logistic regression relationships for Palmer amaranth visual control and plant height percentages at 4 WAT as a function of glyphosate application rate for the resistant and the susceptible biotypes in the 1st experiment and the repetition experiment, both established in the Tidewater Agricultural and Extension Research Center, in Suffolk, VA in February and March of 2011, respectively.

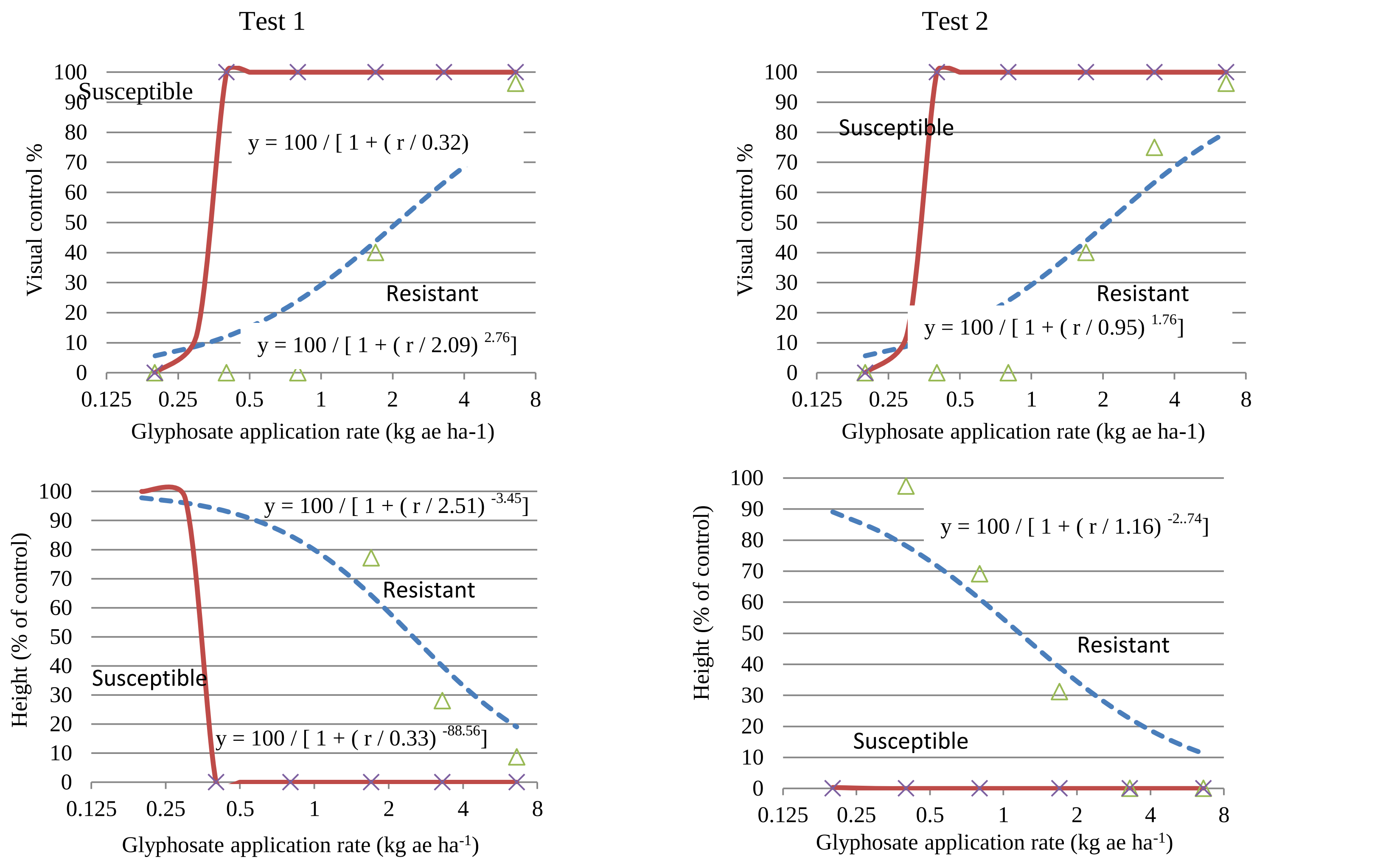
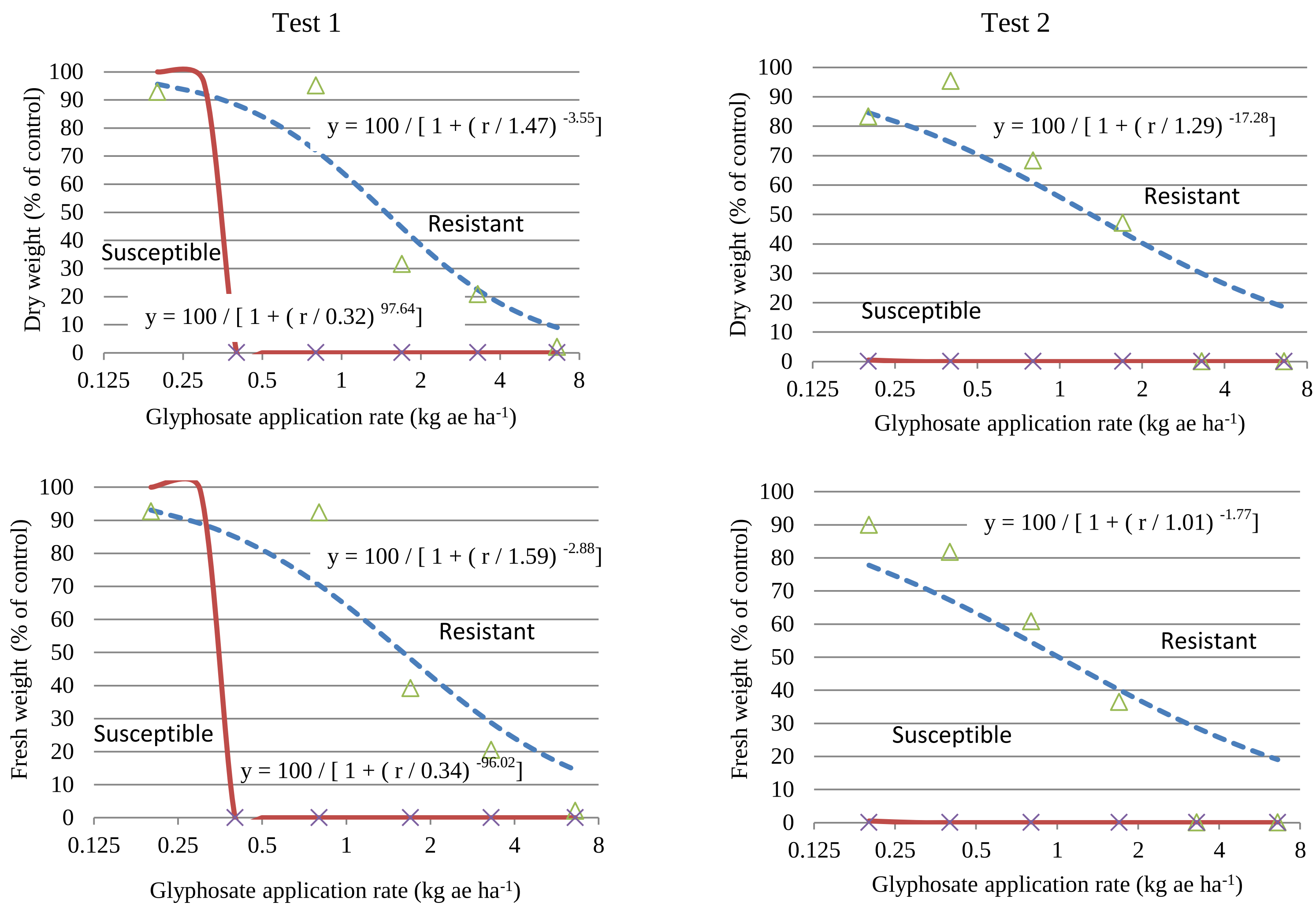


Figure 5.1 (Continued).



SOURCES OF MATERIAL

1. Acifluorfen, Ultra Blazer herbicide. United phosphorus Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406.
2. Ammonium sulfate. Fisher Scientific, 1 Reagent Lane, Fair Lawn, NJ 07410.
3. Bentazon, Basagran herbicide. Arysta lifescience, North America, LLC, 15401 Weston Parkway, Suite 150, Cary, NC, 27513.
4. Chlorimuron + Thifensulfuron, Synchrony XP. Dupont Crop Protection Co., Inc. Wilmington, DE 19898.
5. Chlorimuron ethyl + flumioxazin + thifensulfuron methyl, Envive herbicide. E. I. DuPont de Nemours and Company, 1007 Market Street, Wilmington, Delaware 19898.
6. Crop oil concentrate, Agri-Dex Spray Adjuvant. Helena Chemical Co., Collierville, TN 38017.
7. Fluazifop-P-butyl + Fenoxaprop-P-ethyl, Fusion herbicide. Syngenta Crop Protection Inc., Greensboro, NC 27409.
8. Flumioxazin + chlorimuron, Valor XLT herbicide.Valent U.S.A. Corporation, Walnut Creek, CA 94596-8025.
9. Flumioxazin, Valor SX herbicide. Valent U.S.A. Corporation, Walnut Creek, CA 94596-8025.

10. Fluometuron, Cotoran herbicide. Makhteshim Agan of North America, Inc. 4515 Falls of Neuse Road, Suite 300, Raleigh NC 27609.
11. Fomesafen, Reflex herbicide. Syngenta Crop Protection Inc., Greensboro, NC 27409.
12. Glufosinate, Ignite 280 herbicide. Bayer Cropscience, P.O. Box 12014, T.W. Alexander Dr., Research Triangle Park, NC 27709.
13. Glyphosate + imazethapyr, Extreme herbicide. BASF Corporation. 26 Davis Drive, Research Triangle Park, NC 27709.
14. Glyphosate, Roundup Weathermax herbicide. Monsanto Company, St. Louis, MO 63167.
15. Imazethapyr, Pursuit herbicide. BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709.
16. Liberty Link cotton (Fibermax FM1735LLB2 in 2008; Fibermax FM958LL in 2009). Bayer Cropscience, P.O. Box 12014, T.W. Alexander Dr., Research Triangle Park, NC 27709.
17. Liberty Link soybean variety Southern States LL499N, Southern States Cooperative, Inc. 6606 West Broad St., Richmond, VA 23230-1717.
18. Linuron, Linex herbicide. Tessenderlo Kerley Inc., 2255 N. 44th street, Suite 300, Phoenix, AZ 85008.
19. Metribuzin + chlorimuron ethyl, Canopy herbicide. E. I. Du Pont de Nemours and Company, 1007 Market Street, Wilmington, Delaware 19898.

20. Metribuzin + chlorimuron, Canopy herbicide. Dupont Crop Protection Co., Inc. Wilmington, DE 19898.

21. Metribuzin, Sencor herbicide. Bayer Cropscience, P.O. Box 12014, T.W. Alexander Dr., Research Triangle Park, NC 27709.

22. Metro-mix® soil mix, Sun Gro Horticulture. 15831 NE 8th Street, Suite 100, Bellevue, WA 98008.

23. Miracle-Gro® soil mix. World Headquarters, 14111 Scottslawn Road, Marysville, Ohio 43041.

24. Oxyfluorten, Goal herbicide. Dow agrosciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268.

25. Paraquat, Gramoxone Inteon herbicide. Syngenta Crop Protection Inc., P.O. Box 18300, Greensboro, NC 27419.

26. Pendimethalin, Prowl H2O herbicide. BASF Ag. Products, Research Triangle Park, NC 27709.

27. Premier Promix, Premier Horticulture Inc., 127 South 5th Street, #300, Quakerstown, PA 18951.

28. Prometryn + trifloxysulfuron, Suprend herbicide. Syngenta Crop Protection Inc., Greensboro, NC 27409.

29. Roundup Ready soybean Southern States variety RT 5760N,Southern States Cooperative, Inc. 6606 West Broad St., Richmond, VA 23230-1717
30. Roundup Ready soybean Southern States variety RT 5760N. Southern States Cooperative, Inc. 6606 West Broad St., Richmond, VA 23230-1717.
31. Saflufenacil, Sharpen herbicide. BASF Corporation. 26 Davis Drive, Research Triangle Park, NC 27709.
32. SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513.
33. S-metolachlor + fomesafen, Prefix herbicide. Syngenta Crop Protection, Inc. P. O. Box 18300 Greensboro, North Carolina 27419-8300
34. S-metolachlor + metribuzin, Boundary herbicide. Syngenta Crop Protection Inc., Greensboro, NC 27409.
35. S-metolachlor, Dual Magnum herbicide. Syngenta Crop Protection Inc., Greensboro, NC 27409.
36. Spray table, Allen Machine Works, 607 E. Miller Road, Midland, MI 48640.
37. Statistical Analysis Systems, version 9.1, SAS Institute Inc., SAS Campus Drive, Cary, NC, 27513.
38. Sulfentrazone + cloransulam, Sonic herbicide. Dow AgroSciences LLC • Indianapolis, IN 46268 U.S.A.

39. Sulfentrazone + imazethapyr, Authority Assist herbicide. FMC Corporation, Agricultural Products Group, 1735 Market Street, Philadelphia PA 19103.
40. Sulfentrazone + metribuzin, Authority MTZ herbicide. FMC Corporation, Agricultural Products Group, 1735 Market Street, Philadelphia PA 19103.
41. Supplemental lighting, Sunlight Supply, Inc., 5408 NE 88th Street, Vancouver, WA 98665.
42. Teejet 80015 flat fan spray nozzles, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189.
43. Thifensulfuron-methyl, Harmony SG herbicide. Dupont Crop Protection Co., Inc. Wilmington, DE 19898.