ABSTRACT

HOFFNER, AMY E. Distribution of Herbicide-Resistant Palmer Amaranth (*Amaranthus palmeri*) in North Carolina and Management in Soybean (*Glycine max*). (Under the direction of Co-Advisors, Drs. David L. Jordan and Alan C. York).

Palmer amaranth (*Amaranthus palmeri*) has become one of the most problematic weeds to control in the southeastern United States due to the rapid growth characteristics of this weed with crops and development of herbicide-resistant biotypes, including those resistant to glyphosate and acetolactate synthase (ALS)-inhibiting herbicides. A survey was conducted during fall 2010 to determine distribution of Palmer amaranth across the Coastal Plain and Piedmont of North Carolina and to evaluate these accessions for resistance to fomesafen, glufosinate, glyphosate, and thifensulfuron-methyl. Palmer amaranth was found in 126 of 242 predetermined sites and expressed resistance to glyphosate and thifensulfuron-methyl in 98% and 85% of populations, respectively. Resistance to fomesafen was not observed in these accessions while one accession was suggestive of glufosinate resistance. The survey reveals the widespread prevalence of glyphosate and resistant Palmer amaranth in North Carolina.

Experiments were conducted during 2010 and 2011 to compare Palmer amaranth control, soybean yield, and estimated economic return when glyphosate or glufosinate was applied postemergence following no preemergence herbicides, *S*-metolachlor or *S*-metolachlor plus fomesafen to the appropriate soybean cultivar in soybean at populations of approximately 178,000 or 483,000 plants ha^{-1}. Palmer amaranth control, soybean yield, and estimated economic return often increased as the intensity of the herbicide program increased and as the soybean population increased. As expected, when glyphosate-resistant Palmer amaranth was present, glufosinate was more effective than glyphosate in controlling Palmer amaranth.

In other experiments, sequential applications of preemergence herbicides followed by glufosinate or multiple applications of glufosinate alone were generally more effective than preemergence herbicides alone or single applications of glufosinate in controlling Palmer amaranth. Results from this research can be used to further refine strategies including herbicides and cultural practices in controlling Palmer amaranth and protecting soybean yield.

Distribution of Herbicide-Resistant Palmer Amaranth (*Amaranthus palmeri*) in North Carolina and Management in Soybean (*Glycine max*)

by

Amy E. Hoffner

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Masters of Science

Crop Science

Raleigh, North Carolina

2012

APPROVED BY:

Dr. David Jordan, Co-Chair	Dr. Alan York, Co-Chair
Dr. Jim Dunphy	Dr. Wesley Everman

DEDICATION

I would like to dedicate this to my family, especially my parents, Alan and Connie Hoffner; and to Justin Poirier for their never-ending support and belief in me.

BIOGRAPHY

Amy Hoffner was born on a dairy farm in rural Mount Ulla, North Carolina. Amy was a lot more interested in horses than agriculture growing up, but when her brother transitioned the dairy into certified organic production, a whole new world of agriculture opened up to her. While gaining her Bachelor's degree in Animal Science from North Carolina State University, she began working for the Organic Cropping Systems Lab in the Crop Science department at NCSU. Working for the Organic Lab introduced her to crop research and convinced her to pursue a Master's degree studying weed science under Dr. David Jordan.

ACKNOWLEDGMENTS

I would like to express immense gratitude to all those who made my life a little easier along the way. First of all I would like to thank my parents, Alan and Connie Hoffner. And I would like to thank Justin Poirier, who has been my rock these last few years.

I would also like to thank Dr. David Jordan and Dr. Alan York for bearing with me and allowing me to continue my education while under their direction. And I would like to thank Dr. Jim Dunphy and Dr. Wesley Everman for serving on my committee.

Last, but definitely not least, I would like to send an enormous thank you to Rick Seagroves, Peter Eure, Charlie Cahoon, Samuel Wells and to those who provided technical assistance to a degree I could never have otherwise met. I would especially like to thank Jamie Hinton for providing help anytime I needed it and for keeping my spirits high when I needed it the most.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Distribution and Herbicide Resistance of Palmer Amaranth (*Amaranthus Palmeri*) in North Carolina

Amy E. Hoffner, Alan C. York, David L. Jordan, and Wesley J. Everman*

ABSTRACT

Glyphosate resistance in Palmer amaranth has increased dramatically across the southern United States. A survey conducted in 2005 detected that 17% of fields sampled in North Carolina contained glyphosate-resistant Palmer amaranth. During the fall of 2010, a total of 242 predetermined sites in North Carolina were surveyed to determine distribution of Palmer amaranth and to determine if and where resistance to fomesafen, glufosinate, glyphosate, and thifensulfuron-methyl occured. Palmer amaranth was present at 126 sites. Ninety-eight percent of Palmer amaranth populations were glyphosate-resistant. No apparent resistance was noted for fomesafen while one population was suggestive of glufosinate resistance. Eighty-five percent of populations expressed resistance to thifensulfuron-methyl. Results

*First, second, third, and fourth authors: Graduate Research Assistant, William Neal Reynolds Professor Emeritis, Professor, and Assistant Professor, Department of Crop Science, North Carolina State University, Campus Box 7620, Raleigh, NC 27695.

from this survey reveal the scope of resistance to glyphosate and acetolactate synthase-inhibiting herbicides in North Carolina.

Nomenclature: Fomesafen; glufosinate; glyphosate; thifensulfuron-methyl; Palmer amaranth *Amaranthus palmeri* S. Wats.

Key Words: weed survey.

INTRODUCTION

The vast majority of corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] in North Carolina is currently planted with glyphosate-resistant cultivars or hybrids (Owen et al. 2011). Glyphosate has often been applied multiple times during a growing season and for several consecutive years with few other herbicides included. This approach, while providing excellent weed control in most instances (Culpepper and York 1998), has placed unprecedented selection pressure on weed communities and has contributed to an ecological weed shift (Shaw et al. 2010).

Glyphosate resistance in Palmer amaranth was first confirmed in North Carolina in populations collected during 2005 (Culpepper et al. 2008; Whitaker 2009). Levels of resistance varied by population, with some populations requiring over 20 times more glyphosate to reduce shoot fresh weight 50% as compared with susceptible populations (Whitaker 2009). Glyphosate-resistant Palmer amaranth is now common across the Southeast and Mid-South regions of the United States (Heap 2012).

Palmer amaranth is currently one of the most common and troublesome weeds in many southern states due to its competitive nature and resistance to multiple herbicides (Heap 2012; Webster 2009). A survey was conducted in the fall of 2005 to determine the extent and distribution of glyphosate-resistant Palmer amaranth in North Carolina (Culpepper et al. 2008). It is generally accepted that glyphosate-resistant Palmer amaranth has become more common and more widespread since 2005. To observe the change in the extent and distribution of the problem, a survey was conducted in fall of 2010, 5 years after the initial confirmation of resistance. Determining how distribution of glyphosate-resistant Palmer amaranth has changed since 2005 and determining if resistance to other herbicides has increased will be important in assisting growers develop of effective management strategies to control this weed. Therefore, objectives were to (1) determine the distribution of glyphosate-resistant biotypes of Palmer amaranth compared with the distribution in 2005, and (2) determine if resistance to fomesafen, glufosinate, and thifensulfuron-methyl is present in these Palmer amaranth populations.

MATERIALS AND METHODS

During the fall of 2010, a survey was administered across the Coastal Plain and Piedmont regions of North Carolina using a grid sampling procedure. A total of 242 predetermined sites were selected (Figure 1). Some sites were in forests, pastures, swamps, or residential areas, and no Palmer amaranth was present. If no Palmer amaranth was found at the pre-designated site, an effort was made to survey surrounding areas within a 1.61 km radius. A total of 126 Palmer amaranth populations were sampled from soybean and cotton fields.

Plants from seed collected at these sites were grown in a greenhouse in four pots (7.5 by 12 cm) per herbicide rate using a commercial growing medium (Metro Mix 200®, Scotts-Sierra Horticultural Products Company, Marysville, OH 43044). A known glyphosate-susceptible and a known glyphosate-resistant populations were included for comparison in the experiment with glyphosate (Whitaker 2009). Each pot was fertilized with a water soluble fertilizer (Peters Professional® Water Soluble 20-20-20 Fertilizer, Scotts-Sierra Horticultural Products Company, Marysville, OH 43044) 10 and 20 d after emergence. Irrigation was applied using automatic sprinklers.

When Palmer amaranth was 10 to 15 cm in height, in separate experiments plants were treated with the potassium salt of glyphosate (Roundup Weathermax herbicide®, Monsanto Co. St. Louis, MO 63167) at 0, 280, 560, and 840 g ae ha^{-1}, glufosinate-ammonium (Ignite 280 herbicide®, Bayer CropScience, Research Triangle Park, NC 27709) at 430, 860, and 1290 g ae ha^{-1}, fomesafen (Reflex herbicide® Syngenta Crop Protection, Greensboro, NC 27709) at 280, 560, and 8400 g ae ha^{-1}, and thifensulfuron-methyl (Harmony GT herbicide®, E. I. DuPont de Nemours and Co., Wilmington, DE 19898) at 4.4, 18, and 70 g ae ha^{-1}. Glufosinate and thifensulfuron-methyl were applied with nonionic surfactant (Induce® adjuvant, Helena Chemical Co., Collierville, TN 38017) at 0.25% (v/v). Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 145 L ha^{-1} (glyphosate) at 275 kPa and 187 L ha^{-1} (fomesafen, glufosinate, thifensulfuron-methyl) at 375 kPa using regular flat-fan nozzles (TeeJet TP 11002 flat-fan spray nozzles, TeeJet Corp., Wheaton, IL 60189). Rates selected in these experiments included the manufacturer's suggested use rate for soybean: glyphosate (840 g ha^{-1}), glufosinate (60 g ha^{-1}), fomesafen

(280 g ha^{-1}), and thifensulfuron-methyl (4.5 g ha^{-1}) (Anonymous 2012a, 2012b, 2012c, 2012d). Pots contained 4 to 6 plants, treatments were replicated four times, and the experiment was repeated with each herbicide. The number of surviving plants was recorded 14 d after fomesafen, glufosinate, and glyphosate were applied and 28 days after thifensulfuron-methyl application.

RESULTS AND DISCUSSION

Compared to 2005, Palmer amaranth was more readily found in the far eastern and northeastern counties in 2010 (Figures 2 and 3). Palmer amaranth was also much more readily found in the Piedmont in 2010 compared with 2005. Glyphosate resistance was found in 98% of the 126 Palmer amaranth-infested fields sampled in 2010 (Figure 3). Whitaker (2009) reported that the Palmer amaranth in 18% of 290 fields expressed resistance to glyphosate during 2005, primarily in Wayne, Duplin, Sampson, Hoke, Robeson, and Scotland counties (Figure 4). Susceptible biotypes were found in only one field in Duplin County and one field in Iredell County in 2010 (Figure 3). Similar to 2005 (Whitaker 2008), populations in 2010 varied in response to glyphosate. At some sites, all plants screened were resistant to the highest rate of glyphosate whereas in other populations some plants were killed by the lowest rate, and some plants survived the highest rate suggesting continued segregation of populations (data not shown). All plants in the known susceptible biotype were killed completely by glyphosate at the lowest rate (data not shown).

It is acknowledged that the survey was biased toward finding glyphosate resistance. With approximately 95% of the cotton and soybean planted in North Carolina being glyphosate-tolerant, odds were high that fields sampled had been treated with glyphosate, thus increasing the probability that glyphosate resistance would be found. Nevertheless, the results indicate that glyphosate-resistant biotypes of Palmer amaranth have become much more common and widespread since the initial discovery in 2005 with Palmer amaranth from 18% of fields sampled expressing resistance.

With the exception of occasional plants not being controlled completely when fomesafen was applied at 280 or 560 g ha^{-1}, Palmer amaranth was controlled completely by fomesafen at 840 g ha^{-1} (data not shown). Although subjective, plant response to fomesafen at lower rates appeared to be representative of a typical rate response to fomesafen for susceptible plants rather than a reflection of resistance. Also, the vast majority of Palmer amaranth plants showed no indication of resistance to glufosinate. However, one population had one plant that was not controlled by glufosinate compared with complete control of other plants, although response was inconsistent across experimental runs. This plant expressed little symptomology associated with glufosinate. Seed from these plants will be used to confirm resistance in this population, although it is possible that incomplete control was caused by factors other than resistance. Of the 126 sites with Palmer amaranth present during 2010, 85% survived thifensulfuron-methyl at 70 g ha^{-1}, a rate approximately 16 times the rate generally applied to non-STS cultivars to control weeds in soybean (Figure 5). However, resistance was not expressed homogenously within and across populations (data not shown). Whitaker (2009) reported that 17% of samples collected during 2005 expressed resistance to thifensulfuron-methyl.

Collectively, these results document the widespread presence of glyphosate- and ALS-inhibitor-resistance across North Carolina. Although there appears to be no resistance to fomesafen, one plant from one population of Palmer amaranth escaped glufosinate in one run, suggesting possible glufosinate resistance. Although Palmer amaranth resistance to protoporphyrinogen oxidase (PPO) inhibitors like fomesafen has not been reported elsewhere (Heap 2012) and was not found in the populations screened here, absence of evidence of resistance does not establish that resistant alleles are not present in these populations. Approximately 12,000 plants were screened for resistance to each herbicide when considering the number of populations, herbicide rates, number of plants per experimental unit, number of replications, and repeating the experiment. Initial frequency of herbicide resistance would be expected to be very low (Preston and Powles 2002), especially given weed control failures with fomesafen and glufosinate associated with possible resistance have not been reported. Initial frequency of resistance is postulated to be several orders of magnitude lower than the number of plants screened in this research (Preston and Powles 2002). Therefore, while herbicide-resistant alleles may be present in these populations, the frequency may be at levels below those detectable using this screening procedure.

ACKNOWLEDGMENTS

This research was supported by the North Carolina Soybean Growers Association and the North Carolina Cotton Producers Association. Charlie Cahoon, Peter Eure, Jamie Hinton, and Rick Seagroves provided technical assistance.

LITERATURE CITED

Anonymous. 2012a. Roundup Weathermax. Monsanto Co., St. Louis, MO.

Anonymous. 2012b. Ignite 280 herbicide label. Bayer CropScience, Research Triangle Park, NC.

Anonymous. 2012c. Reflex herbicide label. Syngenta Crop Protection, Greensboro, NC.

Anonymous. 2012d. Harmony GT herbicide label. E. I. DuPont de Nemours and Co., Wilmington, DE.

Culpepper, A. S., J. R. Whitaker, A. W. MacRae, and A.C. York. 2008. Distribution of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. J. Cotton Sci. 12:306-310.

Culpepper A. S. and A. C. York. 1998. Weed management in glyphosate-tolerant cotton. J. Cotton Sci. 2:174-185.

Heap, I. 2012. International survey of herbicide resistant weeds. Available at http://www.weedscience.org.

Owen, M.D.K., B. G. Young, D. R. Shaw, R. G. Wilson, D. L. Jordan, P. M. Dixon, and S. C. Weller. 2011. Benchmark study on glyphosate-resistant crop systems in the United States. Part 2: Perspectives. Pest Manag. Sci. DOI 10.1002/ps.2159.

Preston, C. and S. B. Powles. 2002. Evolution of herbicide resistance in weeds: initial frequency of target site-based resistance to acetolactate synthase-inhibiting herbicides in *Lolium rigidum*. Heredity. 88:8-13.

Shaw, D. R., M.D.K. Owen, P. M. Dixon, S. C. Weller, B. G. Young, R. G. Wilson, and D. L. Jordan. 2010. Benchmark study on glyphosate-resistant cropping systems in the

United States. Part 1: Introduction to 2006-2008. Pest Manag. Sci. DOI 10.1002/ps.2160.

Webster, T. M. 2005. Weed Survey – southern states: broadleaf crop subsection. Proc. South. Weed Sci. Soc. 62:517-520.

Whitaker, J. R. 2009. Distribution, biology, and management of glyphosate-resistant Palmer amaranth in North Carolina. PhD thesis. Raleigh, NC: North Carolina State University. 245p.

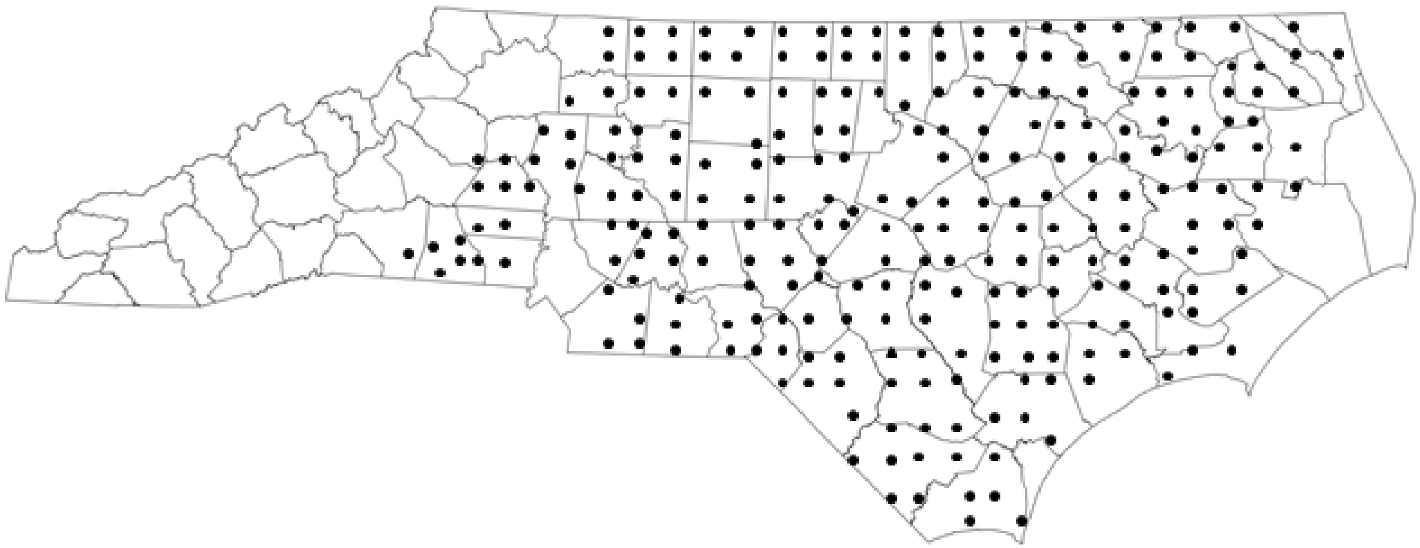

Figure 1. Location of 242 predetermined sites visited during September and October 2010 to document Palmer amaranth and collect seed if present.

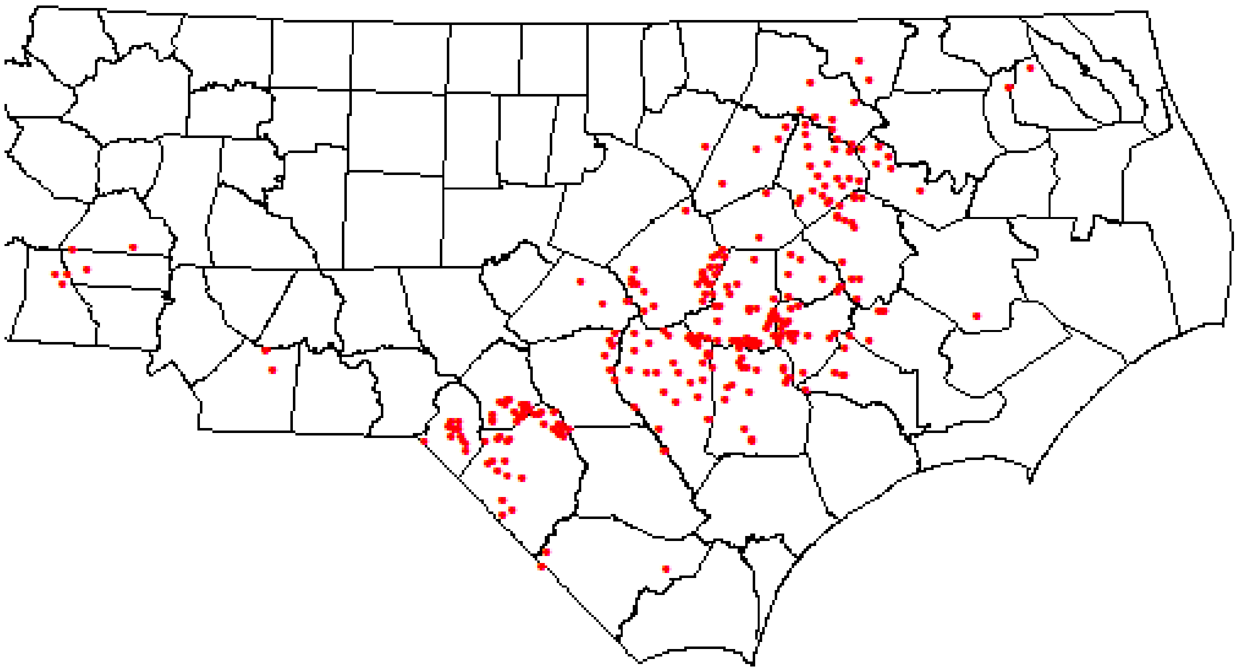

Figure 2. Locations of 290 fields surveyed during September and October 2005 to document Palmer amaranth and collect seed. Data are from Whitaker (2009).

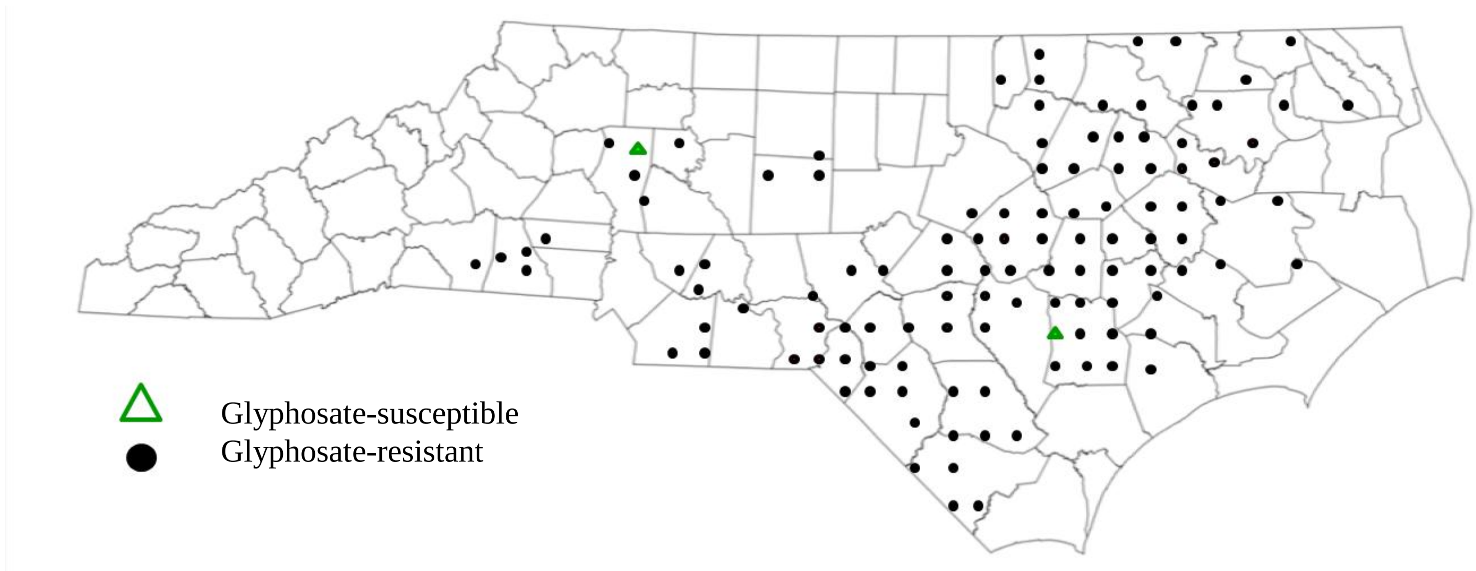

Figure 3. Location of 126 sites in North Carolina where glyphosate-resistant populations of Palmer amaranth were observed during 2010.

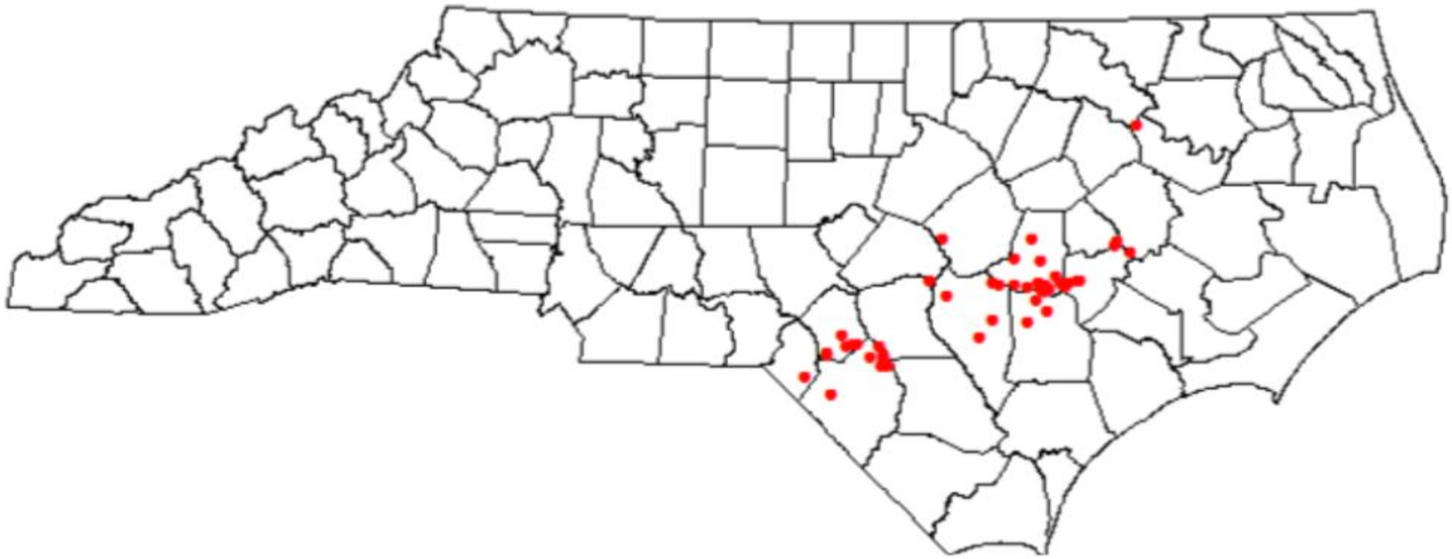

Figure 4. Location of 49 fields in North Carolina with glyphosate-resistant populations of Palmer amaranth during 2005. Data are from Whitaker (2009).

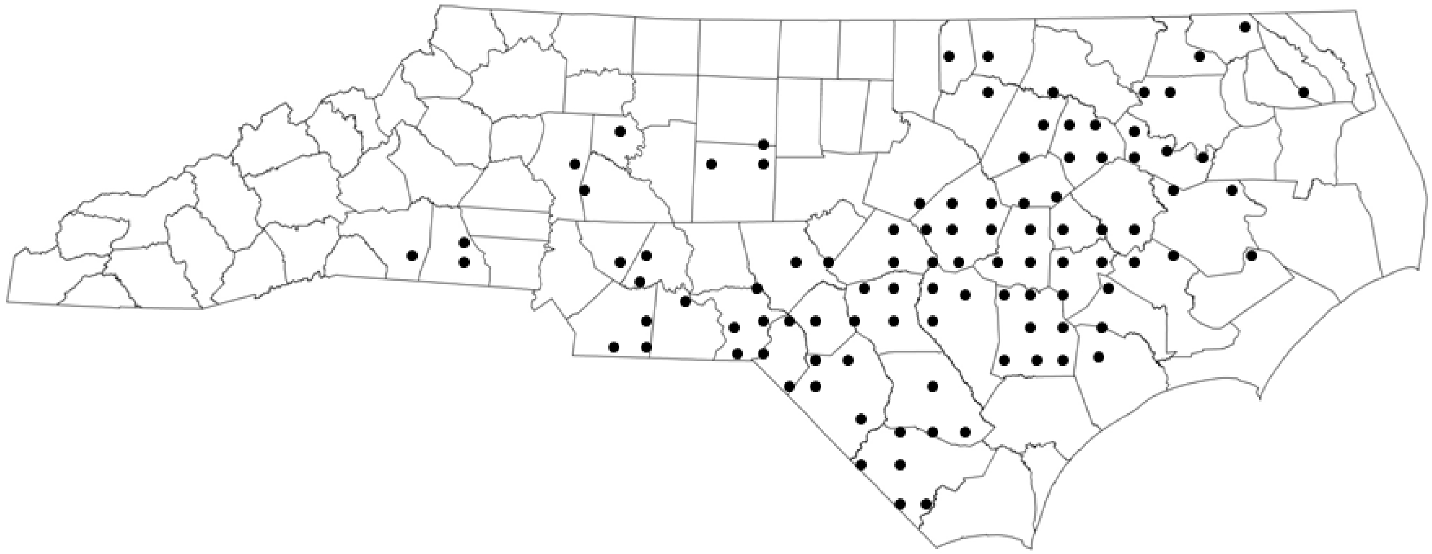

Figure 5. Location of 101 sites in North Carolina where ALS inhibitor-resistant populations of Palmer amaranth were observed during 2010.

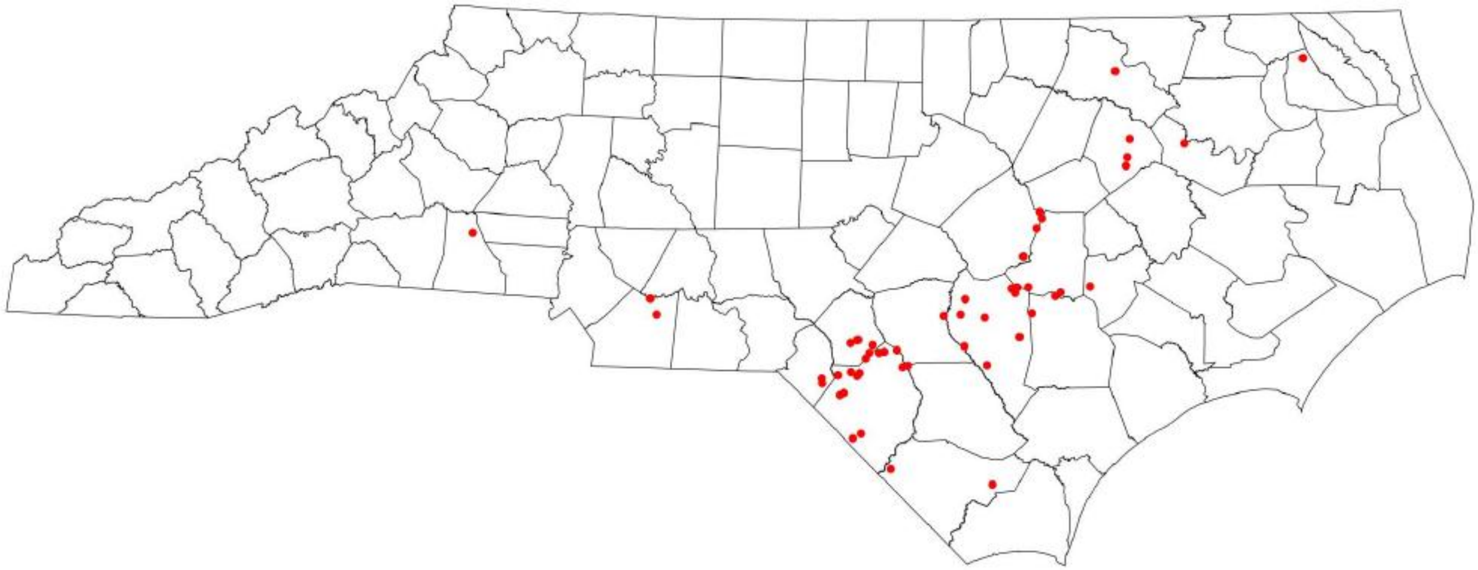

Figure 6. Location of 52 fields in North Carolina with ALS-inhibitor-resistant populations of Palmer amaranth during 2005.

CHAPTER 2

Influence of Soybean Population and Herbicide Program on Palmer Amaranth (*Amaranthus palmeri*) Control, Soybean (*Glycine max*) Yield, and Economic Return

Amy E. Hoffner, David L. Jordan, Alan C. York, E. James Dunphy, and Wesley J. Everman*

ABSTRACT

Palmer amaranth has become one of the most prominent and difficult weeds to control in soybean in North Carolina. A survey was conducted in North Carolina during fall 2010 to estimate the magnitude of this problem. Palmer amaranth was present in 39% of 2,512 fields representing 0.24% of soybean ha in North Carolina. In recent years, growers have reduced soybean seeding rates in an effort to decrease production costs. However, given the increase in prevalence of Palmer amaranth and the difficultly in controlling this weed due to herbicide resistance, growers may need to re-consider reductions in seeding rates. Therefore, research was conducted during 2010 and 2011 to determine if Palmer amaranth control, soybean yield, and economic return were affected by soybean plant population, preemergence (PRE) and postemergence (POST) herbicides, and herbicide resistant traits (glufosinate-resistant

---

*First, second, third, fourth, and fifth authors: Graduate Research Assistant, Professor, William Neal Reynolds Professor Emeritis, Professor, and Assistant Professor, Department of Crop Science, North Carolina State University, Campus Box 7620, Raleigh, NC 27695.

and glyphosate-resistant cultivars). Applying PRE or POST herbicides and increasing soybean population increased Palmer amaranth control, soybean yield, and economic return when compared with POST herbicides only or when lower soybean populations were present. Efficacy of glufosinate and glyphosate did not vary in most instances, most likely because these herbicides were applied timely and the frequency of glyphosate resistance did not exceed 10% in these fields.

Nomenclature: Fomesafen; glufosinate; glyphosate; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Wats.; soybean, *Glycine max* L. Merr.

Key Words: Glyphosate resistance, integrated weed management, seeding rate.

INTRODUCTION

Effective weed management continues to be an important component of profitable soybean [*Glycine max* (L.) Merr.] production in North Carolina. In recent years, herbicide-resistant weed populations have developed and have limited the effectiveness of herbicide options for growers. Populations of Palmer amaranth (*Amaranthus palmeri* S. Wats) and horseweed (*Conyza canadensis* L.) in the coastal plain of North Carolina resistant to glyphosate have been confirmed (1, 2). Resistance to acetolactate synthase (ALS)-inhibiting herbicides also has been confirmed in North Carolina (1, 2). Managing herbicide-resistant weed populations continues to be a challenge, especially Palmer amaranth, where alternatives to glyphosate and ALS-inhibiting herbicides require timely application (3, 4). During fall 2010, 242 specific sites were sampled in North Carolina to determine the geographical range of Palmer amaranth and to determine if these populations were resistant to glyphosate. Of these specific sites, 52% had Palmer amaranth present with 98% of these populations expressing resistance to glyphosate and 85% expressing resistance to thifensulfuron-methyl (5). Glyphosate-resistant Palmer amaranth has become the most challenging weed in cotton (*Gossypium hirsutum* L.) and soybean production in the southeastern United States (6, 7, 8).

Cultural practices, such as cultivar selection, row pattern, and plant populations, can influence weed management (9, 10). Residual herbicides applied PRE and POST herbicides other than glyphosate are important in managing glyphosate-resistant Palmer amaranth in soybean (11, 12, 13). Glufosinate applied to glufosinate-resistant cultivars is an alternative to glyphosate for control of Palmer amaranth. Developing a strategy for controlling Palmer amaranth that is as sustainable and effective as programs in glyphosate-resistant crops has become one of the most important weed management challenges in the southeastern United States (11, 12, 13).

In North Carolina, soybean at populations below those established in many fields yield as well as higher populations considered "standard" by the farming community (Dunphy, E.J., personal communication). Reducing input costs in soybean by using lower seeding rates, especially when transgenic cultivars are planted which include substantial technology fees, is a reasonable approach to soybean production. While research has demonstrated that higher plant populations and narrow rows suppress weeds more effectively than lower plant populations or production in wider row spacings (14, 15, 16, 17), Norsworthy and Oliver (18) reported that applying a second application of glyphosate was more economical than increasing the seeding rate. Kratochvil et al. (19) reported that a population 80% of a traditional seeding rate (345,000 plants ha^{-1} vs. 432,500 seed ha^{-1}) increased profit \$14 to \$28 ha^{-1}. However, under high populations of weeds, and most especially glyphosate-resistant Palmer amaranth, there is concern that lower populations will be susceptible to greater weed interference and possibly lower yield. Owen (12) indicated that increased difficulty in controlling weeds with glyphosate most likely will occur due to prolonged use of glyphosate. Guillermo et al. (14) suggested that higher seeding rates should be used in fields where weeds are difficult to control due to shifts in populations or development of herbicide resistance within weed communities. Given that Palmer amaranth resistance to glyphosate has increased dramatically in North Carolina (5), research is needed to better define the role of seeding rate on weed management programs for soybean. Therefore, research was conducted at five locations in North Carolina during 2010 and 2011 to compare Palmer amaranth control, soybean yield, and economic return with combinations of PRE and POST herbicides applied to glufosinate- and glyphosate-resistant cultivars at two soybean populations. A survey of fields to determine the extent of Palmer amaranth infestation also was conducted during 2010 within the latter portion of the growing season.

MATERIALS AND METHODS

Survey of Soybean Fields in North Carolina. A total of 2,512 soybean fields in North Carolina were surveyed during 2010 from mid-August through September to determine the extent of Palmer amaranth escapes. This pool of fields represents 0.24% of the 62,700 ha of soybean harvested in North Carolina during 2010 (20). The procedure involved estimating the percentage of total ha within each field with at least one Palmer amaranth plant present. The survey did not involve walking or driving across soybean fields but was a result of viewing the field from one side. Although the average field size in the survey was 6.2 ha, this procedure most likely under estimated infestation in some fields. The percentage of ha with Palmer amaranth was grouped into fields with up to 50% of ha infested and fields with more than 50% of ha infested.

Interactions of Plant Population, Herbicide Resistant Trait, and Herbicide Program. The experiment was conducted in five fields in North Carolina during 2010 and 2011 at the Upper Coastal Plain Research Station near Rocky Mount in fields with natural and relatively high populations of Palmer amaranth. The experiment was conducted during both years in one field (referred to as Field B13) consisting of a Lynchburg fine sandy loam soil (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults). The experiment was also conducted in Field E2 (2010) and Field E3 (2011) consisting of the same soil series. A final experiment in 2011 was conducted in Field C11 consisting of a Nahunta loam (fine-silty, siliceous, subactive, thermic Aeric Paleaquults). Soybean was planted after disking and field cultivation in rows spaced 20 cm apart. Plot size was 12 rows by 9 m in length. In 2010, soil moisture conditions were marginal for soybean emergence at planting and resulted in lower than desired populations but adequate for production. Soil conditions at planting during 2011 were very dry and fields were irrigated with a traveling gun system delivering 1.5 cm within 3 d after planting to ensure uniform emergence.

Treatments consisted of two levels of herbicide resistance trait (cultivars expressing either glyphosate- or glufosinate-resistance) (HRT), two levels of soybean population (referred to as low or high), three levels of PRE herbicide (none, *S*-metolachlor, *S*-metolachlor plus fomesafen), and two levels of POST herbicide (none and a single POST application). The glufosinate-resistant cultivar was LL 595 N (Southern States Cooperative, Inc., 9120 W. Marlboro St., Farmville, NC 27828). The glyphosate-resistant cultivar was AG5605 (Monsanto Company, St. Louis, MO 63107). *S*-metolachlor (Dual II Magnum® herbicide, Syngenta Crop Protection, Greensboro, NC 27709) and *S*-metolachlor plus fomesafen (Prefix® herbicide, Syngenta Crop Protection, Greensboro, NC 27709) were applied at 1500 and 1200 + 270 g ae ha^{-1}, respectively. Glufosinate-ammonium (Ignite 280® herbicide, Bayer CropScience, Research Triangle Park, NC 27709) and potassium salt of glyphosate (Roundup PowerMAX™ herbicide Monsanto Company, St. Louis, MO 63107) were applied at 560 g and 840 g ae ha^{-1}, respectively. Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 145 L ha^{-1} using 8002 regular flat-fan nozzles (Teejet Corporation, Wheaton, IL 60187) at 275 kPa. Planting dates, dates of herbicide application, and soybean populations are listed in Table 1.

Soybean and Palmer amaranth densities were determined 2 weeks after planting immediately prior to POST herbicide application by counting plants in two, 0.5-m randomly selected areas within each plot (Tables 1 and 2). Visible estimates of percent Palmer amaranth control were recorded 2 and 8 weeks after planting using a scale of 0 to 100, where 0 = no control and 100 = complete control. Soybean yield was determined, and estimated economic return was calculated based on North Carolina Cooperative Extension Service enterprise budgets (21). Seed, overhead, management, and weed control costs were removed from the budget to establish a base production cost of \$393 ha^{-1}. Appropriate seed, herbicide, and application costs were then added based on treatments in the experiment. Seed cost was determined based on \$99 ha^{-1} for a seeding rate of 345,800 plants ha^{-1}. Cost of *S*-metolachlor, *S*-metolachlor plus fomesafen, glufosinate, and glyphosate were set at \$41 ha^{-1},

$42 ha^{-1}, $45 ha^{-1}, and $15 ha^{-1}, respectively. Application cost was $9.88 ha^{-1}. Soybean price was set at $0.44 kg^{-1}.

The experimental design was a split-plot with HRT serving as whole plot units and combinations of soybean populations and herbicide treatments serving as sub-plot units. Treatments were replicated four times. Data for Palmer amaranth control, soybean yield, and estimated economic return were subjected to ANOVA using the Proc GLM procedure in SAS (SAS Institute, GLM Procedure, 100 Campus Drive, Cary, NC 27513) by experiment (combination of field and year) for a two (HRT) by two (soybean population) by three (PRE herbicide treatment) by two (POST herbicide treatment) factorial arrangement of treatments. Palmer amaranth control 2 weeks after POST herbicide application generally reflected control 8 weeks after POST herbicide application and will be the only visible ratings discussed. Significant year and field interactions were noted for Palmer amaranth control, soybean yield, and estimated economic return. Therefore, data are presented individually by year/field combination. Means of significant main effects and interactions were separated using Fisher's Protected LSD test at $p \leq 0.05$. Main effects and interactions not stated in the text exceeded $p = 0.05$

RESULTS AND DISCUSSION

Survey of Soybean fields in North Carolina. The percentage of ha within the 2,512 fields with at least one Palmer amaranth plant in the field was estimated to be 39% with 61% not having Palmer amaranth present (data not shown in tables). The percentage of fields with between 1 and 50% of ha infested was 22% while 17% of fields was infested at a level of 51 to 100% by Palmer amaranth (data not presented in tables). Results from this survey, combined with those of Hoffner et al. (5), reveal the magnitude of Palmer amaranth infestation in North Carolina.

Interactions of Plant Population, Herbicide Resistant Trait, and Herbicide Program. Palmer amaranth population in absence of PRE herbicides ranged from 74 to 165 plants m^{-2} (Table 2). When *S*-metolachlor or *S*-metolachlor plus fomesafen were applied, the Palmer amaranth population decreased to 10 plants m^{-2} or less. No difference in Palmer amaranth density was noted when comparing *S*-metolachlor and *S*-metolachlor plus fomesafen. When activated by rainfall or irrigation, these herbicides often control Palmer amaranth for several weeks during the season (22).

The interaction of soybean population by POST herbicide was significant for Palmer amaranth control in Field E2 during 2010. When pooled over HRT and PRE herbicides, control was 50 to 55% without POST herbicides (data not shown in tables). Applying a POST herbicide to the low seeding rate increased control to 81%, while the combination of the high seeding rate and POST herbicide controlled Palmer amaranth 94% (data not shown in tables). Soybean population also influenced the interaction of PRE herbicide and HRT in this field. In absence of PRE herbicides, Palmer amaranth was controlled more effectively when glufosinate was applied in the high population compared with the low population (Table 3). The most effective control in this HRT was *S*-metolachlor plus fomesafen in the high population. Although PRE herbicides increased control when glyphosate was applied, control was not affected by soybean population (Table 3). In contrast to these results, soybean population did not interact with HRT or herbicide treatments in fields B13 and C11. When pooled over HRT and PRE and POST herbicides, Palmer amaranth control was greater in Fields B13 (2010) and C11 (2011) when soybean was planted at a higher population compared with control at lower soybean populations (control of 75% vs. 64% and 72% vs. 67%, respectively, data not shown in tables).

An interaction of PRE by POST by HRT was observed in Field E2 during 2010. In the absence of POST herbicides, Palmer amaranth control by *S*-metolachlor exceeded that of no PRE herbicide while *S*-metolachlor plus fomesafen was more effective than *S*-metolachlor alone (Table 4). Applying glufosinate or glyphosate after a residual PRE herbicide increased control over each POST herbicide alone.

In Fields B13 during both years and Field C11 in 2011, the interaction of PRE and POST herbicide was significant for Palmer amaranth control. *S*-metolachlor plus fomesafen was more effective than *S*-metolachlor alone in 2 of 3 fields when POST herbicides were not applied and in 1 of 3 fields when POST herbicides were applied (Table 5). As expected, impact of PRE herbicides on Palmer amaranth control was minimized when POST herbicides were applied compared with no POST herbicide, although control increased in 2 of 3 fields when *S*-metolachlor plus fomesafen was applied compared with no PRE herbicide.

The interaction of POST herbicides and HRT was significant for Palmer amaranth control in Field B13 during 2010. When pooled over soybean populations and PRE herbicides, Palmer amaranth control increased from 57% to 81% (glufosinate) and 43% to 94% (glyphosate) (data not shown in tables). Additionally, the value of PRE herbicides was noted for both HRT, with *S*-metolachlor plus fomesafen being the most effective PRE treatment (Table 6).

In Field E3 during 2011, the interaction of soybean population, PRE herbicide, POST herbicide, and HRT was significant for Palmer amaranth control. Increasing the soybean population increased Palmer amaranth control from 83 to 85% to 98% when *S*-metolachlor was applied alone (Table 7). This response was not observed when POST herbicides were applied. *S*-metolachlor plus fomesafen controlled Palmer amaranth at least 95% regardless of soybean population or POST herbicides.

Soybean yield during 2010 was low compared with yield during 2011 due to dry conditions throughout most of the growing season. Soybean yield was higher in Fields E2 during 2010 and Field E3 during 2011 when the soybean population increased independent of PRE or POST herbicides and HRT (Table 8). Applying *S*-metolachlor alone or with fomesafen increased yield over no PRE in each of these fields. Increasing the soybean population increased estimated economic return for Field E3 during 2011 (Table 9). Applying *S*-metolachlor or *S*-metolachlor plus fomesafen increased estimated economic return over no PRE treatment. Additionally, applying a POST herbicide increased estimated economic return (Table 9).

Soybean yield and economic return were affected by the interaction of PRE and POST herbicides in Field B13 and C11 during 2011. In Field B13, a POST herbicide did not increase yield compared with no POST herbicides when *S*-metolachlor or *S*-metolachlor plus fomesafen were applied (Table 10). The lowest yield in this field was noted when neither PRE nor POST herbicides were applied. In Field C11, yield was similar when *S*-metolachlor plus fomesafen were applied irrespective of POST herbicides or when a POST herbicide was applied irrespective of PRE herbicide treatment. Estimated economic return reflected soybean yield in Field C11. In Field B13, no difference in economic return was noted among treatments except when comparing the no PRE or POST treatment with *S*-metolachlor plus fomesafen.

The interaction of soybean population by POST herbicide by HRT was significant for both yield and estimated economic return in Fields B13 and C11 in 2011. Increasing the soybean population and applying either glufosinate or glyphosate increased yield in both fields compared with yield at lower soybean populations with or without POST herbicides (Table 11). Applying a POST herbicide in the low population or not including a POST herbicide in the higher population affected yield similarly in both fields. The lowest yield was noted in absence of POST herbicides at the lowest soybean population. Estimated economic return reflected yield in Field B13 for glyphosate and for glufosinate in Field C11. In Field B13 following glufosinate, the highest estimated economic return was noted after glufosinate was applied at the higher soybean population. Applying glyphosate resulted in similar estimated economic returns regardless of soybean population in Field C11. In the absence of POST herbicides, estimated economic return was greater with the higher soybean population.

ACKNOWLEDGMENTS

This research was supported by grower check off funds administered through The North Carolina Soybean Growers Association. Southern States Cooperative, Inc. and Monsanto provided the soybean seed used in these experiments. Charlie Cahoon, Peter Eure, Jamie Hinton, Rick Seagroves, Sam Wells, and staff at the Upper Coastal Plain Research Station provided technical assistance.

LITERATURE CITED

Bullen, G., J.E. Dunphy, E. Weddington. 2010. Soybean budget-full season, conventional tillage 2010. Online. North Carolina Cooperative Extension. http://www.ag-econ.ncsu.edu/extension/budgets/wheat/SoybeanFullConv2010.pdf

Culpepper, A.S., T.L Grey, W.K. Vencill, J.M. Kichler, T.M. Webster, S.M. Brown, A.C. York, J.W. Davis, W.W. Hanna. 2006. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci. 54:620-626.

Culpepper, A.S., A.C. York, A.W. MacRae, and J. Kichler. 2008. Glyphosate-resistant Palmer amaranth response to weed management programs in Roundup Ready and Liberty Link Cotton. Page 1689 *in* Proceedings of the Beltwide Cotton Conferences. Memphis, TN: National Cotton Council.

Caldwell, D. 2007. For N.C. soybean growers, less really is more. Perspectives. Online. The Magazine of the College of Agriculture and Life Sciences, North Carolina State University, Raleigh, NC.

Everman, W.J. 2012. Chemical weed control in soybeans. Pages 253-263 in 2012 North Carolina Agricultural Chemicals Manual. Pub. AG-1. 430 pages.

Frans, R., R. Talbert, D. Marx, and H. Crowley. 1986. Experimental design and techniques for measuring and analyzing plant responses to weed control practices. *In* N. D. Camper, ed. Research Methods in Weed Science. 3rd ed. Champaign, IL: Southern Weed Science Society. Pp. 37–38.

Harder, D.B., C.L. Sprague, K.A. Renner. 2007. Effect of soybean row width and population on weed, crop yield and economic return. Weed Technol. 21:744-752.

Heap, I. 2012. The international survey of herbicide resistant weeds. Online. January 16, 2012.

Hoffner, A.E., D.L. Jordan, A.C. York. 2012. Geographical distribution of herbicide resistance in Palmer Amaranth (*Amaranthus palmeri*) populations across North Carolina. Abstr. 7th International IPM Symposium: IPM on the World Stage (in press).

Mueller, T.C., P.D. Mitchell, B.G. Young, and A.S. Culpepper. 2005. Proactive versus reactive management of glyphosate-resistant or –tolerant weeds. Weed Technol. 19:924-933.

Place, G.T., S.C. Reberg-Horton, J.E. Dunphy, A.N. Smith. 2009. Seeding rate effects weed control and yield for organic soybean production. Weed Technol. 23:497-502.

Shaw, D.R., M.D. Owen, P.M. Dixon, S.C. Weller, B.G. Young, R.G. Wilson, D.L. Jordan. 2011. Benchmark study on glyphosate-resistant crop systems in the United States. Part 1: Introduction to 2006-2008. Pest Manag. Sci. 25, 2, 183-191.

Sosnoskie, L.M., J.M. Kichler, R.D. Wallace, and A.S. Culpepper. 2011. Multiple resistance in Palmer amaranth to glyphosate and pyrithiobac confirmed in Georgia. Abstr. Weed Sci. Soc. Amer. 59(3):321-325.

Sosnoskie. L.M., T.M. Webster, A. MacRae, T.L. Grey, and A.S. Culpepper. 2009. Movement of glyphosate-resistant Palmer amaranth pollen in-field. Abstr. Weed Sci. Soc. Amer. 49:63.

Webster, T.M. 2005. Weed Survey – southern states: broadleaf crop subsection. Proc. South. Weed Sci. Soc. 62:517-520.

Whitaker, J. R. 2009. Distribution, biology, and management of glyphosate-resistant Palmer amaranth in North Carolina. PhD thesis. Raleigh, NC: North Carolina State University. 245p.

Whitaker, J.R., A.C. York, D.L. Jordan, A.S. Culpepper. 2010. Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol. 24:403-410.

Table 1. Planting date, soybean plant population, dates of preemergence and postemergence herbicide application and estimated level of resistance to glyphosate at Rocky Mount during 2010 and 2011.

Year	Field	Planting date	Soybean population		Date of application		Resistance to glyphosate[a]
			Low	High	Preemergence	Postemergence	
			— plants ha^{-1} —				
2010	B13	May 24	122,000	342,000	May 24	June 10	Yes (5%)
2010	E2	May 24	145,000	464,000	May 24	June 10	No
2011	B13	June 7	221,000	560,000	June 7	June 21	Yes (5%)
2011	C11	June 7	208,000	519,000	June 7	June 21	Yes (20%)
2011	E3	June 7	193,000	533,000	June 7	June 21	No

[a]Resistance to glyphosate not confirmed in these fields but has been confirmed previously at this location; percentages refer to estimated percent of Palmer amaranth population being resistant.

Table 2. Palmer amaranth population as affected by preemergence herbicides at Rocky Mount during 2010 and 2011.[a]

Year	Field	Palmer amaranth population		
		No preemergence	*S*-metolachlor	*S*-metolachlor plus fomesafen
		plants m^{-2}		
2010	B13	124 a	4 b	1 b
2010	E2	165 a	10 b	6 b
2011	B13	74 a	5 b	0 b
2011	C11	163 a	4 b	0 b
2011	E3	76 a	5 b	0 b

aMeans within a year and field combination followed by the same letter are not significantly different based on Fisher's Protected LSD test at $p < 0.05$. Data are pooled over soybean populations and herbicide resistance traits. Postemergence herbicides had not been applied when Palmer amaranth density was recorded.

Table 3. The influence of herbicide resistance trait, soybean plant population, and preemergence herbicide on Palmer amaranth control 2 wks after POST application in Field E2 during 2010.[a]

		Palmer amaranth control	
		Herbicide resistance trait[d]	
Soybean population[b]	Preemergence herbicides[c]	Glyphosate	Glufosinate
		%	
Low	None	43 c	34 d
Low	*S*-metolachlor	73 b	74 b
Low	*S*-metolachlor plus fomesafen	86 a	82 a
High	None	49 c	49 c
High	*S*-metolachlor	84 ab	77 b
High	*S*-metolachlor plus fomesafen	93 a	97 a

Table 3 Continued

[a]Means within a herbicide resistance trait followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data are pooled over postemergence herbicides.

[b]Low and high soybean populations were 145,000 and 464,000, respectively.

[c]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[d]Glufosinate and glyphosate applied to appropriate herbicide-resistant cultivar at 560 g ha^{-1} and 840 g ha^{-1}, respectively.

Table 4. The influence of herbicide resistance trait, preemergence herbicide, and postemergence herbicide on Palmer amaranth control 2 wks after POST application in Field E2 during 2010.[a]

		Palmer amaranth control	
		Herbicide resistance trait[c]	
Preemergence herbicide[b]	Postemergence herbicide	Glufosinate	Glyphosate
		%	
None	No	0 e	0 d
S-metolachlor	No	33 d	54 b
S-metolachlor plus fomesafen	No	62 b	46 c
None	Yes	46 c	59 b
S-metolachlor	Yes	64 ab	81 a
S-metolachlor plus fomesafen	Yes	70 a	85 a

Table 4 Continued

[a]Means within a herbicide resistance trait followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data are pooled over soybean population.

[b]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[c]Glufosinate and glyphosate applied to appropriate herbicide-resistant cultivar at 560 and 840 kg ha^{-1}, respectively.

Table 5. The influence of preemergence and postemergence herbicides on Palmer amaranth control 2 wks after POST application.[a]

Preemergence herbicides[b]	Postemergence herbicides[c]	2010 Field B13	2011 Field B13	2011 Field C11
		%		
None	No	6 d	0 b	14 d
S-metolachlor	No	65 c	92 a	62 c
S-metolachlor plus fomesafen	No	88 ab	99 a	90 b
None	Yes	82 b	93 a	65 c
S-metolachlor	Yes	89 ab	100 a	87 b
S-metolachlor plus fomesafen	Yes	91 a	100 a	98 a

[a]Means within a year and field followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data are pooled over herbicide resistance traits and soybean populations.

[b]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[c]Glufosinate and glyphosate applied to appropriate herbicide-resistant cultivar at 560 and 840 g ha^{-1}, respectively.

Table 6. Palmer amaranth control 2 wks after POST application as influenced by herbicide resistance trait and preemergence herbicide treatment during 2010 in Field B13.[a]

	Palmer amaranth control	
	Herbicide resistance trait[c]	
Preemergence herbicide[b]	Glufosinate	Glyphosate
	%	
None	49 c	29 c
S-metolachlor	78 b	71 b
S-metolachlor plus fomesafen	94 a	93 a

[a]Means within a herbicide resistance trait followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data are pooled over soybean population.

[b]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[c]Glufosinate and glyphosate applied to appropriate herbicide-resistant cultivar at 560 and 840 g ha^{-1}, respectively.

Table 7. The influence of herbicide resistance trait, soybean population, and preemergence and postemergence herbicides on Palmer amaranth control 2 wks after POST application in Field E3 during 2011.[a]

	Herbicide application timing		Palmer amaranth control Herbicide resistance trait[d]	
Soybean population[b]	Preemergence[c]	Postemergence	Glufosinate	Glyphosate
			%	
Low	None	No	0 d	0 d
Low	*S*-metolachlor	No	83 bc	85 bc
Low	*S*-metolachlor plus fomesafen	No	95 ab	100 a
Low	None	Yes	76 c	78 c
Low	*S*-metolachlor	Yes	98 a	100 a
Low	*S*-metolachlor plus fomesafen	Yes	100 a	100 a
High	None	No	0 d	0 d
High	*S*-metolachlor	No	98 a	98 a
High	*S*-metolachlor plus fomesafen	No	95 ab	100 a

Table 7 Continued

High	None	Yes	85 bc	85 bc
High	*S*-metolachlor	Yes	100 a	100 a
High	*S*-metolachlor plus fomesafen	Yes	100 a	100 a

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

[b]Low soybean population in Field E3 in 2011 was 193,000 plants m^{-2}. High soybean population in this field was 533,000 plants m^{-2}.

[c]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[d]Glufosinate and glyphosate applied to appropriate herbicide-resistant cultivar at 560 and 840 g ha^{-1}, respectively.

Table 8. Soybean yield as influenced by soybean population and preemergence herbicide in Fields E2 during 2010 and Field E3 during 2011.[a]

Treatment factor	2010 Field E2	2011 Field E3
	kg ha^{-1}	
Soybean population[b]		
Low	200 b	2210 b
High	430 a	3310 a
Preemergence herbicide[c]		
None	250 b	1910 b
S-metolachlor	350 a	3130 a
S-metolachlor plus fomesafen	340 a	3240 a

Table 8 Continued

---

[a]Means within a field and treatment factor followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$.

[b]Low soybean population in Fields E2 (2010) and E3 (2011) were 145,000 and 193,000 plants ha^{-1}, respectively. High soybean populations in these respective fields were 464,000 and 533,000 plants ha^{-1}.

[b]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

Table 9. Estimated economic return as influenced by soybean population, preemergence herbicide, or postemergence herbicide in Field E3 during 2011.[a]

Treatment factor	Economic return
	$ ha^{-1}
Soybean population[b]	
Low	585 b
High	1017 a
Preemergence herbicide[c]	
None	415 b
S-metolachlor	962 a
S-metolachlor plus fomesafen	1026 a
Postemergence herbicide[d]	
No	562 b
Yes	1039 a

Table 9 Continued

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

[b]Low and high soybean populations in Field E3 during 2011 were 193,000 and 533,000 plants m^{-2}, respectively.

[c]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[c]Postemergence herbicides included glufosinate and glyphosate applied to appropriate herbicide-resistant cultivars. at 560 and 840 g ha^{-1}, respectively

Table 10. Soybean yield and estimated economic return as influenced by preemergence and postemergence herbicide treatments during 2011 in Fields B13 and C11.[a]

	Postemergence	Soybean yield		Economic return	
Preemergence herbicides[b]	Herbicides[c]	Field B13	Field C11	Field B13	Field C11
		—— $kg\ ha^{-1}$ ——		—— $\$\ ha^{-1}$ ——	
None	No	720 b	1620 c	-112 b	288 c
S-metolachlor	No	930 a	3420 b	-57 ab	1118 b
S-metolachlor plus fomesafen	No	1120 a	3990 a	48 a	1415 a
None	Yes	940 a	3820 a	-31 ab	1339 a
S-metolachlor	Yes	1000 a	4070 a	-56 ab	1408 a
S-metolachlor plus fomesafen	Yes	1040 a	4200 a	-34 ab	1471 a

Table 10 Continued

[a]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data are pooled over herbicide resistance traits and soybean populations.

[b]*S*-metolachlor and *S*-metolachlor plus fomesafen applied at 1500 and 1200 + 270 g ha^{-1}, respectively.

[c]Postemergence herbicides included glufosinate and glyphosate applied to appropriate herbicide-resistant cultivars. at 560 and 840 g ha^{-1}, respectively.

Table 11. Soybean yield and estimated economic return as influenced by herbicide resistance trait, soybean plant population, and postemergence herbicide treatment during 2011 in Fields B13 and C11.[a]

		Soybean yield				Economic return			
		Herbicide resistance trait				Herbicide resistance trait			
		Field B13		Field C11		Field B13		Field C11	
Soybean population[b]	POST herbicide[c]	Glufosinate	Glyphosate	Glufosinate	Glyphosate	Glufosinate	Glyphosate	Glufosinate	Glyphosate
		$kg\ ha^{-1}$				$\$\ ha^{-1}$			
Low	No	1420 c	540 c	2860 c	1980 c	224 c	-237 c	924 c	481c
Low	Yes	2180 b	2290 b	3790 b	3620 b	544 b	601 b	1326 b	1263 ab
High	No	2240 b	2680 b	3620 b	3580 b	507 bc	705 b	1201 b	1153 b
High	Yes	3720 a	3850 a	4560 a	4150 a	1195 a	1255 a	1625a	1408 a

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

[b]Low soybean populations in Fields B13 and C11 during 2011 was 221,000 and 208,000 plants m^{-2}, respectively. High soybean populations in these fields were 560,000 and 519,000 plants m^{-2}, respectively.

[c]Glufosinate and glyphosate applied to appropriate herbicide-resistant cultivar at 560 and 840 g ha^{-1}, respectively.

CHAPTER 3

Palmer Amaranth (*Amaranthus palmeri*) Control with Sequential Herbicide Applications in Glufosinate-Resistant Soybean (*Glycine max*)

Amy E. Hoffner, David L. Jordan, Alan C. York, and Wesley J. Everman*

Abstract

Palmer amaranth has become one of the most challenging weeds to control in soybean in the southern United States. In separate experiments, research was conducted during 2010 and 2011 in North Carolina to compare sequential applications of preemergence (PRE) herbicides followed by postemergence (POST) applications of glufosinate or multiple POST applications of glufosinate. Although some variation in control was noted, combinations of PRE and POST herbicide provided the greatest control of Palmer amaranth and highest soybean yield. In 1 of 3 experiments, sequential applications of glufosinate were more effective than a single application. Yield was higher in 2 of 3 experiments when glufosinate was applied irrespective of timing of application when compared with the non-treated control. In the experiment where glufosinate was applied at various POST timings, sequential applications of the herbicide provided the best control and highest yield.

---

*First, second, third, and fourth authors: Graduate Research Assistant, Professor, William Neal Reynolds Professor Emeritis, and Assistant Professor, Department of Crop Science, North Carolina State University, Campus Box 7620, Raleigh, NC 27695.

Nomenclature: soybean, *Glycine max* L.; glufosinate.

Keywords: flumioxazin; chlorimuron; *S*-metolachlor; fomesafen; sulfentrazone; cloransulam; acetolactate synthase (ALS)-inhibiting herbicides.

INTRODUCTION

Presence of glyphosate-resistant Palmer amaranth in North Carolina has increased the need to develop comprehensive herbicide programs that include alternative modes of action (MOA) (Everman et al. 2007). Glufosinate-resistant soybean allows producers to apply glufosinate to control problematic weeds like Palmer amaranth (Coetzer et al. 2002). Sequential programs, either as PRE followed by POST applications or multiple POST applications of herbicides, can be effective in controlling weeds, especially glyphosate-resistant Palmer amaranth (Culpepper et al. 2011).

Residual herbicides can play a major role in protecting yield from early season weed interference and increase the diversity of MOAs as a resistance-management tool (Everman et al. 2007). Similar results for Palmer amaranth control with flumioxazin were observed by Askew et al. (2002), with flumioxazin providing excellent control of Palmer amaranth.

Timely applications of glufosinate in glufosinate-resistant soybean can be effective in controlling glyphosate-resistant and glyphosate-susceptible Palmer amaranth (Coetzer et al. 2002). Reed et al. (2011) reported that multiple applications of glufosinate in a total POST herbicide program controlled Palmer amaranth effectively. However, most recommendations by Cooperative Extension Service representatives include sequential applications of PRE herbicides followed by timely POST herbicides, especially in fields where glyphosate-resistant Palmer amaranth is present.

Glyphosate-resistant Palmer amaranth is now found throughout the Piedmont and Coastal Plain of North Carolina (Hoffner et al. 2012). In a comprehensive survey of 242 predetermined sites in North Carolina during fall 2010, 126 sites had Palmer amaranth, and of the sites where this weed was present, 98% of populations expressed resistance to glyphosate. Also, 85% of these populations expressed resistance to thifensulfuron-methyl, an acetolactate synthase (ALS)-inhibiting herbicide. Given the widespread presence of Palmer amaranth and resistance of this weed to glyphosate and ALS-inhibiting herbicides, developing strategies that include PRE herbicides and glufosinate will be critical for production of soybean and other crops throughout North Carolina. Therefore, research was conducted in order to compare efficacy of sequential applications of PRE and POST herbicides and multiple POST applications of glufosinate.

MATERIALS AND METHODS

One experiment were conducted at 5 sites in North Carolina during 2010 and 2011 at the Upper Coastal Plain Research Station near Rocky Mount in fields with natural and relatively high populations of Palmer amaranth expressing varying degrees of glyphosate resistance. Soil during 2010 was a Norfolk loamy sand (fine-loamy, kaolinitic, thermic, Typic Kandiudults) for both the PRE followed by POST herbicide experiment and the experiment with multiple POST applications of glufosinate. During 2011, these experiments were conducted in a field with a Nahunta loam soil (fine-silty, siliceous, thermic, Aeric

Paleaquults). The experiment with multiple applications of glufosinate was also conducted during 2011 in a field with a Lynchburg fine sandy loam soil (fine-loamy siliceous, thermic, Aeric Paleaquults). The glufosinate-resistant soybean cultivar LL 595N (Southern States Cooperative, Inc., Farmville, NC 27828) was planted after disking and field cultivation in rows spaced 20 cm apart with a final plant population of 342,000 plants ha^{-1} (2010) and 526,000 plants ha^{-1} (2011). Lower final stand in 2010 compared with 2011 was a result of environmental conditions that adversely affected soybean emergence and stand establishment. Plot size was twelve rows by 9 m in length. In 2010, soil moisture conditions were conducive for soybean emergence. However, in 2011 soybean was irrigated with a traveling gun system delivering 1.5 cm within 3 d after planting to ensure uniform emergence.

In the experiment with sequential application of PRE and POST herbicides, treatments consisted of seven levels of PRE herbicides, including no PRE, flumioxazin (Valor SX®, Valent USA Corporation, Walnut Creek, CA 94596) alone at 70 g ai ha^{-1} or with chlorimuron (Valor XLT herbicide®, E. I. DuPont de Nemours and Co., Wilmington, DE 19898) at 21 g ai ha^{-1}, the sodium salt of fomesafen (Reflex herbicide®, Syngenta Crop Protection, Greensboro, NC 27709) at 280 g ae ha^{-1}, *S*-metolachlor (Dual II Magnum®, Syngenta Crop Protection, Greensboro, NC 27709) at 1500 g ai ha^{-1}, *S*-metolachlor plus fomesafen (Prefix herbicide®, Syngenta Crop Protection, Greensboro, NC 27709) at 1200 + 270 g ha^{-1}, and sulfentrazonee plus cloransulam-methyl (Authority First herbicide®, FMC Corporation, Philadelphia, PA 19103) at 280 + 36 g ai ha^{-1}, respectively. Each of these PRE herbicides were followed by no POST herbicide or a single application of glufosinate-ammonium (Ignite280® herbicide, Bayer CropScience, Research Triangle Park, NC 27709) at 670 g ai ha^{-1} 2 wk after planting or sequential applications of glufosinate at 400 g ha^{-1} at 2 and 4 wk after planting (WAP). In the experiment with total POST applications of glufosinate, treatments consisted of glufosinate applied 2 WAP at 400 and 670 g ai ha^{-1} (referred to as POST 1) followed by no additional applications of glufosinate or followed by a second application of glufosinate at 400 g ai ha^{-1} at 3 WAP (referred to as POST 2) or 4 WAP (referred to as POST 3).

Palmer amaranth size ranged from 5 to 10 cm in height when glufosinate was applied in the experiment with PRE and POST herbicides. In the experiment with multiple applications of glufosinate only, Palmer amaranth height was 5 to 10 cm at POST 1, 5 to 20 cm at POST 2, and 5 to 40 cm at POST 3. The range in size of Palmer amaranth reflected differences in emergence of weeds caused by PRE herbicides prior to the POST application in experiment with PRE and POST herbicides and the balance between timing of emergence of Palmer amaranth and growth of Palmer amaranth when comparing combinations of POST timings in the experiment with multiple applications of glufosinate. In both experiments, glufosinate was applied with nonionic surfactant (Induce adjuvant, Helena Chemical Company, Memphis, TN 38017) at 0.25% (v/v) using a CO_2-pressurized backpack sprayer calibrated to deliver 145 L ha^{-1} using flat-fan nozzles (Teejet Corporation, Wheaton, IL 60187) at 275 kPa.

Percent Palmer amaranth control was estimated visually and was recorded 2, 4, and 10 WAP in both experiments using a scale of 0 to 100% where 0 = no control and 100% = complete control (Frans et al. 1986). Soybean yield was determined in each plot and adjusted to final moisture of 15%.

The experimental design was a randomized complete block with four replications. Data for Palmer amaranth control and soybean yield were subjected to ANOVA using the Proc GLM procedure in SAS (SAS Institute, GLM Procedure, Cary, NC 27513) considering the factorial arrangement of treatments. Means of significant main effects and interactions were separated using Fisher's Protected LSD test at $p \leq 0.05$.

RESULTS AND DISCUSSION

Experiment 1:

The interaction of year by PRE by POST herbicide was significant for Palmer amaranth control at 2, 4, and 10 WAP and for soybean yield (Table 1). Therefore, data were analyzed by year. While the main effect of PRE herbicide was significant for Palmer amaranth control 2, 4, and 10 WAP during 2010, the main effect of POST herbicide was not significant at 2 and 4 WAP but was at 10 WAP (Table 2). The interaction of PRE by POST was not significant for any parameter during 2010. However, the interaction of PRE by POST herbicides was significant for all parameters in 2011 (Table 2).

At 2 WAP in 2010, no differences in Palmer amaranth control were noted among PRE herbicides (Table 3). However, by 4 and 10 WAP, differences among PRE herbicides became apparent. At 4 WAP, *S*-metolachlor was the least effective PRE herbicide, controlling Palmer amaranth only 66%, while all other PRE herbicides controlled this weed 85 to 99%. By 10 WAP, control by flumioxazin alone or with chlorimuron was 93 to 98% while fomesafen alone or with *S*-metolachlor provided 77 to 80% control. Sulfentrazone plus cloransulam-methyl controlled Palmer amaranth 66% while *S*-metolachlor provided only 56% control. Whitaker et al. (2010) found similar results for Palmer amaranth control with flumioxazin and fomesafen PRE.

No differences in Palmer amaranth control due to POST application of glufosinate were noted 2 and 4 WAP (Table 3). By 10 WAP control was similar when glufosinate was applied either once or sequentially. Lack of a difference in single and sequential applications most likely reflect limited weed emergence after the first POST application and rapid closure of the soybean canopy.

All PRE herbicides increased soybean yield in 2010 (Table 3). Yield of soybean recieving *S*-metolachlor plus fomesafen exceeded that of soybean treated with flumioxazin alone, sulfentrazone plus cloransulam-methyl, or flumioxazin plus chlorimuron. Surprisingly, yield following a single application of glufosinate was lower than soybean without a POST application or soybean receiving sequential applications of glufosinate.

No differences in Palmer amaranth control among PRE treatments were noted at 2 WAP for any glufosinate treatment during 2011(Table 4). When no PRE was applied, a single application of glufosinate provided the most control at 2 WAP (Table 4).

At 4 WAP, there were several differences in control by PRE herbicides when glufosinate was not applied (Table 5). Flumioxazin alone, flumioxazin plus chlorimuron, *S*-metolachlor plus fomesafen, and fomesafen alone controlled Palmer amaranth at least 95%. Sulfentrazone plus cloransulam-methyl and *S*-metolachlor alone controlled this weed 81 and 73%, respectively. When a single application of glufosinate was applied, all PRE herbicide, including no PRE herbicide controlled Palmer amaranth similarly, at least 89%. When glufosinate was applied sequentially control by *S*-metolachlor alone and no PRE decreased to 85% and 10%, respectively.

Many differences in Palmer amaranth control among PRE herbicides were observed at 10 WAP, especially in absence of glufosinate (Table 6). Results for Palmer amaranth control at 10 WAP were similar to results at 4 WAP in that flumioxazin, flumioxazin plus chlorimuron, *S*-metolachlor plus fomesafen, and fomesafen alone provided the best control (Table 6). Sulfentrazone plus cloransulam-methyl and *S*-metolachlor alone provided intermediate control between the most effective PRE herbicides and the non-treated control. When glufosinate was applied only once, no difference in control among PRE herbicides was observed.

There were no significant differences in soybean yield among PRE herbicide treatments when glufosinate was applied, regardless of the number of glufosinate applications (Table 7). In the absence of glufosinate, soybean yield following fomesafen, *S*-metolachlor, and sulfentrazone plus cloransulam-methyl was intermediate between the non-treated control and flumioxazin alone or with chlorimuron or *S*-metolachlor plus fomesafen.

Experiment 2:

In the total POST experiment where glufosinate was applied sequentially 2, 3, and 4 WAP, the interaction of glufosinate rate by sequence of glufosinate application was not significant for Palmer amaranth control at 4 and 10 WAP or for soybean yield (Table 8). Although glufosinate rate as a main effect or as an interaction with year or sequence of glufosinate application was no significant, the interaction of experiment by sequence was significant. In 2010, multiple applications of glufosinate controlled Palmer amaranth 4 and 10 WAP (91 to

94% control at 4 WAP, 97 to 99% at 10 WAP) than a single application (72% control at 4 WAP, 82% at 10 WAP) (Table 9). In systems with two applications, timing of the second application had no effect. Also, Palmer amaranth control was similar with two and three applications. Soybean yield was unaffected by the number of glufosinate applications. However, glufosinate POST increased yield 62 to 112%. During 2011, in Field 1, Palmer amaranth control 4 and 10 WAP was similar with all glufosinate applications and was at least 97%. In the second field, while control 4 WAP was similar with all treatments of glufosinate, control at 10 WAP was greater where glufosinate was applied sequentially compared with a single application.

During 2011, in Field 1, soybean receiving a single application of glufosinate and non-treated soybean yielded similarly. Yield was increased when a second application of glufosinate was made 3 WAP. In the second field during 2011, soybean yield exceeded that of the non-treated control when glufosinate was applied irrespective of sequence of application. However, soybean yield was lower with three applications of glufosinate compared with two applications only. Given Palmer amaranth control was high with the program containing three applications, lower yield most likely reflected soybean injury. The total amount of glufosinate applied in this treatment exceeds the manufacturer’s recommendations (Anonymous, 2012).

The most consistent control will be obtained with multiple applications of herbicides either as PRE followed by POST or sequential POST applications of glufosinate. However, in the long-term sequential application of PRE and POST herbicides is the best approach when considering resistance management.

ACKNOWLEDGMENTS

The North Carolina Soybean Growers Association and Bayer CropScience provided partial funding for this research. Appreciation is expressed to Jamie Hinton, Rick Seagroves, Dewayne Johnson, Peter Eure, and staff at the Upper Coastal Plain Research Station.

LITERATURE CITED

Anonymous. 2012. Ignite280® herbicide label. Bayer CropScience, Research Triangle Park, NC.

Askew, S.D., J.W. Wilcut, and J.R. Cramer. 2002. Cotton (*Gossypium hirsutum*) and weed response to flumioxazin applied preplant and postemergence directed. Weed Technol. 16:184-190.

Coetzer, E., A. Kassim, D.E. Peterson. 2002. Glufosinate efficacy on *Amaranthus* species in glufosinate-resistant soybean (*Glycine max*). Weed Technol. 16:326-331.

Culpepper, A.S., A.C. York, L.E. Steckel. 2011. Glyphosate-resistant Palmer amaranth management in cotton. Abst. Proceedings Southern Weed Science Society. 64:226.

Everman, W.J., I.C. Burke, J.R. Allen, J. Collins, and J.W. Wilcut. 2007. Weed control and yield with glufosinate-resistant cotton weed management systems. Weed Technol. 21(3):695-701.

Frans, R., R. Talbert, D. Marx, and H. Crowley. 1986. Experimental design and techniques for measuring and analyzing plant responses to weed control practices. *In* N. D. Camper, ed. Research Methods in Weed Science. 3rd ed. Champaign, IL: Southern Weed Science Society. Pp. 37–38.

Hoffner, A.E., D.L. Jordan, A.C. York. 2012. Geographical distribution of herbicide resistance in Palmer Amaranth (*Amaranthus palmeri*) populations across North Carolina. Abstr. 7th International IPM Symposium: IPM on the World Stage (in press).

Reed, J.D., P.A. Dotray, J.W. Keeling. 2011. Palmer amaranth (*Amaranthus palmeri S*. Wats.) management in Glytol™ + LibertyLink® cotton. Abst. Proceedings, Southern Weed Science Society. 64:260.

Whitaker, J.R., A.C. York, D.L. Jordan, and A.S. Culpepper. 2010. Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol. 24(4):403-410.

Table 1. P>F for Palmer amaranth control and soybean yield as influenced by year, PRE, and POST herbicides.

Treatment factors	Palmer amaranth control (wks after planting) 2	4	10	Soybean yield
	——————%	——————	——————	kg ha^{-1}
Year	0.0367	<0.0001	<0.0001	<0.0001
PRE	<0.0001	<0.0001	<0.0001	0.0003
POST	0.1754	<0.0001	<0.0001	<0.0001
PRE*POST	0.0901	<0.0001	0.0084	0.0076
Year*PRE	0.1907	0.0991	0.0001	0.2335
Year*POST	0.0121	0.0002	0.3958	<0.0001
Year*PRE*POST	<0.0001	<0.0001	0.0592	0.0074
CV (%)	10.6	14.7	18.0	19.5

Table 2. P>F for Palmer amaranth control and soybean yield as influenced by PRE, and POST herbicides for each year.

	Palmer amaranth control (wks after planting)			
Treatment factors	2	4	10	Soybean yield
	——— % ———			kg ha^{-1}
2010				
PRE	<0.0001	<0.0001	<0.0001	0.0015
POST	0.3071	0.2229	0.0363	0.0268
PRE*POST	0.5490	0.0898	0.1466	0.0268
CV (%)	11.7	18.0	23.5	18.9
2011				
PRE	<0.0001	<0.0001	<0.0001	0.0180

Table 2 Continued

POST	<0.0001	<0.0001	<0.0001	<0.0001
PRE*POST	<0.0001	<0.0001	0.0011	0.0049
CV (%)	9.5	11.3	13.1	17.8

Table 3. Palmer amaranth control and soybean yield as influenced by main effects of PRE and POST herbicide treatments during 2010.[a]

Herbicides	Herbicide rate	Palmer amaranth control (wks after planting) 2	4	10	Soybean yield
	g ha^{-1}		%		kg ha^{-1}
PRE herbicides					
None		43 b	19 d	29 e	1150 c
Flumioxazin	700	100 a	99 a	98 a	1460 b
Sulfentrazone plus cloransulam-methyl	28 + 36	97 a	85 b	66 cd	1450 b
S-metolachlor plus fomesafen	1200 + 270	100 a	95 ab	77 c	1680 a
Flumioxazin plus chlorimuron	70 + 21	100 a	98 a	93 ab	1420 b
Fomesafen	280	97 a	89 ab	80 bc	1570 ab
S-metolachlor	1500	97 a	69 c	56 d	1500 ab

Table 3 Continued

POST herbicides					
None		91 a	76 a	64 b	1500 a
Glufosinate	670	88 a	78 a	73 a	1340 b
Glufosinate then glufosinate	400 then 400	93 a	83 a	76 a	1530 a

[a]Means within a treatment factor and column followed by the same letter are not different according to Fisher's Protected LSD test at $p \leq 0.05$. Data for PRE herbicides are pooled over levels of POST herbicides. Data for POST herbicides are pooled over levels of PRE herbicides.

Table 4. Palmer amaranth control 2 wks after planting as influenced by the interaction of PRE and POST herbicide treatments during 2011.[a]

PRE herbicides	PRE herbicide rate	Glufosinate rate (kg ha^{-1})		
		0	0.67	0.40 then 0.40
	g ha^{-1}	%		
None		0 d	83 b	63 c
Flumioxazin	700	100 a	100 a	100 a
Sulfentrazone plus cloransulam-methyl	280 + 36	100 a	100 a	100 a
S-metolachlor plus fomesafen	1200 + 270	100 a	100 a	100 a
Flumioxazin plus chlorimuron	700 + 21	100 a	100 a	100 a
Fomesafen	280	100 a	100 a	100 a
S-metolachlor	1500	100 a	100 a	100 a

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

Table 5. Palmer amaranth control 4 wk after planting as influenced by the interaction of PRE and POST herbicide treatments during 2011.[a]

PRE herbicides	PRE herbicide rate	Glufosinate rate (kg ha^{-1}) 0	0.67	0.40 then 0.40
	g ha^{-1}	%		
None		0 e	89 abc	100 a
Flumioxazin	700	98 ab	99 ab	100 a
Sulfentrazone plus cloransulam-methyl	280 + 36	81 cd	100 a	93 abc
S-metolachlor plus fomesafen	1200 + 270	98 ab	100 a	100 a
Flumioxazin plus chlorimuron	70 + 21	100 a	100 a	100 a
Fomesafen	280	95 abc	100 a	98 ab
S-metolachlor	1500	73 d	98 a	85 bcd

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

Table 6. Palmer amaranth control 10 wk after planting as influenced by the interaction of PRE and POST herbicide treatments during 2011.[a]

PRE herbicides	PRE herbicide rate	Glufosinate rate (kg ha^{-1}) 0	0.67	0.40 then 0.40
	g ha^{-1}	%		
None		0 e	88 a-d	81 bcd
Flumioxazin	700	94 abc	100 a	100 a
Sulfentrazone plus cloransulam-methyl	280 + 36	80 cd	100 a	93 a-d
S-metolachlor plus fomesafen	1200 + 270	90 a-d	96 abc	97 abc
Flumioxazin plus chlorimuron	70 + 21	100 a	100 a	96 abc
Fomesafen	280	91 a-d	100 a	98 ab
S-metolachlor	1500	76 d	91 a-d	91 a-d

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

Table 7. Soybean yield as influenced by the interaction of PRE and POST herbicide treatments during 2011.[a]

PRE herbicides	PRE herbicide rate	Glufosinate rate (kg ha^{-1})		
		0	0.67	0.40 then 0.40
	g ha^{-1}	——— kg ha^{-1} ———		
None		1340 e	3800 abc	3850 abc
Flumioxazin	700	3940 ab	3500 a-d	3770 a-d
Sulfentrazone plus cloransulam-methyl	28 + 36	2880 d	3850 abc	3740 a-d
S-metolachlor plus fomesafen	1200 + 270	3400 a-d	3550 a-d	4090 a
Flumioxazin plus chlorimuron	70 + 21	3720 a-d	4000 ab	3870 abc
Fomesafen	280	3130 bcd	3890 abc	4240 a
S-metolachlor	1500	3020 cd	3350 a-d	3530 a-d

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

Table 8. Experiment 2. P > F for Palmer amaranth control and soybean yield as influenced by glufosinate rate and sequence of sequential applications.

	Palmer amaranth control (WAP)		
Treatment factors	4	10	Soybean yield
Experiment (Exp)	0.0069	0.0118	<0.0001
Glufosinate rate (Rate)	0.1470	0.1740	0.0595
Glufosinate sequence (Sequence)	0.0168	<0.0001	0.6848
Rate*Sequence	0.0916	0.4830	0.4055
Exp*Rate	0.9591	0.0815	0.1020
Exp*Sequence	0.0041	0.0100	0.0077
Exp*Rate*Sequence	0.2024	0.1064	0.7318
CV (%)	11.4	7.5	17.3

Table 9. Experiment 2. Palmer amaranth control 4 and 10 weeks after planting (WAP) and soybean yield as influenced by the glufosinate rate and sequence of application.

Glufosinate application timing (WAP)				2011	
2	3	4	2010	Field 1	Field 2
				Palmer amaranth control 4 WAP (%)	
Yes	No	No	72 b	99 a	97 a
Yes	No	Yes	94 a	97 a	96 a
Yes	Yes	No	92 a	98 a	100 a
Yes	Yes	Yes	91a	100 a	100 a
				Palmer amaranth control 10 WAP (%)	
Yes	No	No	82 b	98 a	89 b
Yes	No	Yes	97 a	100 a	100 a
Yes	Yes	No	99 a	98 a	100 a
Yes	Yes	Yes	98 a	100 a	100 a

Table 9 Continued

				Soybean yield (kg ha^{-1})	
Yes	No	No	1040 a	2950 b	3030 a
Yes	No	Yes	1020 a	3350 ab	2990 a
Yes	Yes	No	970 a	3360 a	2940 a
Yes	Yes	Yes	1240 a	3030 ab	2530 b
No	No	No	600 b	2780 b	870 c

[a]Means within a year or year and field combination for each parameter followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data are pooled over glufosinate rates. Data for the non-treated control were not included in the statistical analyses to allow consideration of treatment structure.