12-2014

Integration of Herbicide Programs with Cultural and Mechanical Practices for Managing Glyphosate-Resistant Palmer amaranth (Amaranthus palmeri) in Soybean (Glycine max)

Holden Bell
University of Arkansas, Fayetteville

Integration of Herbicide Programs with Cultural and Mechanical Practices for Managing Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri*) in Soybean (*Glycine max*)

Integration of Herbicide Programs with Cultural and Mechanical Practices for Managing Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri*) in Soybean (*Glycine max*)

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

By

Holden Douglas Bell
University of Arkansas
Bachelor of Science in Crop Management, 2011

December 2014
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

Dr. Jason K. Norsworthy
Thesis Director

Dr. Nathan A. Slaton
Committee Member

Dr. Larry C. Purcell
Committee Member

Dr. Robert C. Scott
Committee Member

Dr. Michael P. Popp
Committee Member

Abstract

Herbicide-resistant Palmer amaranth is the most troublesome weed in Arkansas row crops, causing producers to rely heavily on multiple mechanisms of action to reduce selection pressure for further evolution of herbicide resistance and to successfully produce a profitable crop. It is critical for the sustainability of weed management not only to adequately control this weed but also to reduce the soil seedbank using both non-chemical and chemical practices. Studies were conducted to determine the effect of soybean row spacing, seeding rate, and herbicide program on Palmer amaranth emergence, survival, and seed production in soybean, the effect of drill-seeded soybean population on Palmer amaranth emergence with and without a residual preemergence (PRE)-applied herbicide, and the impact of integrating cover crops and deep tillage with herbicide programs for glyphosate-resistant Palmer amaranth control in glyphosate- and glufosinate-resistant soybean. Herbicide application timing and choice of herbicide had more of an impact on Palmer amaranth control than either row spacing or seeding rate and greater control was observed in PRE plus postemergence (POST)-applied residual programs compared to POST-only residual programs, regardless of seeding rate and row spacing. Narrow-row soybean reached 95% canopy formation quicker than plants in wide rows, in turn resulting in greater suppression of Palmer amaranth emergence. In drill-seeded soybean, a PRE-applied residual herbicide was more beneficial in reducing Palmer amaranth emergence than increasing soybean density. Using a combination of cover crop and deep tillage along with the addition of a PRE followed by POST-applied residual herbicide program, Palmer amaranth was effectively controlled throughout the season with limited weed seed return to the soil seedbank in both glufosinate- and glyphosate-resistant soybean. Overall, herbicide programs were the strongest factor influencing Palmer amaranth control; however, the addition of a cover crop,

deep tillage, and narrow row spacing play a vital role in reducing selection pressure on herbicides, thus reducing risks for new cases of herbicide resistance.

Acknowledgment

The author expresses his deepest thanks to all the people who provided support and guidance; without their help this thesis would not have been possible. I would like to first thank Dr. Jason K. Norsworthy, my major professor, for his time, patience, friendship and advice throughout the entire process.

Gratitude is also extended to my committee members, Dr. Michael P. Popp, Dr. Larry C. Purcell, Dr. Robert C. Scott, and Dr. Nathan A. Slaton. Their support was a valuable resource in completing this degree. Also, there have been additional faculty at the University of Arkansas that have spent their time teaching or helping me in various ways. I would like to thank my fellow Graduate students for the help they all put in on these trials and for the fun times outside of work. I would like to especially thank Tyson and Rachel Raper for opening up their home and allowing me to stay there during all the back-and-forth trips from Oklahoma to Arkansas. You are truly great friends, and I'll never forget the generosity.

I would like to thank my family who have been examples of hard work and dedication and all the prayers for me throughout my lifetime. My mom and dad who taught me at a young age to never give up on something and always put the Lord first. You have been the best parents I could ask for and have given me the best memories that I will never forget. Nawnie and Pawpaw for all the help and guidance they have given me and been the best grandparents I could ever ask for. Momma Nee and Dee who have shown what true perseverance is and never giving up and a true love for the outdoors. My brothers Will and Josh who had a major influence on me growing up. To Josh, who always has a vision and a passion for something he loves and taking the risks to make that dream come true. You have taught me a lot more than you can imagine.

The Minihan's for all the prayers, guidance, and fun times. I knew we were going to be family since day one and I could not ask for better in-laws.

To Dr. Ken Savage, without you I would not be here today. You have taught me so much about weed science and life. To his wife Nancy, thank you for all the lunches throughout the summer while working. You both have been so great to me and my family and I can never repay you. Dr. Don Harlan, thanks for taking me on as a summer worker and teaching me about research. I owe a lot of where I am today to you and Ken.

To my wife, Kaylin, who has stuck by me and always encouraged me through hard times. You have been an inspiration through all your hard work, patience, and always loving me. For all the times you've heard me talk about Palmer amaranth and listened to my presentations and never once complained. To Henry, I hope I can be a good example and raise you to be the best you can be and I hope you will be proud of me. You have been a fighter since day one and never gave up. You've already inspired me more than you'll ever know.

The Lord for answering so many prayers and guiding me through life. I would not be the person I am today if it wasn't for you. There are too many people that have helped me get to where I am today to list. I'll never forget everyone's help, guidance, and prayers throughout this time and throughout my life. I love you all.

Table of Contents

List of Tables

CHAPTER II

CHAPTER III

CHAPTER IV

List of Figures

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER I

Introduction

Since the beginning of cultivation, *Amaranthus* spp. have ties to both Old and New World people either as wild or cultivated grains. *Amaranthus* spp. have been used for pot-herbs, dye-plants, fetishes, and ornamentals (Sauer 1950). The seeds of *Amaranthus* spp. have been reported to have nutritional analyses comparable to true cereals and are edible when toasted and milled. The leaves and shoots of young amaranths can be boiled and eaten as greens or potherbs and are said to taste comparable to species of the cabbage family (Duke 1992; Sauer 1967; Singh 1961). Furthermore, Native American tribes (Cocopa, Mohave, Navajo, Pima, and Yuma) baked the leaves and ground the seed of Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] into meal for consumption (Moerman 1998; Sauer 1967; Singh 1961; Steckel 2007).

More recently, Palmer amaranth has become one of the most problematic weed species throughout much of the Southern U.S. due to its emergence period from early April to the first killing frost, abundant seed production (≥ 250,000 seed female^{-1}), rapid upright growth, and herbicide resistance (DeVore et al. 2013; Jha and Norsworthy 2009; Keeley et al. 1987; Klingaman and Oliver 1994; Monks and Oliver 1988; Norsworthy et al. 2008; Scott and Smith 2011). During the mid-1990's, Palmer amaranth went from being the 23rd and 10th most troublesome weed in soybean and cotton, respectively, to the 2nd and 1st most troublesome in these same crops by 2008 and 2009 for many Southern U.S. states (Webster and Nichols 2012). During the fall of 2011, crop consultants from Arkansas, Louisiana, Mississippi, and Tennessee were surveyed to determine the prevalence of weed species in soybean in the midsouth U.S. (Riar et al. 2013). This survey reported Palmer amaranth and morningglories as being the most problematic weed species in soybean production in all four states.

One of the main factors leading to the rapid rise of Palmer amaranth as one of the most problematic weed species was the loss of glyphosate efficacy. Glyphosate [*N*-(phosphonomethyl)glycine] is a nonselective, broad-spectrum, postemergence (POST) herbicide that inhibits 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), thus depleting tryptophan, tyrosine, and phenylalanine (amino acids vital for protein synthesis and biosynthetic pathways leading to plant growth) (Amrhein et al. 1980; Senseman 2007). Glyphosate-resistant [Roundup Ready® (RR)] soybean [*Glycine max* (L.) Merr.] cultivars were first sold in 1996 and currently greater than 70% of soybean hectarage in Arkansas is planted using RR soybean [Jeremy Ross (Arkansas Soybean Extension Specialist), personal communication]. The introduction of glyphosate-resistant (GR) crops resulted in a monoculture weed control program based solely around glyphosate (Young et al. 2006). Producers relied on this highly efficacious herbicide (glyphosate) for broad-spectrum weed control, resulting in multiple POST applications and the overdependence of a single mechanism of action (MOA), hence, increasing the risk of herbicide-resistant weeds evolving (Beckie 2006; Norsworthy et al. 2012).

Glyphosate-resistant Palmer amaranth was first confirmed in Georgia in 2005, followed by Arkansas in 2006, and currently GR Palmer amaranth is reported in 28 states in the U.S. (Heap 2014; Norsworthy, personal communication). With the evolution of herbicide resistance [glyphosate and acetolactate synthase (ALS)-inhibiting herbicides] in Palmer amaranth, soybean producers have few effective POST herbicide options to manage Palmer amaranth (Riar et al. 2013).

Glufosinate [2-amino-4-(hydroxymethylphosphinyl)butanoic acid] is a nonselective, contact, POST herbicide that inhibits glutamine synthetase which allows toxic amounts of ammonia to accumulate in the plant. Hence, glufosinate kills plant tissues and ultimately results in plant death of many annual and perennial weed species when applied in a timely manner (Coetzer et al. 2001; Droge et al. 1992; Gardner et al. 2006; Norris et al. 2002; Senseman 2007; Shauck and Smeda 2012). Glufosinate-resistant soybean [LibertyLink ® (LL)] cultivars were first available on a limited basis to producers in 1999 (Wiesbrook et al. 2001). The addition of LL soybean gave producers another effective MOA for over-the-top control of GR Palmer amaranth.

Soil-applied residual herbicides are efficacious for an extended period of time compared to POST herbicides (i.e. glufosinate or glyphosate) that are only efficacious on the weeds present at the time of application (Ellis and Griffin 2002; Taylor-Lovell et al. 2002; Weisbrook et al. 2001). However, residual herbicide molecules must be in a soil solution in order for germinating weeds to absorb the herbicide, making residual herbicides highly dependent on precipitation for activation (Johnson et al. 2012; Krausz et al. 2001; Stewart et al. 2010). The addition of soil-applied residual herbicides to POST herbicide programs not only increases MOA diversity, but also decreases the risk of herbicide-resistance or reduces the spread of herbicide-resistance once it evolves.

There is a renewed need for research on how the incorporation of cultural and mechanical management practices can influence weed management, particularly GR Palmer amaranth. Some examples of these management practices are cover crops, row spacing, seeding rate, and tillage practices. Cover crops can suppress weeds by providing a physical barrier on the soil surface and the release of allelochemicals that can inhibit plant growth and potentially reduce the number of in-season herbicide applications (Weston 1996). Weed control has been reported to increase and weed biomass, emergence, density, and survival have been reported to decrease as soybean row spacing is narrowed, seeding rates are increased, and a one-time deep tillage event is employed (DeVore et al. 2013; Harder et al. 2007; Hock et al. 2006; Norsworthy et al. 2007; Young et al. 2001).

Since the occurrence of herbicide-resistant weeds, producers are beginning to understand the need of using an integrated weed management strategy to control these problematic weeds. An overreliance on any effective weed management tool will result in its loss whether the tool be chemical or nonchemical in nature. Hence, producers must take a multi-faceted approach to weed management by incorporating highly efficacious herbicide programs with both cultural and mechanical practices to manage herbicide-resistant weeds and decrease the evolution of resistance. Therefore, the objectives of this research were to:

(1) determine the effect of integrating fall planted cereals and deep tillage with herbicide programs for glyphosate-resistant Palmer amaranth management in glyphosate- and glufosinate-resistant soybean,
(2) determine the effect of drill-seeded soybean density on Palmer amaranth emergence with and without a preemergence residual herbicide, and
(3) determine the effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth management.

Literature Cited

Amrhein N, Deus B, Gehrke P, Steinrucken HC (1980) The site of inhibition of the shikimate pathway by glyphosate II. Interference of glyphosate with chorismate formation in vivio and in vitro. Plant Physiol 66:830-834

Beckie HJ (2006) Herbicide-resistant weeds: management tactics and practices. Weed Technol 20:793-814

Coetzer E, Al-Khatib K, Loughin TM (2001) Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. Weed Sci 49:8-13

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263-270

Dröge W, Broer I, Pühler A (1992) Transgenic plants containing the phosphinothricin-*N*-acetyltransferase gene metabolize the herbicide L-phosphinothricin (glufosinate) differently from untransformed plants. Planta 187:142-151

Duke JA (1992) Handbook of edible weeds. CRC Press, Inc., 2000, Boca Raton, Florida 33431

Ellis JM, Griffin JL (2002) Benefits of soil-applied herbicides in glyphosate-resistant soybean (*Glycine max*). Weed Technol 16:541-547

Gardner AP, York AC, Jordan DL, and Monks DW (2006) Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J Cotton Sci 10:328-338

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744-752

Heap I (2014) The Internation Survey of Herbicide Resistant Weeds. http://www.weedscience.org/summary/home.aspx. Accessed: April 26, 2014

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci 54:38-46

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Johnson WG, Chahal GS, Regehr DL (2012) Efficacy of various corn herbicides applied preplant incorporated and preemergence. Weed Technol 26:220-229

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199-204

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523-527

Krausz RF, Young BG, Kapusta G, Matthews JL (2001) Influence of weed competition and herbicides on glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:530-534

Moerman DE (1998) Native American ethnobotany. Portland, OR: Timber

Monks DW, Oliver LR (1988) Interactions between soybean (*Glycine max*) cultivars and selected weeds. Weed Sci 36:770-774

Norris JL, Shaw DR, Snipes CE (2002) Influence of row spacing and residual herbicides on weed control in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:319-325

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK, Jha P, Bridges Jr. W (2007) Sicklepod (*Senna obtusifolia*) survival and fecundity in wide- and narrow-row glyphosate-resistant soybean. Weed Sci 55:252-259

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci Special Issue Pp. 31-62

Riar DS, Norsworthy JK, Steckel LE, Stephenson IV DO, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the Midsouth United States-soybean: A consultant's perspective. Weed Technol 27:612-622

Sauer JD (1950) The grain amaranths and their relatives: a survey of their history and classification. Ann Mo Bot Gard 37:561-632

Sauer JD (1967) The grain amaranths and their relatives: A revised taxonomic and geographic survey. Ann Mo Bot Gard 54:103-137

Scott B, Smith K (2011) Prevention and control of glyphosate-resistant pigweed in soybean and cotton. University of Arkansas Cooperative Extension Service Printing Services FSA 2152-PD-3-11RV 4 pp

Senseman SA (2007) Herbicide Handbook. 9th ed. Lawrence, Kan. Weed Science Society of America

Shauck TC, Smeda RJ (2012) Control of glyphosate-resistant corn (*Zea mays*) with glufosinate or imazethapyr plus imazethapyr in a replant situation. Weed Technol 26:417-421

Singh H (1961) Grain amaranths, buckwheat and chenopods. Indian Counc Agric Res Cereal Crop Ser 1:1-46

Steckel LE (2007) The dioecious *Amaranthus* spp.: Here to stay. Weed Technol 21:567-570

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre- and postemergence herbicide efficacy in soybean. Weed Technol 24:234-243

Taylor-Lovell S, Wax LM, Bollero G (2002) Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol 16:502-511

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the Southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145-157

Weisbrook ML, Johnson WG, Hart SE, Bradley PR, Wax LM (2001) Comparison of weed management systems in narrow-row, glyphosate- and glufosinate-resistant soybean (*Glycine max*). Weed Technol 15:122-128

Weston LA (1996) Utilization of allelopathy for weed management in agroecosystems. Agron J 88:860-866

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307

Young BG, Young JM, Gonzini LC, Hart SE, Wax LM, Kapusta G (2001) Weed management in narrow- and wide-row glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:112-121

CHAPTER II

Integrating Fall Planted Cereals and Deep Tillage with Herbicide Programs for Glyphosate-Resistant Palmer Amaranth Management in Glyphosate- and Glufosinate-Resistant Soybean

Abstract: A field experiment was conducted at Marianna, AR in 2012 and 2013 to test various combinations of (1) soybean production systems: full-season tillage (rye plus deep tillage using a moldboard plow), full-season (no rye plus no tillage), late-season tillage (wheat plus deep tillage), and late-season (no wheat plus no tillage); (2) soybean cultivars: glufosinate- or glyphosate-resistant; and (3) four herbicide programs for management of glyphosate-resistant Palmer amaranth. At soybean harvest, Palmer amaranth control was 95 to 100% when flumioxazin plus pyroxasulfone was applied PRE. Both years full-season tillage and late-season tillage systems in combination with flumioxazin plus pyroxasulfone applied PRE increased Palmer amaranth control over the same systems in the absence of flumioxazin plus pyroxasulfone applied PRE. The addition of tillage to the full-season and late-season systems reduced Palmer amaranth densities at harvest. Similarly, Palmer amaranth seed production was generally lower in the full-season tillage and late-season tillage systems compared to the full-season and late-season no tillage systems, regardless of soybean cultivar and herbicide programs. Soybean grain yields and partial returns were generally greater when flumioxazin plus pyroxasulfone was applied PRE. Overall, the use of deep tillage in the full-season or late-season systems in combination with a PRE application of flumioxazin plus pyroxasulfone provided greater control of Palmer amaranth, decreasing both density and seed production and increasing soybean grain yields and partial returns.

Nomencalture: Palmer amaranth, *Amaranthus palmeri* (S.) Wats; soybean, *Glycine max* (L.) Merr.; rye, *Secale cereale* L.

Key words: cover crop, glufosinate-resistant, glyphosate-resistant, Palmer amaranth, POST, PRE, seed production, soil-applied residual, tillage.

Introduction

Glyphosate [*N*-(phosphonomethyl)glycine] was first sold as a nonselective, postemergence (POST) herbicide in 1974, as Roundup® by Monsanto Co. (St. Louis, MO 63167) (Baylis 2000; Duke and Powles 2008; Franz et al. 1997; Senseman 2007). Today, glyphosate-containing products are approved for weed control in over 100 crops worldwide and are registered in more than 130 countries across the world (Backgrounder 2005). In 2000, Baylis reported that glyphosate was the fastest growing, biggest selling agrochemical globally.

Several factors contributed to the rapid adoption of glyphosate in agriculture. Since glyphosate is nonselective, it was primarily used for broad-spectrum weed control prior to planting or directed applications to avoid crop contact. Glyphosate inhibits 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) leading to a depletion of the aromatic amino acids (tryptophan, tyrosine, and phenylalanine), which are vital for protein synthesis and plant growth (Amrhein et al. 1980; Senseman 2007). Glyphosate is deemed an environment friendly herbicide because it binds tightly to soil (minimizing leaching/movement to groundwater), has a short half-life (rapidly broken down by soil microbes), and exhibits no atmospheric contamination (non-volatile). Toxicologically, glyphosate is one of the safest pesticides, with acute toxicity less than a common household aspirin (glyphosate LD_{50} for rats >5g kg^{-1}). It has no known detrimental health or health safety issues for humans when used properly (Baylis 2000; Duke and Powles 2008; Geisy et al. 2000; Williams et al. 2000). Even with these positive attributes, glyphosate was not seen as a vital large-scale herbicide until the mid-90s with the commercialization of glyphosate-resistant (GR) crops.

Glyphosate-resistant [Roundup Ready® (RR)] soybean [*Glycine max* (L.) Merr.] were first sold in 1996 followed by canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.), corn

(*Zea mays* L.), sugarbeet (*Beta vulgaris* L.), and alfalfa (*Medicago sativa* L.) (Duke and Powles 2008; Sammons et al. 2007). Since then, adoption of transgenic GR crops has been unprecedented and frequently exclusive for weed control in large areas of the United States. In 2009, > 90% of soybean hectarage in the U.S. was planted in GR soybean and adoption in Argentina was almost 90% within the first four years of introduction (Duke and Powles 2009; Powles 2008; Green 2009). Worldwide, more than 80% of the 120 million ha of transgenic crops grown are glyphosate-resistant, partly because of the economic advantage and the ease of weed control that the glyphosate technology delivers (Duke and Powles 2009).

Glufosinate [2-amino-4-(hydroxymethylphosphinyl)butanoic acid] is a nonselective, contact, POST herbicide (Coetzer et al. 2001; Gardner et al. 2006; Norris et al. 2002). Glufosinate inhibits glutamine synthetase, allowing toxic ammonia to rapidly accumulate in the plant, killing plant tissues and resulting in plant death (Droge et al. 1992; Senseman 2007; Shauck and Smeda 2012). Glufosinate-resistant crops were first released in 1995 (Duke and Powles 2009), and in 1999, glufosinate-resistant soybean [LibertyLink® (LL)] became available on a limited basis (Wiesbrook et al. 2001).

Environmental conditions (soil moisture, relative humidity, light intensity, etc.) are known to influence the efficacy of POST, contact herbicides such as glufosinate (Coetzer et al. 2001; Eubank et al 2008; Senseman 2007). Coetzer et al. (2001) determined glufosinate translocation was greater at high relative humidity (90%) than in low relative humidity (35%) environments.

Amaranthus species, also known as, “pigweeds,” are some of the most problematic weeds in many cropping systems. Understanding the biology and reproduction characteristics of this genus is essential for effective control (Sellers et al. 2003). Palmer amaranth could characteristically be controlled by glyphosate; however, the confirmed cases of glyphosate-resistant biotypes now calls for alternatives to weed management strategies based primarily on glyphosate (Whitaker et al. 2010).

In 2005, the first confirmed case of glyphosate resistance in Palmer amaranth was reported in Georgia (Culpepper et al. 2006). Palmer amaranth is highly competitive because of a rapid growth rate, an extended emergence period, and prolific seed production, and for these reasons, glyphosate resistance was rapidly confirmed in 10 Georgia counties and 11 North Carolina counties during 2005 and 2006 (Culpepper et al. 2008; Horak and Loughlin 2000; DeVore et al. 2013; Jha and Norsworthy 2009; Scott and Smith 2011). In June 2005, Palmer amaranth plants [biotype was later screened and confirmed glyphosate-resistant (GR), at the University of Arkansas at Fayetteville in 2006] were reported to have survived at least two glyphosate applications in a soybean cropping system in Mississippi County, AR (Norsworthy et al. 2008). Today, glyphosate-resistant Palmer amaranth has been confirmed in 28 states in the U.S. (Heap 2014; Norsworthy, personal communication).

The use of cover crops is a cultural practice that can be an effective means to control weeds and use of fewer herbicide applications (Weston 1996). There are two means by which cover crops suppress weeds: physical suppression and release of allelochemicals. Winter annual cover crops are used in many agronomic cropping systems. Winter wheat (*Triticum aestivum* L.) suppresses weed growth by acting as a living, physical mulch and by releasing allelochemicals (Weston 1996). Gallagher et al. (2003) reported 6% or more control of early-season common ragweed (*Ambrosia artemisiifolia* L.) in a wheat cover crop compared to no cover crop, and soybean yields were up to 31% greater. Moore et al. (1994) reported that soybean yields were 69% and 91% greater than bare soil treatments for rye [*Secale cereale* (L.) 'Danko'] and triticale

(*X Triticosecale* Wittmack 'OAC Wintri') mulch treatments, respectively. Moore et al. (1994) also reported live cereal cover crop treatments reduced the emergence of common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) by 78% when compared with no-cover crop treatments.

Combining cover crops with herbicide programs provides the potential of increasing weed control. Reddy et al. (2003) reported that PRE and POST herbicide programs combined with crimson clover [*Trifolium incarnatum* (L.) Dixie] or rye [*Secale cereale* (L.) Elbon] cover crops in soybean controlled barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], broadleaf signalgrass [*Urochloa platyphylla* (Griseb.) Nash], entireleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], and hyssop spurge (*Euphorbia hyssopifolia* L.) 92% or better and 85% or better control of browntop millet [*Brachiaria ramose* (L.) Stapf.] and yellow nutsedge (*Cyperus esculentus* L.).

Using cover crops as a means for weed control can reduce the selection pressure of herbicides, thus reducing the risk of resistance. Cereal crops incorporated into a conservation-tillage, glyphosate-resistant cotton (*Gossypium hirsutum* L.) production system can reduce the selection pressure of glyphosate by aiding in early-season weed management (Norsworthy et al. 2011).

Tillage has long been a part of farming, although as tillage decreases, soil organic matter usually increases. Organic matter stores carbon and reduces the amount of CO_2 (carbon dioxide) that can contribute to global warming. Two main types of tillage are practiced in the United States, conservation and conventional tillage. Conservation tillage is measured immediately after crop planting and is defined as 30% or more of the soil covered by previous residues; reduced tillage is defined as 15 to 30% of the soil being covered by residue; and conventional tillage is defined as any set of practices that leaves less than 15% of the soil covered by crop residues after planting (Horowitz et al. 2010).

Tillage has a strong effect on weed diversity and changes in tillage practices select for different weed species. Leon and Owen (2006) determined that when using conventional tillage, specifically the moldboard plow, fewer seedlings of common waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] emerged throughout the major period of common waterhemp emergence (April-July) compared to no-till, and seedlings in no-till emerged for a longer duration than with other tillage operations. Common cocklebur (*Xanthium strumarium* L.) emergence was reduced by 59 to 69% in no-tillage compared to tilled fields (Norsworthy and Oliveira 2007). Reddy (2005) reported redvine [*Brunnichia ovata* (Walt.) Shinners] could be managed with deep tillage during the fall. Barnes and Oliver (2003) determined conventional tillage provided better sicklepod [*Senna obtusifolia* (L.) Irwin and Barnaby] control than in no-till; however, soybean yields were greater in no-till compared to conventional tillage. DeVore et al. (2013) reported that when soybean had either rye or wheat cover crop in combination with a one-time moldboard plow, a type of deep tillage, Palmer amaranth emergence in soybean was reduced as much as 98%.

The introduction of GR crops allowed a rapid reduction of tillage (Powles 2008; Duke and Powles 2008; Duke and Powles 2009) because weeds that had been controlled with tillage could now be controlled with the broad-spectrum glyphosate. Producers discovered many advantages of reduced tillage, such as time savings and savings on equipment and fuel costs (Lithourgidis et al. 2006). Furthermore, reduced tillage is beneficial to the environment by reducing soil erosion and reduced erosion can also retain soil moisture for longer periods of time allowing more water to be available to plants (DeFelice et al. 2006; Lithourgidis et al. 2005).

Herbicide-resistant weeds could be a threat to conservation-tillage systems in that tillage would have to be used to control resistant weeds if effective herbicides are not available.

The objective of this study was to determine how various production systems in combination with either a glufosinate- or glyphosate-resistant soybean cultivar and multiple herbicide programs affect Palmer amaranth control, density, and seed production, as well as, soybean grain yield and economic partial returns.

Materials and Methods

The experiment was conducted at the Lon Mann Cotton Research Station in Marianna, AR, during 2012 and 2013 in adjacent fields. The soil series was a Convent silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) with 9% sand, 80% silt, 11% clay, 1.8% organic matter, and a soil pH of 6.6. The experiment in 2012 was conducted under dryland conditions; however, a sprinkler irrigator, calibrated to deliver 2.5 cm of water per irrigation event, was used at each application timing to ensure the residual herbicides were activated (Figure 1a). In 2013, polypipe, with holes spaced every one meter, was located on the high end of the graded field so that the test site could be border irrigated throughout the growing season (Figure 1b). The experiment was organized in a split-split plot design with four replications. The main plot factors were four soybean production systems: 1) rye plus tillage (full-season tillage), 2) wheat plus tillage (late-season tillage), 3) no rye plus no tillage (full-season), and 4) no wheat plus no tillage (late-season). Tillage refers specifically to deep tillage with a moldboard plow at an approximate 25-cm depth and tillage will be referring to deep tillage with a moldboard plow throughout the remainder of the chapter. Immediately following tillage on November 9, 2011 and October 25, 2012, the deep-tilled plots were tilled to a 5-cm depth with a field cultivator to allow for a smooth seedbed. The same day 'Wrens Abruzzi' rye (*Secale cereale* L.) and 'Agripro® Coker 9553' wheat (*Triticum aestivum* L.) were drill seeded at 79 kg ha^{-1} and 134 kg ha^{-1}, respectively, using a John Deere grain drill (Deere & Company World Headquarters, Moline, IL 61265).

The subplot factor was either a GR soybean cultivar (AG 5232 in 2012 and AG 5233 in 2013) or a glufosinate-resistant soybean cultivar (Halomax 494 in 2012 and 2013). In the spring of 2012 and 2013, the rye cover crop was desiccated with glyphosate at 870 g ae ha^{-1} two weeks prior to planting the full-season soybean. Biomass production of the rye was measured prior to planting soybean by collecting biomass in four 1-m^2 quadrats. The full-season soybean cultivars were drill seeded using a John Deere no-till drill (Deere & Company World Headquarters, Moline, IL 61265) on May 23, 2012 and May 9, 2013. Wheat was grown to maturity and harvested with a small-plot combine (Massey Ferguson 8xp, AGCO, Duluth, GA 30096) before soybean was planted in the late-season production system. Immediately following wheat harvest, the late-season soybean cultivars were drill seeded on June 5, 2012 and July 7, 2013. Soybean for both the full-season and late-season production systems were drill seeded on a 19-cm row spacing at a rate of 432,000 seed ha^{-1}.

The sub-subplot factor was four herbicide programs: 1) paraquat (Gramoxone® SL, Syngenta Crop Protection, Greensboro, NC 27419) at 700 g ai ha^{-1} applied PRE (control treatment), 2) paraquat at 700 g ha^{-1} applied PRE followed by (fb) glyphosate (Roundup PowerMAX®, Monsanto Company, St. Louis, MO 63167) at 870 g ae ha^{-1} or glufosinate (Liberty® 280 SL, Bayer CropScience LP, Research Triangle Park, NC 27709) at 595 g ai ha^{-1} applied 14 days after planting (DAP) fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} applied 28 DAP, 3) paraquat at 700 g ha^{-1} applied PRE fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} + (*S*-metolachlor + fomesafen at 1217 g ai ha^{-1} + 266 g ai ha^{-1}, respectively) (Prefix®, Syngenta Crop Protection, Greensboro, NC 27419) applied 14 DAP fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ai ha^{-1} + acetochlor (Warrant®, Monsanto Company, St. Louis, MO 63167) at 1260 g ai ha^{-1} applied 28 DAP, 4) paraquat at 700 g ha^{-1} + (flumioxazin + pyroxasulfone at 82 g ai ha^{-1} + 104 g ai ha^{-1}, respectively) (Fierce®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) applied PRE fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} + (*S*-metolachlor + fomesafen at 1217 g ha^{-1} + 266 g ha^{-1}, respectively) applied 14 DAP fb glyphosate at 870 g ha^{-1} or glufosinate at 595 g ha^{-1} + acetochlor at 1260 g ha^{-1} applied 28 DAP. Each sub-subplot measured 2.25 m by 11 m with a 1.5-m alley.

Herbicide treatments were applied with a CO_2-pressurized backpack sprayer consisting of a handheld boom that contained four 110015 flat-fan nozzles (Teejet Technologies, Springfield, IL 62703) on a 48-cm spacing calibrated to deliver 140 L ha^{-1} at 276 kPa. Weed control estimates were taken at each herbicide application and at harvest relative to the no cover crop, no tillage, and paraquat applied PRE treatments (check plots) on a 0 to 100% scale, where 0 was equal to no weed control and 100 was equal to complete weed control.

After soybean planting, two 0.5-m^2 areas were marked with flags (Gempler's, Janesville, WI 53547) in the center of each sub-subplot to provide a uniform and consistent area to determine Palmer amaranth density and seed production. Palmer amaranth plant counts were taken prior to each herbicide application and prior to soybean harvest in both quadrats. At soybean harvest, the surviving Palmer amaranth plants were collected from the two 0.5-m^2 areas, threshed, and total biomass was weighed. Seeds contained in 0.25 g subsamples were counted with three replications per plot then extrapolated to the total biomass weight to determine the total seed production from the surviving Palmer amaranth. Soybean yield was measured at crop maturity by harvesting each individual sub-subplot with a small-plot combine (Massey Ferguson 8xp, AGCO, Duluth, GA 30096) and correcting grain yield to 13% moisture.

To evaluate relative economic performance across treatments, average chemical and seed costs from two distributors in Northeast Arkansas (Helena Chemical Co., Hughes, AR 72348 and Crop Production Services Inc., Crawfordsville, AR 72327) were used along with current market prices from http://www.themiraclebean.com/markets for both soybean and wheat (Table 1). Chemical application, wheat/rye seeding and tillage costs were obtained from the University of Arkansas Division of Agriculture Research and Extension 2014 Crop Enterprise Budgets available at http://www.uaex.edu/farm-ranch/economics-marketing/farm-planning/enterprise-budgets.aspx. Wheat net returns were calculated based on specific costs and returns for this trial. An example wheat enterprise budget is given in Table 2. These data were used to compare production alternatives by calculating partial returns (PR) where only those revenue and cost items that change across production alternatives are tracked. In other words, the production alternative with highest partial returns would be profit maximizing as other costs and revenue items not tracked would be the same regardless of alternative pursued (Kay et al. 2008).

To assess how robust the dominant production alternative was with highest PR, sensitivity analyses on soybean and wheat prices were conducted. Holding all other costs constant, soybean and wheat prices were separately altered to determine what production alternative had the highest PR for soybean prices ranging from \$0.21 to \$0.52 kg^{-1} and wheat prices from \$0.15 to \$0.29 kg^{-1}. The low end of the price spectrum was chosen at calculated short run breakeven prices (for wheat) to cover operating costs and the 10-year low soybean prices as reported by National Agricultural Statistics Service (NASS;

http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS). The high end of the price spectrum is 10-year highs for soybean and wheat prices as reported by NASS.

Data were analyzed in JMP using ANOVA with the MIXED procedure. Years were analyzed separately due to the differences in environmental conditions. Production system, soybean cultivar, herbicide program, and any interactions containing these effects were considered fixed effects. Replication and any interaction containing replication were considered random effects. Means for significant main effects and their interactions were separated by Fisher's protected LSD test at the 0.05 significance level.

Results and Discussion

Palmer Amaranth Control, Density, and Seed Production. At 14 DAP, only one herbicide program had a PRE residual application of flumioxazin plus pyroxasulfone. All experimental treatments containing flumioxazin plus pyroxasulfone PRE in combination with either the full-season tillage or the late-season tillage system had ≥ 98% Palmer amaranth control in both years (data not shown). Furthermore, whenever flumioxazin plus pyroxasulfone was applied PRE minimal Palmer amaranth (0 plants m^{-2} in 2012 and ≤ 1.4 plants m^{-2} in 2013) were observed, regardless of production system and cultivar (Table 3). In comparison, Palmer amaranth densities ranged from 0.4 to 97.9 plants m^{-2} in 2012 and 2.3 to 47.1 plants m^{-2} in 2013, across production systems in the absence of flumioxazin plus pyroxasulfone PRE.

At 14 DAP, the full-season tillage and the late-season tillage systems in combination with the paraquat-only herbicide program reduced Palmer amaranth densities by 17.8 and 18.5 fold, respectively, in 2012 and by 7.8 and 3.7 fold, respectively, in 2013 compared to the full-season and late-season systems with the same herbicide program (Table 3), thus demonstrating the impact of either a rye or a wheat cover crop in combination with deep tillage on reducing early-season Palmer amaranth.

In 2012, a three-way interaction for Palmer amaranth control was influenced by production system, soybean cultivar, and herbicide program at 28 DAP (Table 4). The use of flumioxazin plus pyroxasulfone PRE resulted in ≥ 99% control across all production systems and soybean cultivars. In the absence of flumioxazin plus pyroxasulfone PRE in the full-season and late-season systems, Palmer amaranth control ranged from 53 to 88% compared to the full-season tillage and late-season tillage systems which ranged from 91 to 100%, across cultivars and herbicide programs. In 2013, Palmer amaranth control was ≥ 96% in the PRE and POST residual herbicide programs at 28 DAP compared to ≥ 92% in the POST-only herbicide program, across production systems (Table 5).

At 28 DAP across production systems, Palmer amaranth densities were 0.0 and ≤ 5.0 plants m^{-2} when flumioxazin plus pyroxasulfone was applied PRE compared to ≤ 170.4 and ≤ 37.3 plants m^{-2} in the absence of a PRE residual herbicide in 2012 and 2013, respectively (Table 6). Similar levels of suppression have been reported by DeVore et al. (2013) where a rye cover crop in combination with a one-time deep tillage (moldboard plow) reduced Palmer amaranth emergence up to 98% over a two-year period in soybean.

At soybean harvest, an interaction for Palmer amaranth control occurred between production system and herbicide program in 2012 (Table 7) and between production system, soybean cultivar, and herbicide program in 2013 (Table 8). In 2012, Palmer amaranth control at harvest when flumioxazin plus pyroxasulfone was applied PRE was ≥ 98%, regardless of production system (Table 7). In comparison, Palmer amaranth control ranged from 29 to 86% in the no residual POST-only programs and 34 to 85% in the POST-residual programs, across production systems. Kelton et al. (2013) reported greater late-season *Amaranthus* spp. control when deep tillage using a moldboard plow was used compared to conventional tillage.

In 2013, Palmer amaranth control at harvest in plots treated with flumioxazin plus pyroxasulfone PRE was 95 to 100% whereas control was more variable, ranging from 83 to 100%, in the absence of PRE-applied flumioxazin plus pyroxasulfone, across production systems and cultivars (Table 8). Generally, greater control occurred in the glufosinate-resistant cultivar (≥ 95%) compared to the glyphosate-resistant cultivar (≥ 83%) in the full-season and late-season systems. This decrease in glyphosate efficacy is most likely due to a GR Palmer amaranth population in this study.

At soybean harvest, Palmer amaranth densities were influenced by the interaction of production systems and herbicide programs (Table 9) and by interaction of production systems and soybean cultivars (Table 10) for both years. For both years, no Palmer amaranth were observed in the established quadrats whenever flumioxazin plus pyroxasulfone was applied PRE (Table 9). Furthermore, generally less Palmer amaranth were present in the full-season tillage and late-season tillage systems compared to the full-season and double crop systems without deep tillage for both the glufosinate- and glyphosate-resistant soybean cultivars (Table 10). For instance in 2012, Palmer amaranth densities in the absence of a PRE-applied residual herbicide ranged from 21.4 to 35.5 plants m^{-2} in the full-season system without deep tillage compared to 0.3 to 5.6 plants m^{-2} in the same system with deep tillage (Table 9).

In 2013, low densities of Palmer amaranth (≤ 1.5 plants m^{-2}) remained at soybean harvest, regardless of production systems or herbicide programs (Table 9). The lower Palmer amaranth densities in 2013 than in 2012 are likely due to the soybean achieving a rapid canopy in 2013 when ample water was available. Also, the early-season Palmer amaranth density in the test site in 2013 was less than that of 2012, which likely contributed to the presence of Palmer amaranth at soybean harvest. Conversely, soybean had limited water in the 2012 growing season. Canopy formation has previously been reported to alter the light environment at the soil surface as well as diurnal temperature fluctuations, both known to influence Palmer amaranth germination (Jha and Norsworthy 2009; Norsworthy 2004).

Palmer amaranth seed production was influenced by the main effects of production system and soybean cultivar in 2012 (Table 11) and by the interaction of production systems and soybean cultivars in 2013 (Table 12). In 2012, the full-season tillage and late-season tillage production systems had less Palmer amaranth seed production (≤ 9,100 seed m^{-2}) compared to the same production systems without deep tillage (≥ 19,300 seed m^{-2}). Furthermore, Palmer amaranth seed production was less for the glufosinate-resistant soybean cultivar (10,300 seed m^{-2}) than the GR soybean cultivar (17,900 seed m^{-2}) (Table 11). Jha and Norsworthy (2012) reported when glufosinate (820 g ai ha^{-1}) was applied to Palmer amaranth at early reproductive development seed production was reduced up to 95%.

In 2013, the two soybean cultivars were different only in the late-season production system (Table 12). Palmer amaranth seed production was 61.3 fold greater in the GR cultivar compared to the glufosinate-resistant cultivar. Furthermore, Palmer amaranth seed production was greater in the late-season production sytem (24,500 seed m^{-2}) compared to the remaining production systems (≤ 3,000 seed m^{-2}) for the GR cultivar.

This research shows that a rye cover crop followed by soybean or wheat with soybean in combination with deep tillage can significantly reduce Palmer amaranth densities, which in turn results in improved weed control. When these cultural and mechanical practices are incorporated into a highly efficacious herbicide program like flumioxazin plus pyroxasulfone applied PRE followed by POST-residual herbicides, Palmer amaranth can be adequately managed with minimal additions to the soil seedbank each fall.

Soybean Grain Yield. A lack of rainfall in 2012 hindered soybean growth and negatively impacted soybean grain yield. A two-way interaction between production system and herbicide program, averaged over soybean cultivar, occurred in 2012. Soybean grain yield for all production systems, except the late-season tillage, was greatest in the presence of flumioxazion plus pyroxasulfone applied PRE followed by POST residual herbicide applications (Table 13).

For soybean grain yield in 2013, a two-way interaction occurred between production system and herbicide program (Table 13) and between soybean cultivar and production system (Table 14). The use of a PRE application of flumioxazin plus pyroxasulfone followed by POST residual herbicide applications at 14 and 28 DAP resulted in the largest numerical soybean grain yield in all production systems, except for the full-season production system (Table 13).

In the absence of flumioxazin plus pyroxasulfone PRE and POST herbicide applications at 14 and 28 DAP, the full-season plus tillage and the late-season plus tillage production systems resulted in an increase of soybean grain yield of 310 kg ha^{-1} and 1,200 kg ha^{-1}, respectively, compared to full-season and late-season production systems without deep tillage (Table 13). Although soybean grain yields were not always different among production systems, yields in programs with an effective herbicide were usually numerically less for production systems that had either a rye or wheat cover crop compared to the absence of a cover crop. This could partly be due to soybean stand reductions, thickness of a mulch barrier, or possible negative allelopathic impacts. Previous research has also reported soybean grain yield in the Midsouth being greater in the absence of cereal cover crops compared to their presence (Reddy 2001).

For the full-season tillage production system, GR soybean had greater soybean grain yield (3,470 kg ha^{-1}) compared to glufosinate-resistant soybean (2,610 kg ha^{-1}) (Table 14). The remaining production systems differed numerically, but were not statistically different between the glufosinate-resistant and GR soybean, thus showing no statistical benefit between the two different soybean cultivars. It should also be noted that these are just two of many available GR and glufosinate-resistant cultivars and is not an indication that one technology out performs in regards to yield. Actually, yield comparison trials in Arkansas indicate the soybean yields for both cultivars possessing glyphosate or glufosinate resistance are comparable.

Economic Partial Returns and Sensitivity Analyses. The low soybean grain yields and increased costs of the rye and wheat seed along with deep tillage costs had a negative impact on partial returns for the 2012 growing season. Wheat grain yields were 4054 kg ha^{-1} and rye biomass was 603 g m^{-2} during the growing season of 2012. Negative partial returns generally occurred for the production systems that did not include residual herbicides and POST herbicide applications at 14 and 28 DAP, except for the late-season tillage production system because of the additional profit associated with the wheat grain yield (Table 15). Greater losses could be assumed since this partial return budget did not take into account all production costs of soybean (i.e. fertilizer, insecticide, fungicide, irrigation costs, etc.) that producers would likely incur. Similar results have been reported by Reddy (2001), where added input costs resulted in either negligible or negative partial returns. Positive partial returns for the different production systems, ranging from \$3.15 to \$417.84 ha^{-1}, occurred when flumioxazin plus pyroxasulfone was applied at soybean planting.

For the 2013 growing season, only positive partial returns were observed (Table 16).

Similar to 2012, the late-season tillage production system generally had larger partial returns, across herbicide programs, compared to the remaining production systems due to the increased profit from the wheat grain yield. During the growing season of 2013, wheat grain yields were 3614 kg ha^{-1} and rye biomass was 534 g m^{-2}. Excluding the late-season plus tillage production system, the greatest partial return ($1,524.17 ha^{-1}) occurred in the full-season production system with the GR soybean cultivar when flumioxazin plus pyroxasulfone was applied PRE.

Overall, the largest partial returns, for both years, were generally associated with the late-season tillage production system due to the additional income generated from the wheat grain yield. Across production systems and soybean cultivars for both years, partial returns were generally greatest in the presence of flumioxazin plus pyroxasulfone applied PRE followed by POST residual herbicide applications in combination with glufosinate or glyphosate.

Sensitivity analyses were calculated to determine the most profitable treatment due to varying soybean market prices by comparing full-season and full-season plus tillage production systems and by comparing late-season and late-season plus tillage production systems in combination with soybean cultivars and herbicide programs in 2012 (Figure 2) and 2013 (Figure 3). Furthermore, varying wheat market prices were used to determine which combination of soybean cultivar and herbicide program was most profitable in the late-season plus tillage production system for both years (Figure 4).

In 2012, the full-season production system in combination with the GR soybean cultivar and flumioxazin plus pyroxasulfone applied PRE treatment had the greatest partial returns when soybean market prices ranged from $0.21 to $0.42 kg^{-1}. Furthermore, greatest partial returns occurred in the full-season plus tillage production system in combination with the GR cultivar and a PRE-applied residual herbicide whenever soybean market prices were between $0.43 to

$0.52 kg^{-1} (Figure 2). When comparing the late-season and late-season plus tillage production systems, the treatment containing late-season plus tillage production system in combination with the GR cultivar and solely glyphosate POST herbicide program was the most profitable treatment across all soybean market prices evaluated.

The full-season, GR, POST (residual)-only treatment was most profitable when soybean market prices ranged from $0.21 to $0.27 kg^{-1}, when comparing the full-season and full-season plus tillage production systems in 2013 (Figure 3). The increase of costs associated with the rye seed, planting, and tillage negatively impacted the partial returns for the full-season plus tillage production system; hence, the full-season production system had greater partial returns across varying soybean market prices.

The additional net returns generated from the wheat in late-season plus tillage production system led to greater partial returns across the different soybean market prices in 2013 (Figure 3). The late-season plus tillage system in combination with the GR cultivar and flumioxazin plus pyroxasulfone PRE-applied treatment was most profitable over the majority of the soybean market prices.

A separate sensitivity analysis was calculated to determine which treatment combination between the late-season and late-season plus tillage production system was the most profitable when soybean market prices were held constant at $0.43 kg^{-1} and wheat market prices were evaluated at breakeven prices ($0.15 kg^{-1} in 2012 and $0.17 kg^{-1} in 2013) for the low end and a 10 yr high ($0.29 kg^{-1}) for the high end of the price spectrum (Figure 4). The larger range in wheat prices during 2012 is due to a lower breakeven price since wheat grain yields were greater during 2012 (4,059 kg ha^{-1}) than 2013 (3,614 kg ha^{-1}). For both years, the late-season plus tillage production system in combination with the GR soybean cultivar was generally the most profitable over the range of wheat prices. Furthermore, the aforementioned production system and soybean cultivar in combination with glyphosate POST (no residual) was most profitable during 2012 and flumioxazin plus pyroxasulfone applied PRE was most profitable during 2013.

Practical Implications

Palmer amaranth control was greater and Palmer amaranth densities and seed production were lower whenever flumioxazin plus pyroxasulfone was applied PRE and was followed by POST applications of glufosinate or glyphosate in combination with effective residual herbicides, regardless of production system. Furthermore, the full-season tillage and the late-season tillage production systems reduced Palmer amaranth densities and seed production; hence, increasing Palmer amaranth control in comparison to the full-season and late-season production systems, regardless of herbicide program. Reducing Palmer amaranth emergence by incorporating different cultural and mechanical practices aids in reducing selection pressure on herbicides, both PRE and POST, thus lessening the risk of herbicide resistance.

Soybean grain yields and partial returns were generally greater in the presence of residual herbicides for both years. Although soybean grain yields were not always greatest for the late-season tillage production system, the partial returns were generally larger due to the additional net returns provided from the wheat enterprise. The additional input cost of rye associated with the full-season tillage production system decreased the overall partial returns in comparison to the late-season system, as the rye was not harvested.

In conclusion, the rye plus deep tillage or wheat plus deep tillage production systems improved Palmer amaranth control and reduced Palmer amaranth density and seed production. When these production systems are incorporated into an effective PRE followed by POST residual herbicide program, as used in this study, Palmer amaranth control further increases, leading to a decrease in Palmer amaranth densities at soybean harvest as well as Palmer amaranth seed production. By decreasing Palmer amaranth seed production, the soil seedbank diminishes and herbicide sustainability increases. Taking an integrated weed management approach to manage a troublesome weed like Palmer amaranth as shown here can improve control while potentially providing added net returns in the wheat enterprise. Most importantly, a diverse system that integrates a multifaceted approach for managing Palmer amaranth and other resistant-prone weeds while focusing on lowering the soil seedbank must be utilized if farmers are to minimize risk of additional weeds evolving herbicide resistance (Norsworthy et al. 2012).

Table 1. Cost associated with chemical, seed, application, equipment, and market price for calculating partial returns in 2012 and 2013.

	Partial return costs	
Chemical[a]	Unit	Price unit^{-1} ($)
Warrant (acetochlor)	L	8.52
Fierce (flumioxazin + pyroxasulfone)	G	0.21
Liberty (glufosinate)	L	20.84
Roundup Weathermax (glyphosate)	L	7.12
Gramoxone (paraquat)	L	8.50
Prefix (*S*-metolachlor + fomesafen)	L	13.22
Seed[a]		
glufosinate-resistant	140,000	57.75
glyphosate-resistant	140,000	61.00
“Wrens Abruzzi” rye	Kg	1.10
“AgriPro Coke 9553” wheat	Kg	0.69
Custom chemical application[b]		
ground application	Ha	14.82
Market price[c]		
soybean	Kg	0.43
wheat	Kg	0.23
Equipment[d]		
grain-drill (9 m)	Ha	22.60
moldboard plow (12-shank)	Ha	17.69

[a] Chemical and seed costs were averaged from prices given by Helena Chemical Co., Hughes, AR 72348 and Crop Production Services Inc., Crawfordsville, AR 72327 during the summer of 2014.

[b] Application cost was determined from the University of Arkansas Division of Agriculture Research and Extension’s 2014 Crop Enterprise Budgets, which can be found at: www.uaex.edu/farm-ranch/economics-marketing/farm-planning/enterprise-budgets.aspx.

[c] Soybean and wheat market prices were based off the August 2014 and September 2014, respectively, prices accessed from the Arkansas Soybean Promotion Board, which can be found at: http://www.themiraclebean.com/markets.

[d] Includes capital recovery, repairs, fuel, and labor costs. Equipment was pulled by a 4WD 225 hp tractor.

Table 2. Wheat Enterprise Budget Adapted from the University of Arkansas Crop Enterprise Budgets by substituting observed yield and cost data.

CROP VALUE	**Unit**	**Yield**	**Price/Unit**	**Revenue**[c]
Crop Value (net of hauling at $0.81 kg^{-1})	kg	3,800[b]	0.22	828.78
OPERATING EXPENSES	**Unit**	**Quantity**	**Price/Unit**	**Costs**
Seed, includes all fees	ha	134.5	0.69	93.29
Nitrogen	kg	116	0.99	114.84
Machinery and equipment[c]				
Diesel fuel, pre-post harvest	L	16.14	0.84	13.54
Repairs and maintenance, pre-post harvest	ha	1.00	10.04	10.04
Diesel fuel, harvest	L	30.17	0.84	25.30
Repairs and maintenance, harvest	ha	1.00	25.84	25.84
Labor	hr	1.23	11.65	14.31
Operating Interest @ 4.75% pa[a] for ½ of operating Expenses	ha	1.00	7.06	7.06
Total Operating Expenses				**$304.22**
Returns to Operating Expenses				**$524.56**
CAPITAL RECOVERY & UNALLOCATED COSTS				
Pre-harvest, post-harvest, and harvest machinery[d]	ha	1	72.50	72.50
TOTAL SPECIFIED EXPENSES				**$376.72**
NET RETURNS				**$452.06**

[a] Abbreviations: pa, per annum

[b] Varies by year and production alternative. An average yield is used here to aid in calculations.

[c] Numbers are different due to rounding errors.

[d] Machinery used were a fertilizer spreader, 12 shank moldboard plow and 9 m grain drill pulled by a 225 hp 4WD tractor, combine with wheat header and grain cart using default useful life, salvage and purchase price information as used in the program. Trials did not require other fertilizer and/or chemical applications as typically required on wheat production. Expenses also did not include any charges for land so that returns are to land and management resources employed.

Table 3. Palmer amaranth density at 14 days after soybean planting as influenced by production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Density							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing	Full-season[b]	Full-season tillage[c]	Late-season[d]	Late-season tillage[e]	Full-season	Full-season tillage	Late-season	Late-season tillage
	g ai or ae[f] ha^{-1}		plants m^{-2}							
Paraquat	700	PRE[a]	97.9 aA[h]	5.5 aBC	29.6 aB	1.6 aC	33.6 aA	4.3 aB	10.6 abB	2.9 aB
Paraquat	700	PRE								
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
Glyphosate	870	28 DAP	87.5 aA	4.8 aB	18.5 aB	3.4 aB	42.4 aA	2.3 aB	11.1 abB	3.6 aB
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	73.6 aA	0.6 aC	24.3 aB	0.4 aC	47.1 aA	2.8 aB	18.5 aB	3.3 aB
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	0.0 bA	0.0 aA	0.0 bA	0.0 aA	0.0 bB	0.0 aB	1.4 bA	0.0 aB

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.
[b] Full-season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 4. Palmer amaranth control at 28 days after soybean planting as influenced by production system, soybean cultivar, and herbicide program at Marianna, AR in 2012.

			Control							
			Production system							
			Full-season[b]		Full-season tillage[c]		Late-season[d]		Late-season tillage[e]	
			Soybean cultivar							
Herbicide program	Rate	Application timing	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant
	g ai or ae[f] ha^{-1}		%							
Paraquat	700	PRE[a]								
Glufosinate[g]/	595	14 DAP[a]								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
Glyphosate	870	28 DAP	84 bB[h]	69 bC	95 bAB	92 aAB	88 abAB	53 bD	99 aA	99 aA
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	83 bBC	75 bC	93 bAB	91 aAB	73 bC	71 bC	100 aA	98 aA
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	100 aA	100 aA	100 aA	99 aA	100 aA	100 aA	100 aA	100 aA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.
[b] Full-season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within soybean cultivar within a production system and uppercase letters are used to compare soybean cultivars within a production system with a herbicide program. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$. Overall model LSD for the interaction of production system*soybean cultivar*herbicide program = 12.

Table 5. Palmer amaranth control at 28 days after soybean planting as influenced production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2013.

			Control			
			Production system			
Herbicide program	Rate	Application Timing	Full-season[b]	Full-season tillage[c]	Late-season[d]	Late-season tillage[e]
	g ai or ae[f] ha^{-1}		%			
Paraquat	700	PRE[a]				
Glufosinate[g]/	595	14 DAP[a]				
glyphosate[f]	870	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP	92 bB[h]	99 aA	95 bAB	98 aA
Paraquat	700	PRE				
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1260	28 DAP	100 aA	100 aA	96 abC	98 aB
Paraquat	700	PRE				
+ flumioxazin	82	PRE				
+ pyroxasulfone	104	PRE				
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1260	28 DAP	99 aA	100 aA	98 aB	98 aB

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.

[b] Full-season represents no rye and no tillage.

[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare production systems within a herbicide program. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 6. Palmer amaranth density at 28 days after soybean planting as influenced by production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Density							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing	Full-season[b]	Full-season tillage[c]	Late-season[d]	Late-season tillage[e]	Full-season	Full-season tillage	Late-season	Late-season tillage
	g ai or ae[f] ha^{-1}		plants m^{-2}							
Paraquat	700	PRE[a]	170.4 aA	12.9 aB	42.6 aB	3.8 aB	35.3 aA	5.8 aB	5.5 aB	2.9 aB
Paraquat	700	PRE								
Glufosinate[g]/	595	14 DAP								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
Glyphosate	870	28 DAP	80.8 bA	7.1 abB	7.3 bB	1.3 aB	37.3 aA	0.5 bB	2.8 bB	0.9 abB
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	75.8 bA	2.1 bB	14.0 bB	0.5 aB	2.6 bA	0.1 bA	0.5 bcA	0.0 bA
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	0.0 cA	0.0 bA	0.0 bA	0.0 aA	5.0 bA	0.0 bA	0.1 cA	0.0 bA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.
[b] Full-season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 7. Palmer amaranth control at soybean harvest as influenced by production system and herbicide program, averaged over soybean cultivar at Marianna, AR in 2012.

			Control			
			Production system			
Herbicide program	Rate	Application timing	Full-season[b]	Full-season tillage[c]	Late-season[d]	Late-season tillage[e]
	g ai or ae[f] ha^{-1}		%			
Paraquat	700	PRE[a]				
Glufosinate[g]/	595	14 DAP[a]				
glyphosate[f]	870	14 DAP				
Glufosinate/	595	28 DAP				
Glyphosate	870	28 DAP	29 bB[h]	72 bA	75 bA	86 bA
Paraquat	700	PRE				
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1260	28 DAP	34 bC	67 bB	54 cB	85 bA
Paraquat	700	PRE				
+ flumioxazin	82	PRE				
+ pyroxasulfone	104	PRE				
Glufosinate/	595	14 DAP				
glyphosate	870	14 DAP				
+ *S*-metolachlor	1217	14 DAP				
+ fomesafen	266	14 DAP				
Glufosinate/	595	28 DAP				
glyphosate	870	28 DAP				
+ acetochlor	1260	28 DAP	98 aA	98 aA	98 aA	99 aA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.

[b] Full-season represents no rye and no tillage.

[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within a herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 8. Palmer amaranth control at soybean harvest as influenced by production system, soybean cultivar, and herbicide program at Marianna, AR in 2013.

			Control							
			Production system							
			Full-season[b]		Full-season tillage[c]		Late-season[d]		Late-season tillage[e]	
			Soybean cultivar							
Herbicide Program	Rate	Application timing	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant
	g ai or ae[f] ha^{-1}		%							
Paraquat	700	PRE[a]								
Glufosinate[g]/	595	14 DAP[a]								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
Glyphosate	870	28 DAP	97 aA[h]	83 bB	94 aA	94 bA	97 aA	83 bB	98 bA	98 bA
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	98 aA	92 abB	97 aA	97 abA	99 aA	97 aA	100 aA	100 aA
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	95 aA	98 aA	100 aA	100 aA	100 aA	100 aA	100 aA	100 aA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.
[b] Full-season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within soybean cultivar within a production system and uppercase letters are used to compare soybean cultivars within a production system with a herbicide program. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$. Overall model LSD for the interaction of production system*soybean cultivar*herbicide program = 6.

Table 9. Palmer amaranth density at soybean harvest as influenced by herbicide program and production system, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Density							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing	Full-season[b]	Full-season tillage[c]	Late-season[d]	Late-season tillage[e]	Full-season	Full-season tillage	Late-season	Late-season tillage
	g ai or ae[f] ha^{-1}		plants m^{-2}							
Paraquat	700	PRE[a]	35.5 aA[h]	5.6 aB	8.5 aB	1.3 aB	0.5 aA	0.3 aA	1.5 aA	1.1 aA
Paraquat Glufosinate[g]/ glyphosate[f] Glufosinate/ glyphosate	700 595 870 595 870	PRE 14 DAP[a] 14 DAP 28 DAP 28 DAP	21.5 bA	1.0 bB	12.4 aAB	3.0 aB	0.4 aA	0.0 aA	0.9 abA	0.0 bA
Paraquat Glufosinate/ glyphosate + *S*-metolachlor + fomesafen Glufosinate/ glyphosate + acetochlor	700 595 870 1217 266 595 870 1260	PRE 14 DAP 14 DAP 14 DAP 14 DAP 28 DAP 28 DAP 28 DAP	21.4 bA	0.3 bB	2.8 aB	0.3 aB	0.0 aA	0.0 aA	0.1 bA	0.0 bA
Paraquat + flumioxazin + pyroxasulfone Glufosinate/ glyphosate + *S*-metolachlor + fomesafen Glufosinate/ glyphosate + acetochlor	700 82 104 595 870 1217 266 595 870 1260	PRE PRE PRE 14 DAP 14 DAP 14 DAP 14 DAP 28 DAP 28 DAP 28 DAP	0.0 cA	0.0 bA	0.0 aA	0.0 aA	0.0 aA	0.0 aA	0.0 bA	0.0 bA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.
[b] Full-season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[f] Glyphosate rate is acid equivalent.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 10. Palmer amaranth density at soybean harvest as influenced by production system and soybean cultivar, averaged over herbicide program at Marianna, AR in 2012 and 2013.

	Density			
	2012		2013	
	Soybean cultivar			
Production system	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant
	plants m^{-2}			
Full-season[a]	14.4 aA[e]	24.8 aA	0.1 aA	0.3 bA
Full-season tillage[b]	1.7 bA	1.8 bA	0.1 aA	0.0 bA
Late-season[c]	6.2 bA	5.6 bA	0.1 aB	1.1 aA
Late-season tillage[d]	0.3 bA	1.9 bA	0.3 aA	0.3 bA

[a] Full-season represents no rye and no tillage.
[b] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[c] Late-season represents no wheat and no tillage.
[d] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[e] Lowercase letters are used to compare production systems within a soybean cultivar for each year and uppercase letters are used to compare soybean cultivars within a production system for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 11. Palmer amaranth seed production at soybean harvest as influenced by production system, averaged over soybean cultivar and herbicide program and as influenced by soybean cultivar, averaged over production system and herbicide program at Marianna, AR in 2012.[f]

	Seed production
Production system	seed m^{-2}
Full-season[a]	19,300 A[e]
Full-season tillage[b]	9,100 B
Late-season[c]	24,000 A
Late-season tillage[d]	3,900 B
Soybean cultivar	
Glufosinate-resistant	10,300 A
Glyphosate-resistant	17,900 B

[a] Full-season represents no rye and no tillage.

[b] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[c] Late-season represents no wheat and no tillage.

[d] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

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

[f] Herbicide program 4 (refer to materials and method for description) was excluded from the analysis because of the lack of seed production, regardless of production system and soybean cultivar.

Table 12. Palmer amaranth seed production at soybean harvest as influenced by production system and soybean cultivar, averaged over herbicide program at Marianna, AR in 2013.[f]

	Seed production	
	Soybean cultivar	
Production system	Glufosinate-resistant	Glyphosate-resistant
	seed m^{-2}	
Full-season[a]	1,100 aA[e]	3,000 bA
Full-season tillage[b]	1,100 aA	0 bA
Late-season[c]	400 aA	24,500 aB
Late-season tillage[d]	3,600 aA	2,700 bA

[a] Full-season represents no rye and no tillage.

[b] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[c] Late-season represents no wheat and no tillage.

[d] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[e] Lowercase letters are used to compare production systems within a soybean cultivar and uppercase letters are used to compare soybean cultivars within a production system for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

[f] Herbicide program 4 (refer to materials and method for description) was excluded from the analysis because of the lack of seed production, regardless of production system and soybean cultivar.

Table 13. Soybean grain yield as influenced by herbicide program and production system, averaged over soybean cultivar at Marianna, AR in 2012 and 2013.

			Soybean grain yield							
			2012				2013			
			Production system							
Herbicide program	Rate	Application timing	Full-season[b]	Full-season tillage[c]	Late-season[d]	Late-season tillage[e]	Full-season	Full-season tillage	Late-season	Late-season tillage
	g ai or ae[f] ha^{-1}		kg ha^{-1}							
Paraquat	700	PRE[a]	210 bA[h]	250 cA	60 bB	70 bB	2230 bA	2540 aA	940 bB	2140 bA
Paraquat	700	PRE								
Glufosinate[g]/	595	14 DAP[a]								
glyphosate[f]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP	640 bA	1040 bA	430 bA	650 aA	3340 aA	3210 aA	3100 aA	2740 aA
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	380 bA	900 bcA	570 bA	600 aA	4030 aA	3020 aB	3070 aB	2910 aB
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	1670 aA	1980 aA	1220 aAB	510 aB	3980 aA	3370 aA	3330 aA	3260 aA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.
[b] Full-season represents no rye and no tillage.
[c] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.
[d] Late-season represents no wheat and no tillage.

[e] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.
[f] Glyphosate rate is acid equivalent.
[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.
[h] Lowercase letters are used to compare herbicide programs within a production system and uppercase letters are used to compare a production system within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 14. Soybean grain yield as influenced by soybean cultivar and production system, averaged over herbicide program at Marianna, AR in 2013.

	Soybean grain yield	
	Soybean cultivar	
Production system	Glufosinate-resistant	Glyphosate-resistant
	kg ha^{-1}	
Full-season[a]	3260 aA[e]	3540 aA
Full-season tillage[b]	2610 aB	3470 aA
Late-season[c]	2720 aA	2500 bA
Late-season tillage[d]	2800 aA	2720 bA

[a] Full-season represents no rye and no tillage.

[b] Full-season tillage represents rye in combination with deep tillage using a moldboard plow.

[c] Late-season represents no wheat and no tillage.

[d] Late-season tillage represents wheat in combination with deep tillage using a moldboard plow.

[e] Lowercase letters are used to compare production systems within a soybean cultivar and uppercase letters are used to compare soybean cultivars within a production system. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 15. Soybean partial returns as influenced by production system, soybean cultivar, and herbicide program at Marianna, AR in 2012.

			Partial returns							
			Production system							
			Full-season[b]		Full-season tillage[c]		Late-season[b]		Late-season tillage[d]	
			Soybean cultivar							
Herbicide program	Rate	Application timing	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant
	g ai or ae[e] ha^{-1}		$ ha^{-1}							
Paraquat	700	PRE[a]	-117.61[f]	-147.28	-219.01	-236.73	-194.17	-202.72	368.88	364.57
Paraquat	700	PRE								
Glufosinate[g]/	595	14 DAP[a]								
glyphosate[e]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP	40.38	-104.28	124.70	-62.20	-153.21	-94.28	521.80	541.27
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	-169.78	-238.66	-101.31	-84.40	-143.73	-98.60	435.94	466.87
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	287.37	316.31	318.75	332.54	3.15	211.74	246.88	469.71

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.

[b] *Partial returns* = (*yield* * *market price*) – (*chemical cost* + *application cost* + *seed cost*). Glufosinate-resistant soybean seed costs were $0.41 per 1,000 seed and glyphosate-resistant soybean seed costs were $0.44 per 1,000 seed. Chemical costs were determined

from the average of two chemical companies (Table 1). Application costs were assumed to be $14.82 ha^{-1} application^{-1}. Market price was assumed to be $0.43 kg^{-1} of soybean grain.

[c] *Partial returns* = (*yield* * *market price*) – (*chemical cost* + *application cost* + *soybean seed cost* + *rye seed cost* + *rye planting* + *tillage cost*). Glufosinate-resistant soybean seed costs were $0.41 per 1,000 seed and glyphosate-resistant soybean seed costs were $0.44 per 1,000 seed. Rye seed cost was $1.10 kg^{-1}. Chemical costs were determined from the average of two chemical companies (Table 1). Application costs were assumed to be $14.82 ha^{-1} application^{-1}. Market price was assumed to be $0.43 kg^{-1} of soybean grain. Tillage cost was assumed to be $2.95 ha^{-1}, since tillage is done once every 6 years. Rye planting cost was assumed to be $22.60 ha^{-1}.

[d] *Partial returns* = [(s*oybean grain yield* * *market price*) + (*wheat net returns*)] – (*chemical cost* + *application cost* + *soybean seed cost*). Glufosinate-resistant soybean seed costs were $0.41 per 1,000 seed and glyphosate-resistant soybean seed costs were $0.44 per 1,000 seed. Wheat seed cost was $0.69 kg^{-1}. Chemical costs were determined from the average of two chemical companies (Table 1). Application costs were assumed to be $14.82 ha^{-1} application^{-1}. Market price was assumed to be $0.43 kg^{-1} of soybean grain and $0.23 kg^{-1} of wheat grain. Tillage cost was assumed to be $2.95 ha^{-1}, since tillage is done once every 6 years. Wheat planting cost was assumed to be $22.60 ha^{-1}. Full description of wheat net returns can be found in Table 2.

[e] Glyphosate rate is acid equivalent.

[f] (-) denotes negative value.

[g] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

Table 16. Soybean partial returns as influenced by production system, soybean cultivar, and herbicide program at Marianna, AR in 2013.

			Partial returns							
			Production system							
			Full-season[b]		Full-season tillage[c]		Late-season[b]		Late-season tillage[d]	
			Soybean cultivar							
Herbicide program	Rate	Application timing	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant	Glufosinate-resistant	Glyphosate-resistant
	g ai/ae[e] ha^{-1}		$ ha^{-1}							
Paraquat	700	PRE[a]	641.35	843.83	731.12	798.44	209.41	155.68	1,216.64	1,102.53
Paraquat	700	PRE								
Glufosinate[f]/	595	14 DAP[a]								
glyphosate[e]	870	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP	1,259.32	1,016.59	655.18	1,285.97	942.38	1,127.30	1,304.30	1,370.64
Paraquat	700	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	1,256.12	1,495.10	504.05	1,147.31	1,038.72	883.77	1,348.63	1,347.62
Paraquat	700	PRE								
+ flumioxazin	82	PRE								
+ pyroxasulfone	104	PRE								
Glufosinate/	595	14 DAP								
glyphosate	870	14 DAP								
+ *S*-metolachlor	1217	14 DAP								
+ fomesafen	266	14 DAP								
Glufosinate/	595	28 DAP								
glyphosate	870	28 DAP								
+ acetochlor	1260	28 DAP	1,083.24	1,524.17	777.43	1,077.78	1,120.03	924.95	1,418.68	1,480.56

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.

[b] *Partial returns* = (*yield* * *market price*) – (*chemical cost* + *application cost* + *seed cost*). Glufosinate-resistant soybean seed costs were $0.41 per 1,000 seed and glyphosate-resistant soybean seed costs were $0.44 per 1,000 seed. Chemical costs were determined

from the average of two chemical companies (Table 1). Application costs were assumed to be \$14.82 ha^{-1} $application^{-1}$. Market price was assumed to be \$0.43 kg^{-1} of soybean grain.

[c] *Partial returns* = (*yield* * *market price*) – (*chemical cost* + *application cost* + *soybean seed cost* + *rye seed cost* + *rye planting* + *tillage cost*). Glufosinate-resistant soybean seed costs were \$0.41 per 1,000 seed and glyphosate-resistant soybean seed costs were \$0.44 per 1,000 seed. Rye seed cost was \$1.10 kg^{-1}. Chemical costs were determined from the average of two chemical companies (Table 1). Application costs were assumed to be \$14.82 ha^{-1} $application^{-1}$. Market price was assumed to be \$0.43 kg^{-1} of soybean grain. Tillage cost was assumed to be \$2.95 ha^{-1}, since tillage is done once every 6 years. Rye planting cost was assumed to be \$22.60 ha^{-1}.

[d] *Partial returns* = [(*soybean grain yield* * *market price*) + (*wheat net returns*)] – (*chemical cost* + *application cost* + *soybean seed cost*). Glufosinate-resistant soybean seed costs were \$0.41 per 1,000 seed and glyphosate-resistant soybean seed costs were \$0.44 per 1,000 seed. Wheat seed cost was \$0.69 kg^{-1}. Chemical costs were determined from the average of two chemical companies (Table 1). Application costs were assumed to be \$14.82 ha^{-1} $application^{-1}$. Market price was assumed to be \$0.43 kg^{-1} of soybean grain and \$0.23 kg^{-1} of wheat grain. Tillage cost was assumed to be \$2.95 ha^{-1}, since tillage is done once every 6 years. Wheat planting cost was assumed to be \$22.60 ha^{-1}. Full description of wheat net returns can be found in Table 2.

[e] Glyphosate rate is acid equivalent.

[f] Glufosinate used for the glufosinate-resistant soybean cultivar and glyphosate used for the glyphosate-resistant soybean cultivar.

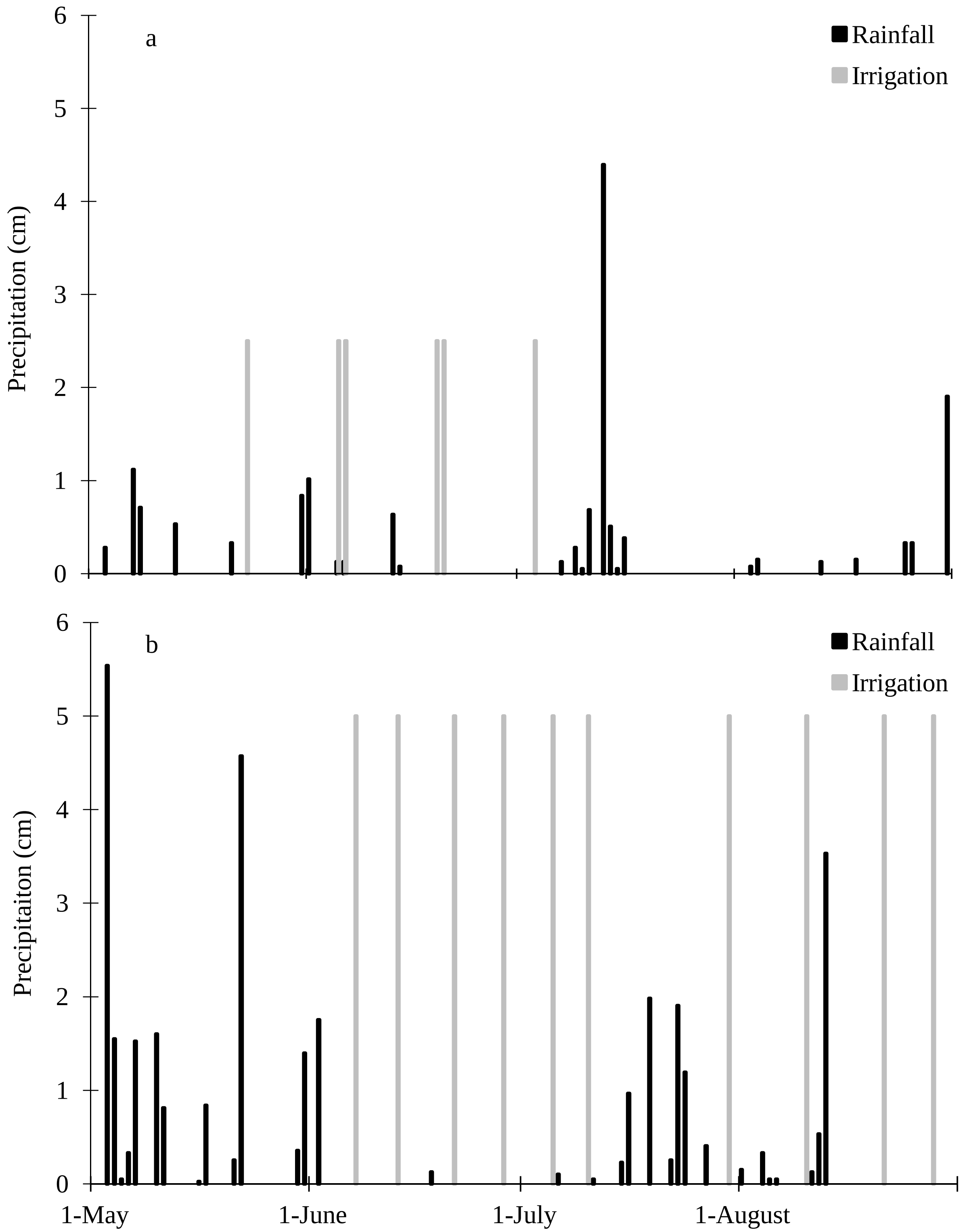

Figure 1. Rainfall and irrigation distribution at Marianna, AR in 2012 (a) and in 2013 (b).

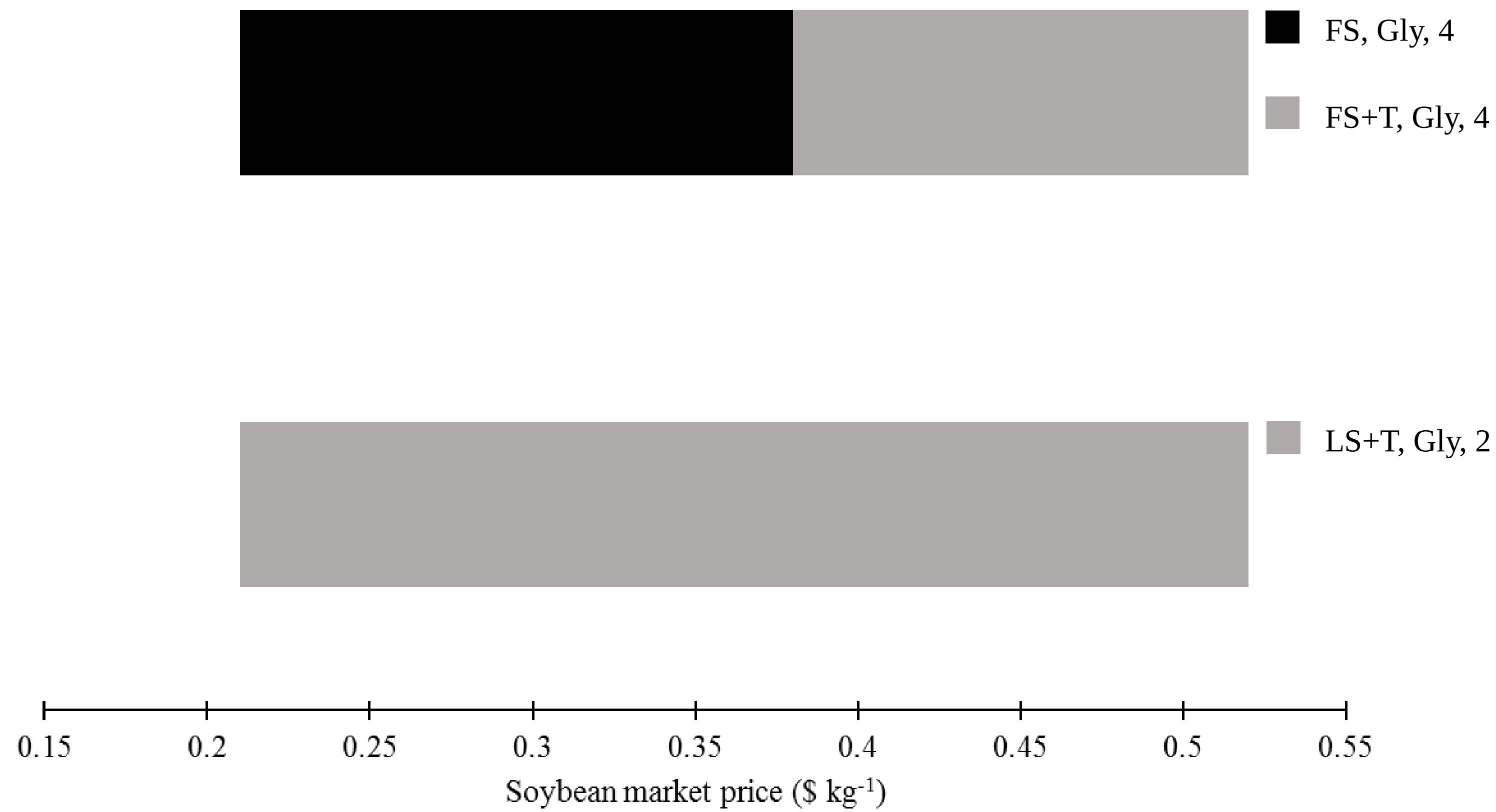

Figure 2. Sensitivity analysis, at Marianna, AR in 2012, comparing all possible treatment combinations for the full-season (FS) and full-season plus tillage (FS+T) and late-season (LS) and late-season plus tillage (LS+T) production systems for the impact of dominant treatment with highest partial returns across 10 year high and low soybean market prices. Abbreviations: Gly, glyphosate-resistant soybean cultivar; 2 and 4 represent specific herbicide programs (see materials and methods for complete description).

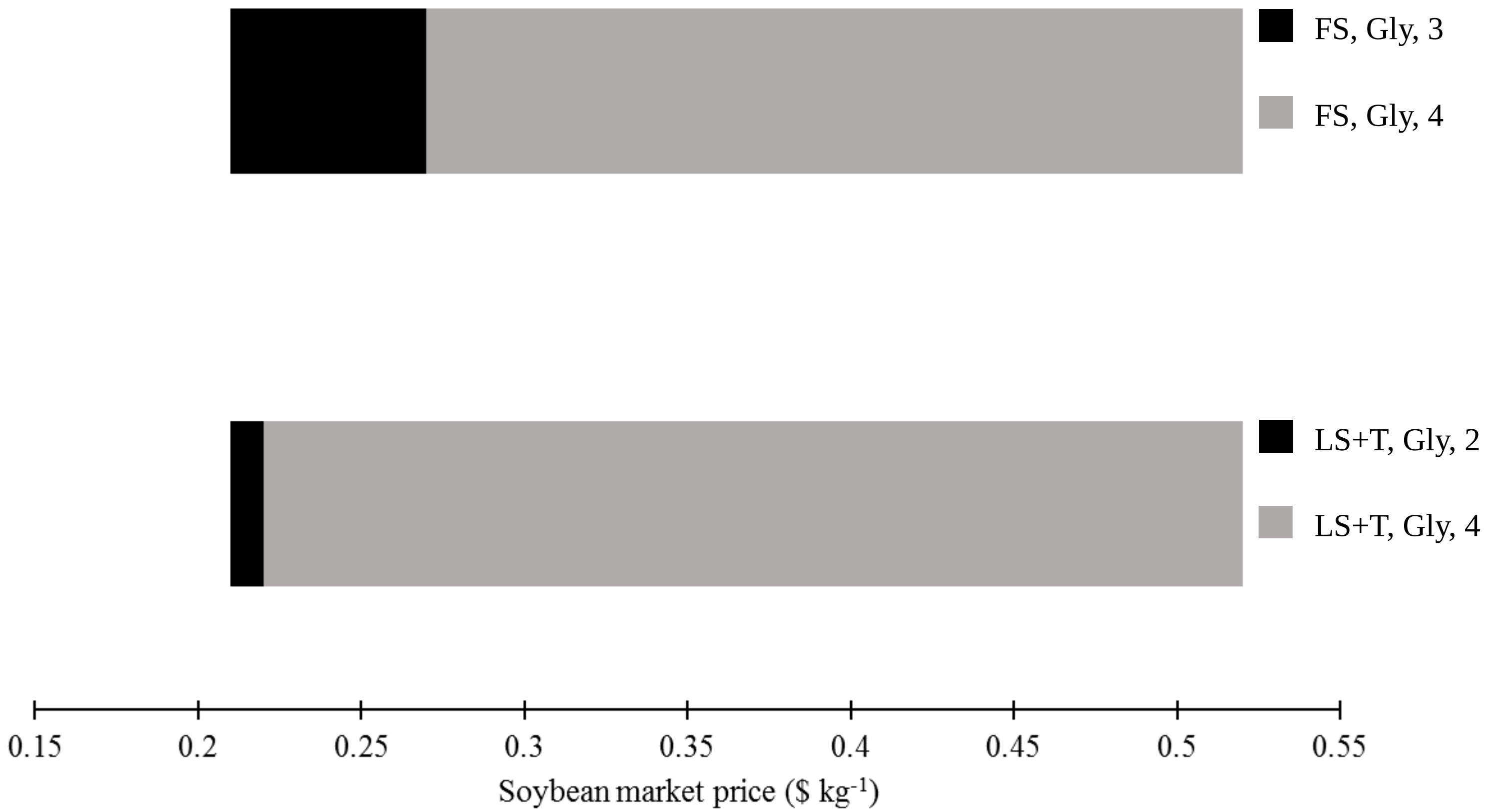

Figure 3. Sensitivity analysis, at Marianna, AR in 2013, comparing all possible treatment combinations for the full-season (FS) and full-season plus tillage (FS+T) and late-season (LS) and late-season plus tillage (LS+T) production systems for the impact of dominant treatment with highest partial returns across 10 year high and low soybean market prices. Abbreviations: Gly, glyphosate-resistant soybean cultivar; 2, 3, and 4 represent specific herbicide programs (see materials and methods for complete description).

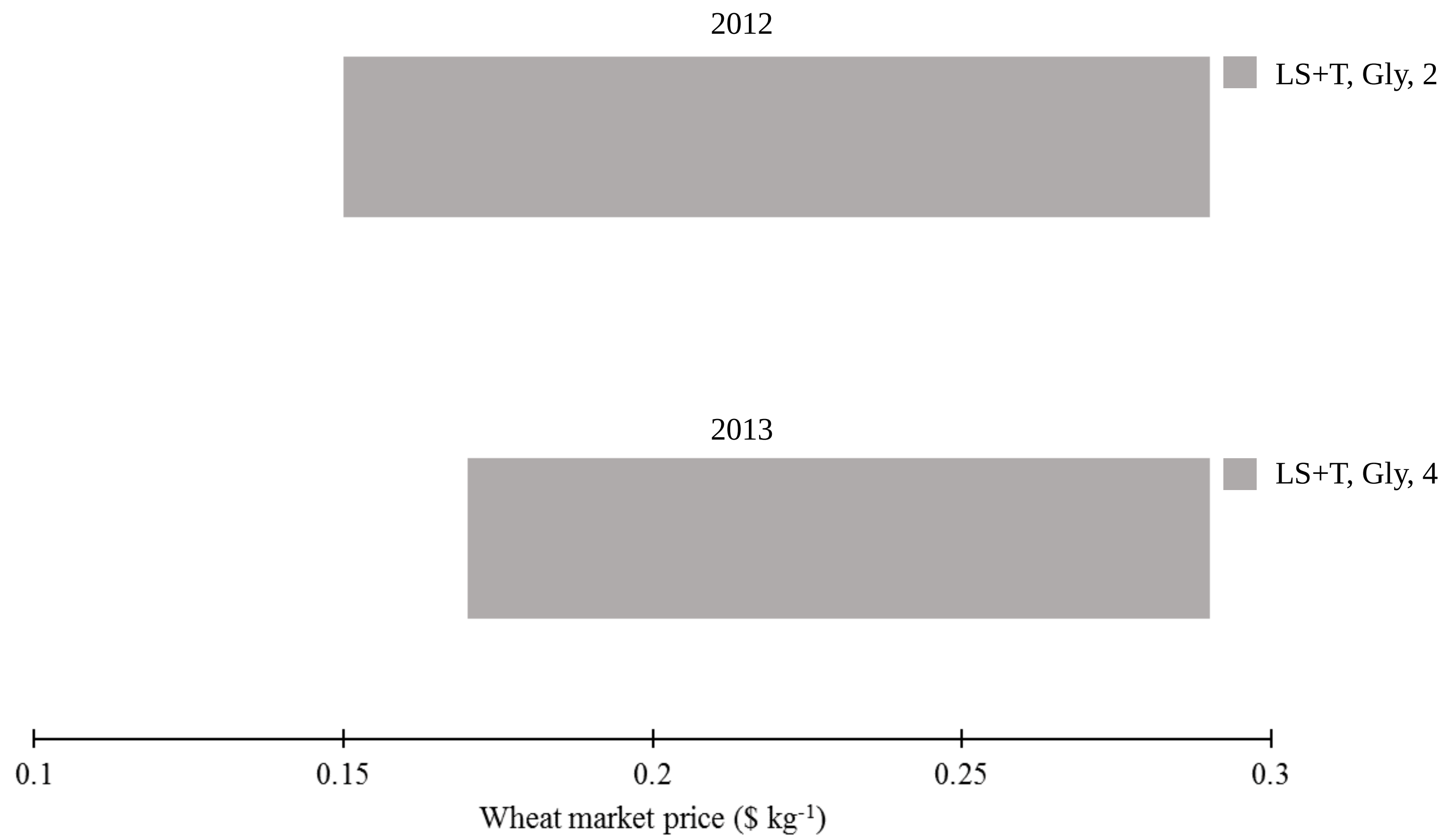

Figure 4. Sensitivity analysis, at Marianna, AR in 2012 and 2013, comparing all possible treatment combinations for the late-season (LS) and late-season plus tillage (LS+T) production systems for the impact of dominant treatment with highest partial returns across breakeven wheat cost ($0.15 and $0.17 kg^{-1} in 2012 and 2013, respectively) and 10 year high wheat market prices. Abbreviations: Gly, glyphosate-resistant soybean cultivar; 2 and 4 represent specific herbicide programs (see materials and methods for complete description).

Literature Cited

Amrhein N, Deus B, Gehrke P, Steinrucken HC (1980) The site of inhibition of the shikimate pathway by glyphosate II. Interference of glyphosate with chorismate formation in vivio and in vitro. Plant Physiol 66:830-834

Backgrounder- History of Monsanto's Glyphosate Herbicides (2005)

Barnes JW, Oliver LR (2003) Cultural practices and glyphosate applications for sicklepod (*Senna obtusifolia*) control in soybean (*Glycine max*). Weed Technol 17:429-440

Baylis AD (2000) Why glyphosate is a global herbicide: strengths, weaknesses and prospects. Pest Manag Sci 56:299-308

Coetzer E, Al-Khatib K, Loughin TM (2001) Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. Weed Sci 49:8-13

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

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

DeFelice MS, Carter PR, Mitchell SB (2006) Influence of tillage on corn and soybean yield in the United States and Canada. Crop Manag doi:10.1094/CM-2006-0626-01-RS

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263-270

Dröge W, Broer I, Pühler A (1992) Transgenic plants containing the phosphinothricin-*N*-acetyltransferase gene metabolize the herbicide L-phosphinothricin (glufosinate) differently from untransformed plants. Planta 187:142-151

Duke SO, Powles SB (2008) Glyphosate: a once-in-a-century herbicide. Pest Manag Sci 64:319-325

Duke SO, Powles SB (2009) Glyphosate-resistant crops and weeds: now and in the future. AgBioForum 12:346-357

Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, Reynolds DB (2008) Glyphosate-resistant horseweed (*Conyza canadensis*) control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. Weed Technol 22:16-21

Franz JE, Mao MK, Sikorski JA (1997) Glyphosate: A Unique Global Herbicide. ACS Monograph 189. Washington D.C.: American Chemical Society Pp. 6-16

Gallagher RS, Cardina J, Loux M (2003) Integration of cover crops with postemergence herbicides in no-till corn and soybean. Weed Sci 51:995-1001

Gardner AP, York AC, Jordan DL, and Monks DW (2006) Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J Cotton Sci 10:328-338

Geisy JP, Dobson S, Solomon KR (2000) Ecotoxicological risk assessment for Roundup herbicide. 2000. Rev Environ Toxicol 167:35-120

Green JM (2009) Evolution of glyphosate-resistant crop technology. Weed Sci 57:108-117

Heap I (2014) The Internation Survey of Herbicide Resistant Weeds. http://www.weedscience.org/summary/home.aspx. Accessed: April 26, 2014

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347-355

Horowitz J, Ebel R, Ueda K (2010) "No-till" farming is a growing practice. Economic Research Service/USDA. Available http://www.ers.usda.gov/Publications/EIB70/EIB70.pdf. Accessed April 1, 2012

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Jha P, Norsworthy JK (2012) Influence of late-season herbicide applications on control, fecundity, and progeny fitness of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) biotypes from Arkansas. Weed Technol 26:807-812

Kay RD, Edwards WM, Duffy PA (2008) Farm Management 6th edition. New York, NY: McGraw-Hill. Pp 175-185

Kelton JA, Price AJ, Patterson MG, Monks CD, Van Santen E (2013) Evaluation of tillage and herbicide interaction for *Amaranthus* control in cotton. Weed Technol 27:298-304

Leon RG, Owen MDK (2006) Tillage and seed dormancy effects on common waterhemp (*Amaranthus tuberculatus*) seedling emergence. Weed Sci 54:1037-1044

Lithourgidis AS, Dhima KV, Damalas CA, Vasilakoglou IB, Eleftherohorinos IG (2006) Tillage effects on wheat emergence and yield at varying seeding rates, and on labor and fuel consumption. Crop Sci 46:1187-1192

Lithourgidis AS, Tsatsarelis CA, Dhima KV (2005) Tillage effects on corn emergence, silage yield, and labor and fuel inputs in double cropping with wheat. Crop Sci 45:2523-2528

Norris JL, Shaw DR, Snipes CE (2002) Influence of row spacing and residual herbicides on weed control in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:319-325

Norsworthy JK (2004) Soybean canopy formations effects on pitted morningglory (*Ipomomea lacunose*), common cocklebur (*Xanthium strumarium*), and sicklepod (*Senna obtusifolia*) emergence. Weed Sci 52:954-960

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK, Still J (2011) Evaluation of cereal and brassicaceae cover crops in conservation-tillage, enhanced, glyphosate-resistant cotton. Weed Technol 25:6-13

Norsworthy JK, Oliveira MJ (2007) Tillage and soybean canopy effects on common cocklebur (*Xanthium strumarium*) emergence. Weed Sci 55:474-480

Powles SB (2008) Evolved glyphosate-resistant weeds around the world: lessons to be learnt. Pest Manag Sci 64:360-365

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15:660-668

Reddy KN (2005) Deep tillage and glyphosate-reduced redvine (*Brunnichi ovata*) and trumpetcreeper (*Campsis radicans*) populations in glyphosate-resistant soybean. Weed Technol 19:713-718

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci 51:987-994

Sammons RD, Heering DC, Dinicola N, Glick H, Elmore GA (2007) Sustainability and stewardship of glyphosate and glyphosate-resistant crops. Weed Technol 21:347-354

Scott B, Smith K (2011) Prevention and control of glyphosate-resistant pigweed in soybean and cotton. University of Arkansas Cooperative Extension Service Printing Services FSA 2152-PD-3-11RV 4 pp

Sellers BA, Smeda RJ, Johnson WG, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329-333

Senseman SA (2007) Herbicide Handbook. 9th ed. Lawrence, Kan. Weed Science Society of America

Shauck TC, Smeda RJ (2012) Control of glyphosate-resistant corn (*Zea mays*) with glufosinate or imazethapyr plus imazethapyr in a replant situation. Weed Technol 26:417-421

Weisbrook ML, Johnson WG, Hart SE, Bradley PR, Wax LM (2001) Comparison of weed management systems in narrow-row, glyphosate- and glufosinate-resistant soybean (*Glycine max*). Weed Technol 15:122-128

Weston LA (1996) Utilization of allelopathy for weed management in agroecosystems. Agron J 88:860-866

Whitaker JR, York AC, Jordan DL, Culpepper AS (2010) Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol 24:403-410

Williams GM, Kroes R, Munro IC (2000) Safety evaluation and risk assessment of the herbicide Roundup and its active ingredient, glyphosate, for humans. Regul Toxicol Pharmacol 31:117-165

CHAPTER III

Effect of Drill-Seeded Soybean Density on Palmer Amaranth (*Amaranthus palmeri*) Emergence With and Without a Preemergence Residual Herbicide

Abstract: Field experiments were conducted in 2013 at two Arkansas locations to determine the effect of drill-seeded soybean density on Palmer amaranth emergence. Experimental factors were multiple soybean seeding rates planted on a 19 cm wide row spacing and the presence or absence of a preemergence (PRE) residual herbicide (flumioxazin plus pyroxasulfone). Soybean groundcover was measured throughout the growing season and daily soil temperature was recorded in selected soybean densities. In the absence of a PRE residual herbicide, at least a 1.7-fold reduction in Palmer amaranth emergence occurred when soybean were present. Differences in Palmer amaranth emergence occurred among soybean densities for both locations, suggesting the value of crop canopy in preventing Palmer amaranth emergence in the absence of an effective residual herbicide. In plots treated with the PRE herbicide, no difference in Palmer amaranth emergence occurred among soybean densities, except for the absence of soybean. Achievement of 95% groundcover by soybean reduced daily soil temperature fluctuations, which in turn reduced Palmer amaranth emergence. For both locations, soybean grain yields were maximized and partial returns were greatest at the highest seeding rate (617,500 seed ha^{-1}). In the presence of flumioxazin plus pyroxasulfone applied PRE, greater grain yields occurred compared to the absence of a PRE herbicide at both Fayetteville and Marianna. Based on this research, an effective PRE-applied residual herbicide has more influence on Palmer amaranth emergence than soybean density and Palmer amaranth germination and emergence is dependent upon daily soil temperature fluctuations, which is a function of soybean density.

Nomenclature: Flumioxazin; pyroxasulfone; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; soybean, *Glycine max* L.

Key words: Emergence, preemergence, residual, soil temperature, soybean density.

Introduction

An estimated 60 species of *Amaranthus*, also known as “pigweeds”, are native to America (Sauer 1967). Palmer amaranth is an erect, branched summer annual growing up to 2 m tall, has a taproot, long-petioled leaves, a terminal spike up to 0.5 m, with few lateral spikes shorter than the terminal spike. Palmer amaranth is a dioecious plant (male and female flowers on separate plants) and the inflorescence of most male and female plants is most distinguishable by females being prickly to the touch compared to male plants having a smoother, softer feel (Bryson and DeFelice 2009; Keeley et al. 1987; Steckel 2007; Steckel et al. 2004; Ward et al. 2013). Female Palmer amaranth plants are prolific seed producers and have been documented to produce up to 1.5 million seed plant^{-1} with little to no interference from other plants (Scott and Smith 2011b). More commonly, female plants produce closer to 200,000 seed when in competition with row crops, especially soybean and cotton (*Gossypium hirsutum* L.). Palmer amaranth is highly competitive because of its rapid growth rate (≤ 0.21 cm per growing degree day, with a base temperature of 10 C), and extended emergence period (April to first killing frost in the Southern U.S.) (Horak and Loughlin 2000; DeVore et al. 2013; Jha et al. 2009; Scott and Smith 2011b). The small seed size of Palmer amaranth (1 to 2 mm), similar to other *Amaranthus* spp., allows the seed to spread through mechanical and biological practices, such as tillage, harvesting, gin trash, water flow from irrigation and/or rainfall, and movement from birds and mammals (Costea et al. 2004, Norsworthy et al. 2009, Norsworthy et al. 2014).

The long-term viability of Palmer amaranth seed in the soil seedbank resembles that of other *Amaranthus* spp., specifically redroot pigweed (*Amaranthus retroflexus* L.) and tall waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] which had viable seed after being buried for 17 years (Burnside et al. 1996; Ward et al. 2013). Palmer amaranth seed viability loss is inversely related to burial depth [shallower planted (10 cm) Palmer amaranth seed lost viability faster than deeper planted Palmer amaranth seed (40 cm)] (Sonoskie et al. 2013). Sonoskie et al. (2013) also reported Palmer amaranth seeds buried at depths ranging from 1 to 40 cm and an initial viability ≥ 96%, lost, on average across all depths, 18 to 31 percentage points of their viability after 6 months of burial, and after 12 months of burial Palmer amaranth seed viabilities were 44, 48, 53, and 61% at depths of 1-, 2.5-, 10-, and 40-cm, respectively. By 24 months after burial, Palmer amaranth seed viability was reduced by 25, 24, 25, and 24% at burial depths of 1-, 2.5-, 10-, and 40-cm, respectively, and by 36 months of burial Palmer amaranth seed was 9, 12, 15, and 22% viable at burial depths of 1-, 2.5-, 10-, and 40-cm, respectively. This study shows the importance of minimizing and ultimately depleting the soil seedbank because of the potential that Palmer amaranth has to germinate and produce seed, which rapidly accumulates in the soil seedbank, if the infested field is not kept weed free with an aggressive approach to weed management.

To develop an effective weed management strategy, an understanding of the emergence pattern of problematic weeds for each particular cropping system is vital to make accurate and timely herbicide applications for control. A major factor to Palmer amaranth's success is that its emergence pattern coincides with the production systems of common row crops in the southern United States such as corn (*Zea mays* L.), cotton, and soybean (DeVore et al. 2013; Jha et al. 2010; Scott and Smith 2011b; Steckel 2007; Webster and Nichols 2012). Prior to glyphosate resistance, typically Palmer amaranth was controlled by multiple over-the-top (OT) broadcast applications of glyphosate. However, as a result of widespread glyphosate- and acetolactate synthase (ALS)-resistant Palmer amaranth, glyphosate and ALS-inhibiting herbicides are no longer effective control options, leaving few OT herbicides available for Palmer amaranth control.

Therefore, controlling Palmer amaranth before or during emergence should be the management focus, rather than relying on postemergence (POST) herbicide applications. If Palmer amaranth can be kept from emerging, the selection pressure placed on POST herbicides and the addition of seeds to the soil seedbank is reduced. No single method of weed control can completely control Palmer amaranth or stop it from emerging, but there are ways to reduce emergence, like PRE-applied residual herbicides and/or lessening diurnal soil temperature fluctuations through achieving a dense crop canopy (Jha et al. 2010; Jha and Norsworthy 2009; Steckel et al. 2004; Whitaker et al. 2010).

Soil-applied residual herbicides are an effective weed management tool for controlling Palmer amaranth and many other weeds early in the cropping season, before crop canopy formation occurs. Whitaker et al. (2010) reported that in a conventional soybean production system, a PRE application of *S*-metolachlor or pendimethalin in addition to either flumioxazin, fomesafen, or metribuzin plus chlorimuron increased control of Palmer amaranth by 27%, 29%, and 22%, respectively, when the first POST herbicide application was applied to 10- to 15-cm tall Palmer amaranth, compared to the nontreated control. Although the addition of the PRE herbicide applications controlled close to 25% of the initial Palmer amaranth emergence, producers might not see this input as beneficial, in terms of season-long control. Whitaker et al. (2010) also reported that Palmer amaranth control was $\geq$ 25% at 90 days after initiation, whenever a PRE application of either metribuzin plus chlorimuron, fomesafen, or flumioxazin was applied compared to no PRE herbicide application. Therefore, relying on a POST-only herbicide program may lead to minimal returns in regards to Palmer amaranth control and suppression.

Herbicides, relative to other means of weed control, are highly effective and often more consistent. However, other weed management practices must be integrated with herbicides to increase diversity and reduce selection for herbicide resistance (Norsworthy et al. 2012). Crop canopy formation has been reported to have a suppressive effect on weeds emerging late in the growing season (Amador-Ramirez et al. 2002; Dalley et al. 2004; Jha et al. 2010; Molin et al. 2004; Renner and Mickelson 1997). Norsworthy (2004) reported a reduction of 33% and 68% for common cocklebur (*Xanthium strumarium* L.) and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] emergence, respectively, as a result of soybean canopy formation compared to emergence of both weeds in the absence of soybean. Jha and Norsworthy (2009) concluded that daily soil thermal amplitudes of 10 to 16 C allowed for Palmer amaranth emergence whereas formation of a soybean canopy lessened soil thermal fluctuations, in turn reducing Palmer amaranth emergence. Soybean density is known to influence crop canopy formation and could potentially reduce selection pressure on POST-applied herbicides. Therefore, the objective of this experiment was to determine the effect of increasing soybean density in combination with or without a PRE-applied residual herbicide on Palmer amaranth emergence and soybean grain yield.

Materials and Methods

A field experiment was conducted in 2013 at the University of Arkansas Research and Extension Center in Fayetteville, AR and at the Lon Mann Cotton Research Station in Marianna, AR. The soil series in Fayetteville was a Leaf silt loam (Fine, mixed, active, thermic Typic

Albaquults) with 34% sand, 53% silt, 13% clay, 1.5% organic matter, and a pH of 6.9. The soil series in Marianna was a Convent silt loam (Coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) with 9% sand, 80% silt, and 11% clay, 1.8% organic matter, and a pH of 6.8. This experiment was organized in a split-plot design and treatments were replicated four times. The main plot factor was soybean seeding rates [0 (no soybean); 123,500; 185,250; 247,000; 308,750; 432,250; 617,500 seed ha^{-1}] planted in lengths of 10 m and the subplot factor was no herbicide application or a pre-packaged mix of flumioxazin plus pyroxasulfone (Fierce®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) applied at 82 plus 104 g ai ha^{-1}, respectively. Each subplot measured 2 m by 4.5 m with a 1 m alley. Seed for both locations were counted with a Seedburo 801 Count-A-Pak® (Seedburo Equipment Co., Des Plaines, IL 60018) for each seeding rate to determine the correct number of seed to be planted in each sub-plot.

Immediately prior to planting, the seedbed was prepared using a field cultivator (Kongskilde Industries Inc., Hudson, IL 61748) to obtain a uniform weed-free seedbed. LibertyLink® (Bayer CropScience, Research Triangle Park, RTP, North Carolina 27709) soybean, variety Halomax 494 (glufosinate-resistant soybean), were drill-seeded with a 10 row Almaco (ALMACO, Nevada, IA 50201) cone-type planter on a 19-cm-wide row spacing on May 15 and May 9, 2013 in Fayetteville and Marianna, respectively. Plots were irrigated using overhead sprinkler irrigation and border irrigation at Fayetteville (Figure 1a) and Marianna (Figure 1b), respectively. After planting, two 0.5-m^2 areas were marked with flags (Gempler's, P.O. Box 5175, Janesville, WI 53547) in the center of each plot to provide a uniform area to determine Palmer amaranth emergence from the natural seedbank throughout the growing season. Soybean density was measured in the same quadrats at four weeks after planting.

Palmer amaranth emergence was monitored weekly in the two quadrats in each sub-plot and Palmer amaranth seedlings were removed after each count at both locations until harvest. The entire test, at both locations, was over-sprayed with glufosinate (Liberty®, Bayer CropScience, Research Triangle Park, RTP, North Carolina 27709) at 595 g ai ha^{-1} and/or clethodim (Select Max®, Valent U.S.A. Corporation, Walnut Creek, CA 94596) at 136 g ai ha^{-1}, as needed, for POST weed control at Fayetteville and Marianna (Table 1).

Whenever soybean reached the cotyledon stage (VC), a Sony Cyber-shot® digital camera (Sony Electronics, San Diego, California 92127) was used to take weekly photographs of the center of each plot. The camera was mounted on a 5 cm diameter pipe at a height of 1.5 m above the crop and facing downward at a 70° angle to insure the pole and photographer's feet were not in the picture. Photographs were taken throughout the growing season from a marked position to decrease variation during the vegetative growth stages of the soybean. Photographs were transferred to a computer, sorted, and individually analyzed to determine the rate (days) of soybean canopy formation using the procedures described by Purcell (2000). Canopy formation was measured by processing the photographs of individual plots with SigmaScan® Pro 5.0 (Systat Software, Inc., San Jose, CA 95110). Values from SigmaScan Pro were exported to Excel (Microsoft®, One Microsoft Way, Redmond, WA 98052), and a linear regression was fit to the data to determine the rate of canopy formation during soybean growth.

The use of digital imagery has been previously reported to be an accurate assessment tool when monitoring crop canopy formation (Purcell 2000; Richardson et al. 2001). Soybean vegetative growth is described as sigmoidal because of slow initial growth followed by a linear, more rapid growth and then growth slows and tapers off as soybean reaches complete canopy formation or maturity (Norsworthy 2004).

Daily minimum/maximum soil temperature data were recorded with Onset HOBO U12 (Onset Computer Corporation, Inc., Bourne, MA 02532) data loggers with three soil temperature probes (TMC6-HD, Onset Computer Corporation, Inc., Bourne, MA 02532) placed at a 2.5-cm depth. Soil temperature was recorded every 15 minutes throughout the growing season for the no soybean density and selected soybean seeding rates of 247,000; 432,250; 617,500 seed ha^{-1} in plots treated with the residual herbicide. Soybean grain was harvested with a small-plot combine (Massey Ferguson 8, AGCO, Duluth, GA 30096). Soybean grain yield was determined by weighing the seed from individual plots, standardized for 13% moisture, and reported in kg ha^{-1}. Grain yield data were entered into Excel and then exported to SigmaPlot® 12.5 (Systat Software, Inc., San Jose, CA 95110) and fit to a nonlinear regression and tested for normality by Shapiro-Wilk's test (Table 2). This approach has successfully been used in previous research (Cerrato and Blackmer 1990; Edwards and Purcell 2005; Edwards et al. 2005; Purcell et al. 2002; Ware et al. 1982).

A partial budgeting analysis was used to compare economic returns across the different treatments in this study. The packaged mixture of flumioxazin plus pyroxasulfone cost (\$0.21 g^{-1} product) and seed cost (\$0.41 per 1,000 seed) were determined from two distributors in Northeast Arkansas (Helena Chemical Co., Hughes, AR 72348 and Crop Production Services Inc., Crawfordsville, AR 72327) by taking the average of the two quoted prices. Current soybean market price (\$0.43 kg^{-1}) from http://www.themiraclebean.com/markets was used to determine the partial returns associated with the alternative treatments. Chemical application cost (\$14.82 ha^{-1} $application^{-1}$) was based on the University of Arkansas Division of Agriculture Research and Extension 2014 Crop Enterprise Budgets available at www.uaex.edu/farm-ranch/economics-marketing/farm-planning/enterprise-budgets.aspx. Sensitivity analyses were calculated by determining the most profitable treatment at varying soybean market prices, limited by the 10-year low and high soybean prices as reported by the National Agricultural Statistics Service (http://www.nass.usda.gov/Statistics_by_Subject/idex/php?sector=CROPS).

Data were subjected to ANOVA with the MIXED procedure in JMP to test for significant main effects and interactions. Locations were analyzed separately due to differences in Palmer amaranth emergence. Soybean density and the presence or absence of the PRE herbicide were considered fixed effects, and replication was considered a random effect. Mean separation was performed using Fisher's protected LSD test at the 5% level of significance.

Results and Discussion

Soybean Canopy Development. Both Fayetteville and Marianna demonstrated similar trends in terms of soybean growth, cumulative Palmer amaranth emergence, and soil temperature fluctuations. The inclusion of a PRE-applied herbicide slightly delayed early-season soybean growth, resulting in all soybean densities achieving 95% canopy formation 3 to 6 days later than plots that did not receive a PRE-applied herbicide (data not shown).

At Fayetteville, the soybean densities achieved 95% soybean canopy formation from 44 to 65 days after soybean emergence (Table 3). At Marianna 48 to 52 days were needed for all soybean densities to achieve 95% canopy formation (Table 4). A possible explanation for Marianna having a narrower range compared to Fayetteville could be attributed to the difference in soybean densities at the two locations and furthermore, Marianna had more growing degree days earlier in the growing season than that of Fayetteville which would be beneficial to plant growth. The lowest density at Fayetteville was 78,000 plants ha^{-1} compared to 120,000 plants ha^{-1} at Marianna.

Cumulative Palmer Amaranth Emergence in the Absence of a PRE Herbicide. The presence of soybean first impacted cumulative Palmer amaranth emergence at Fayetteville 38 days after soybean emergence (DAE). At this observation, soybean groundcover for the three highest soybean densities of 243,000, 280,000, and 383,000 plants ha^{-1} was 77, 87, and 90%, and Palmer amaranth emergence was 26, 22, and 16% relative to the total emergence in the bareground treatment (Figure 2). No further Palmer amaranth emergence occurred after 38 DAE at these densities. This research strongly corresponds with that of Jha and Norsworthy (2009) where soybean canopy negatively impacted Palmer amaranth emergence 32 DAE when soybean light interception was 75%. At 59 DAE, the soybean densities of 78,000, 145,000, and 150,000 had 47, 44, and 29% total Palmer amaranth emergence relative to the total emergence in the bareground treatment, and soybean groundcover was 96, 97, and 98%, respectively. No further emergence occurred at later dates for these densities.

In Marianna at 32 DAE, Palmer amaranth emergence for the three highest soybean densities of 290,000, 425,000, and 588,000 plants ha^{-1}ranged from 31 to 34% of the total bareground emergence, and soybean groundcover was from 65 to 78% (Figure 3). No further Palmer amaranth emergence occurred past 32 DAE for these densities. The presence of soybean first significantly impacted Palmer amaranth emergence relative to the bareground treatment at 52 DAE. The soybean densities of 120,000 and 180,000 plants ha^{-1} had no further Palmer amaranth emergence relative to the total season emergence of the bareground treatment by 52 DAE when soybean groundcover was 95 and 98%, respectively. All soybean densities had $\geq$ 95% canopy formation by 52 DAE at Marianna.

At both locations a similar trend was observed. As soybean groundcover increased, late-season Palmer amaranth emergence decreased and ultimately ceased. Thus, this research reiterates the importance of rapid canopy formation to aid in suppressing late-season Palmer amaranth emergence.

Cumulative Palmer Amaranth Emergence in the Presence of a PRE Herbicide. The magnitude of daily soil temperature fluctuations at a 2.5-cm depth are shown at Fayetteville and Marianna in Figures 4 and 5, respectively. At both Fayetteville and Marianna, a similar relationship occurred between diurnal soil temperature fluctuations and soybean canopy formation. As soybean canopy formation increased, diurnal soil temperature fluctuations decreased. Previous research has reported temperatures ≥ 25 C and daily soil thermal amplitudes of ≥ 7.5 C are conducive for germination of Palmer amaranth and other *Amaranthus* species (Jha and Norsworthy 2009; Leon et al. 2004; Steckel et al. 2004; Thomas et al. 2006). Therefore, the reduction of daily soil temperatures due to soybean canopy formation could possibly be the main factor contributing to the change in emergence of Palmer amaranth, especially considering that light transmittance through soil is limited to a depth of 4 mm (Benvenuti 1995).

At Fayetteville, from the day 95% soybean canopy formation was achieved until the conclusion of the study, average daily soil temperature fluctuations for the soybean densities of 150,000 to 383,000 plants ha^{-1} ranged from 4.9 to 5.6 C compared to 12.9 C in the absence of soybean (Figure 4). At Marianna, average daily soil temperature fluctuations followed a similar trend to that of Fayetteville. Once 95% soybean canopy formation was achieved, average daily soil temperature fluctuations for the soybean densities of 240,000 to 588,000 plants ha^{-1} ranged from 4.4 to 7.5 C compared to 10.2 C in the absence of soybean (Figure 5). Jha and Norsworthy (2009) reported a 76% reduction in Palmer amaranth emergence in soybean at a density of

432,000 seed ha^{-1} compared to bareground when daily soil temperature fluctuations were 5.1 C at a 2.5-cm soil depth in the presence of soybean compared to 10.1 C in the absence of soybean.

At both Fayetteville and Marianna, a similar trend was observed between increasing soybean canopy formation and decreasing Palmer amaranth emergence. This inverse relationship of a reduction in weed seedling emergence due to a developing crop has been previously reported in other weed species such as curly dock (*Rumex crispus* L.) and *Amaranthus* species emergence in alfalfa (*Medicago sativa* L.) (Huarte and Benech Arnold 2003), common lambsquarters (*Chenopodium album* L.), common purslane (*Portulaca oleracea* L.), large crabgrass (*Digitaria sanguinalis* L.), and redroot pigweed (*Amaranthus retroflexus* L.) in sweet corn (*Zea mays* var. *rugosa*) (Mohler and Calloway 1992), and common cocklebur (*Xanthium strumarium* L.) and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] in soybean (Norsworthy 2004; Norsworthy et al. 2007).

Soybean density had no influence on Palmer amaranth emergence in Fayetteville when plots were treated with a PRE application of flumioxazin plus pyroxasulfone (Figure 6). In PRE-treated plots, no Palmer amaranth emergence occurred for the first 30 days nor did it emerge in the highest soybean density of 383,000 plants ha^{-1} throughout the growing season. The fact that no emergence occurred at the highest density likely indicates that soybean canopy formation does reduce Palmer amaranth emergence similar to that observed in the absence of a PRE herbicide even though statistical differences could not be detected in the PRE-treated plots.

Conversely, soybean densities did impact Palmer amaranth emergence at Marianna, first at 41 DAE. The use of flumioxazin plus pyroxasulfone applied PRE in combination with soybean densities reduced Palmer amaranth emergence 50 fold compared to the season-long emergence in the bareground treatment (Figure 7). No further Palmer amaranth emergence occurred in the presence of soybean after 41 DAE. These results correspond with previous research from Mahoney et al. (2014) where the combination of flumioxazin plus pyroxasulfone controlled *Amaranthus* spp. 99 to 100%. Furthermore, in the absence of soybean, Palmer amaranth emergence occurred until 96 DAE, when emergence was 39% of the nontreated bareground treatment. Hence, this research shows that a properly selected and activated PRE herbicide effectively controls early-season Palmer amaranth whereas a dense soybean canopy is a strong suppressant of late-season emergence once the PRE-applied herbicide has dissipated.

Soybean Grain Yield. For both locations, only the main effects of PRE herbicide use and soybean seeding rate impacted soybean grain yield. Soybean grain yield was greater in the presence of flumioxazin plus pyroxasulfone applied PRE compared to its absence at Fayetteville and Marianna; hence, a loss of grain yield occurred due to early-season weed interference or an application of glufosinate during reproductive development of soybean (Figure 8). Increasing the seeding rate positively impacted soybean grain yield at Fayetteville and Marianna; hence, soybean grain yield was maximized at the highest seeding rate.

These results are comparable with previous research from Norsworthy and Oliver (2001) who reported increasing soybean seeding rates of a late maturity group V, determinate soybean resulted in increased soybean grain yields, up to 988,000 seeds ha^{-1} (average density of 821,000 plants ha^{-1}), then soybean grain yield begins to diminish. Edwards and Purcell (2005) likewise reported increased soybean yields in response to increased soybean densities for maturity group 0 and IV cultivars.

Economic Partial Returns and Sensitivity Analyses. Partial returns were calculated for both locations at all seeding rates, in the presence or absence of flumioxazin plus pyroxasulfone applied PRE (Table 5). At both locations, partial returns were greater in the presence of flumioxazin plus pyroxasulfone, than in the absence, for the individual soybean seeding rates. The greatest partial returns occurred at the highest seeding rate, even though this seeding rate had the highest seed costs. Furthermore, a general trend of increasing soybean seeding rates resulted in increasing partial returns. However, these partial returns do not take into account the impact on Palmer amaranth emergence, which was the main goal of this study.

Sensitivity analyses were calculated for both Fayetteville and Marianna (Figure 9). The seeding rate of 617,500 seed ha^{-1} in combination with flumioxazin plus pyroxasulfone applied PRE had the greatest partial returns compared to all other treatment combinations for all soybean market prices evaluated for both locations.

Practical Implications

Since Palmer amaranth is considered the most problematic weed throughout the Midsouth (Arkansas, Louisiana, Mississippi, and Tennessee) in soybean (Riar et al. 2013), producers need information about how to successfully control this weed and minimize its effects on crops. In narrow-row, drill-seeded soybean (19 cm wide row spacing), increased soybean densities can reduce Palmer amaranth emergence in the absence of a PRE residual herbicide or when a PRE residual herbicide is selected that is not as effective as flumioxazin plus pyroxasulfone or fails to be activated due to lack of rainfall or irrigation. Even with soybean canopy formation reducing Palmer amaranth emergence, some plants still emerged regardless of the soybean density or use of flumioxizan plus pyroxasulfone applied PRE. Hence, multifacet strategies that include POST-applied herbicides are still needed in soybean; albeit, drill-seeded soybean and PRE-applied herbicides will reduce selection pressure on POST-applied herbicides (reduces the number of Palmer amaranth plants that must be controlled POST). Based on this research, the application of an effective PRE residual herbicide, like flumioxazin plus pyroxasulfone, in combination with a soybean seeding rate of ≥ 123,500 seed ha^{-1} (lowest seeding rate evaluated) can reduce the selection pressure on POST herbicides compared to POST-only herbicide programs.

Since Palmer amaranth germination and emergence have previously been reported to be dependent on soil temperature fluctuations ≥ 7.5 C (Guo and Al-Khatib 2003; Jha and Norsworthy 2009; Steckel et al. 2004), achieving rapid canopy formation is critical to reducing soil thermal amplitudes and suppression of late-season Palmer amaranth emergence. In the presence of a PRE herbicide, increased soybean densities had no impact on Palmer amaranth emergence. Therefore, increasing the soybean seeding rate can be costly with minimal returns in regards to suppression of Palmer amaranth emergence, especially if a highly effective PRE herbicide is applied.

In conclusion, Palmer amaranth emergence can be minimized throughout the growing season by providing irrigation to the soybean crop for rapid canopy formation and activation of the residual herbicide and seeding soybean at the recommended seeding rate of 370,500 seed ha^{-1} for a narrow-row spacing (P. Chen, personal communication); however, producers could use lower seeding rates if they are (1) using an effective PRE herbicide at planting, (2) consistently achieve a high percentage of soybean emergence in narrow rows which would reduce soil thermal amplitudes and late-season Palmer amaranth emergence, and (3) rely on a properly timed effective POST herbicide to control Palmer amaranth plants that escape early-season control measures.

Table 1. Herbicide, rate, and application date for herbicide applications throughout the growing season at Fayetteville and Marianna, AR in 2013.

Herbicide[a]	Rate	Application date	Location
	g ai ha^{-1}		
Flumioxazin + pyroxasulfone	82 + 104	May 15	Fayetteville
Glufosinate + clethodim	595 + 136	June 3	Fayetteville
Glufosinate	595	July 2	Fayetteville
Flumioxazin + pyroxasulfone	82 + 104	May 9	Marianna
Glufosinate	595	May 22	Marianna
Glufosinate + clethodim	595 + 136	May 30	Marianna
Glufosinate + clethodim	595 + 136	June 19	Marianna

[a] flumioxazin plus pyroxasulfone applied at soybean planting, glufosinate used to control Palmer amaranth, and clethodim used to control broadleaf signalgrass at that particular application date.

Table 2. Nonlinear regression models for determining soybean grain yield as a function of soybean density at Fayetteville and Marianna, AR in 2013.[a]

	Nonlinear regression soybean grain yield model			
	Fayetteville		Marianna	
Herbicide	Model	R^2	Model	R^2
———	$y = \propto (1 - e^{-\beta x})$	———	$y = \propto (1 - e^{-\beta x})$	———
None	$y = 3226.9(1 - e^{-0.00001x})$	0.9950	$y = 3286.3(1 - e^{-0.00001x})$	0.9384
Flumioxazion + pyroxasulfone	$y = 4339.5(1 - e^{-0.00001x})$	0.9684	$y = 4552.3(1 - e^{-0.00001x})$	0.9598

[a] y is soybean grain yield (kg ha^{-1}), e is the constant 2.718, x is soybean density (plants ha^{-1}), $\propto$ and β are parameter estimates.

Table 3. Days required for individual soybean densities, averaged over the presence and absence of a preemergence applied residual herbicide, to obtain 95% groundcover at Fayetteville, AR in 2013.

Soybean density	Emergence	DAE[a] to 95% groundcover	GDD[a] to 95% groundcover	R^{2c}
plants ha^{-1}	%			
78,000	63	65	967	0.97
145,000	78	61	914	0.99
150,000	61	60	897	0.98
243,000	79	55	822	0.91
280,000	65	47	700	0.95
383,000	62	44	654	0.94

[a] Abbreviations: DAE, days after soybean emergence; GDD, growing degree days.
[b] R^2 determined from linear regression of percent groundcover (Purcell 2000).

Table 4. Days required for individual soybean densities, averaged over the presence and absence of a preemergence applied residual herbicide, to obtain 95% groundcover at Marianna, AR in 2013.

Soybean density	Emergence	DAE[a] to 95% groundcover	GDD[a] to 95% groundcover	R^{2c}
plants ha^{-1}	%			
120,000	97	52	834	0.96
180,000	97	50	802	0.96
240,000	97	50	802	0.96
290,000	94	50	802	0.97
425,000	98	49	787	0.97
588,000	95	48	772	0.95

[a] Abbreviations: DAE, days after soybean emergence; GDD, growing degree days.
[b] R^2 determined from linear regression of percent groundcover (Purcell 2000).

Table 5. Economic partial returns for soybean seeding rates in the presence or absence of a preemergence applied residual herbicide at Fayetteville, AR and Marianna, AR in 2013.

	Partial returns			
	PRE applied herbicide[a]		No PRE applied herbicide[b]	
Seeding rate	Fayetteville	Marianna	Fayetteville	Marianna
seed ha^{-1}	$ ha^{-1}			
123,500	1,040.63	990.75	747.90	1,217.70
185,750	1,244.54	1,061.47	1,031.34	1,161.93
247,000	1,204.25	1,514.67	1,049.69	1,184.39
308,750	1,359.79	1,364.66	1,111.10	1,259.98
432,250	1,480.13	1,397.25	1,129.83	1,100.84
617,500	1,663.29	1,735.78	1,167.89	1,414.70

[a] *Partial returns* = (*yield* * *market price*) – (*herbicide cost* + *application cost* + *seed cost*). Seed cost was assumed to be $0.41 per 1,000 seed. Herbicide cost was assumed to be $0.21 g^{-1}. Application cost was assumed to be $14.82 ha^{-1} $application^{-1}$. Market price was assumed to be $0.43 kg^{-1} of soybean grain.

[b] *Partial returns* = (*yield* * *market price*) – (*seed cost*). Seed costs were $0.41 per 1,000 seed. Market price was assumed to be $0.43 kg^{-1} of soybean grain.

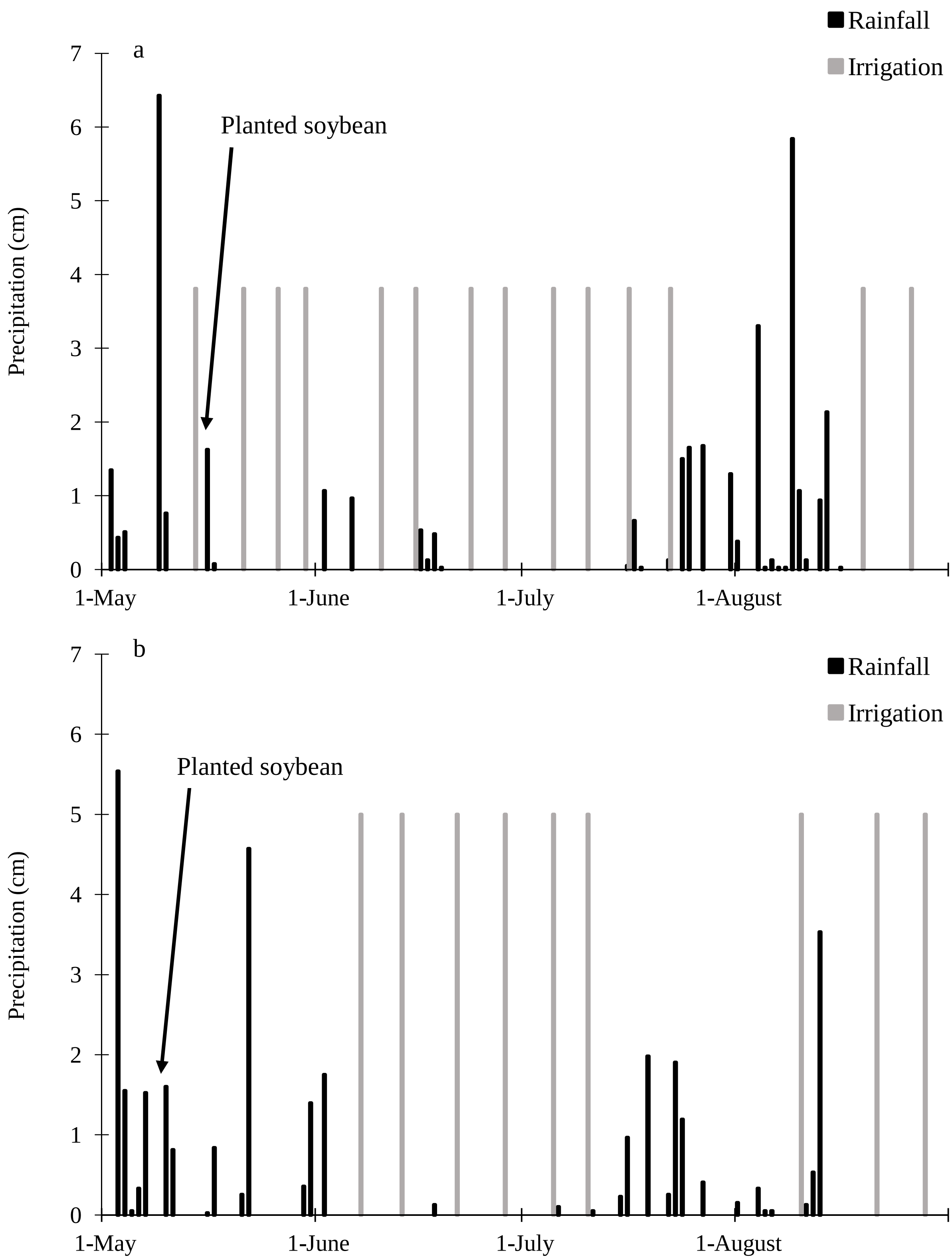

Figure 1. Rainfall and irrigation distribution at Fayetteville (a) and Marianna (b), AR in 2013.

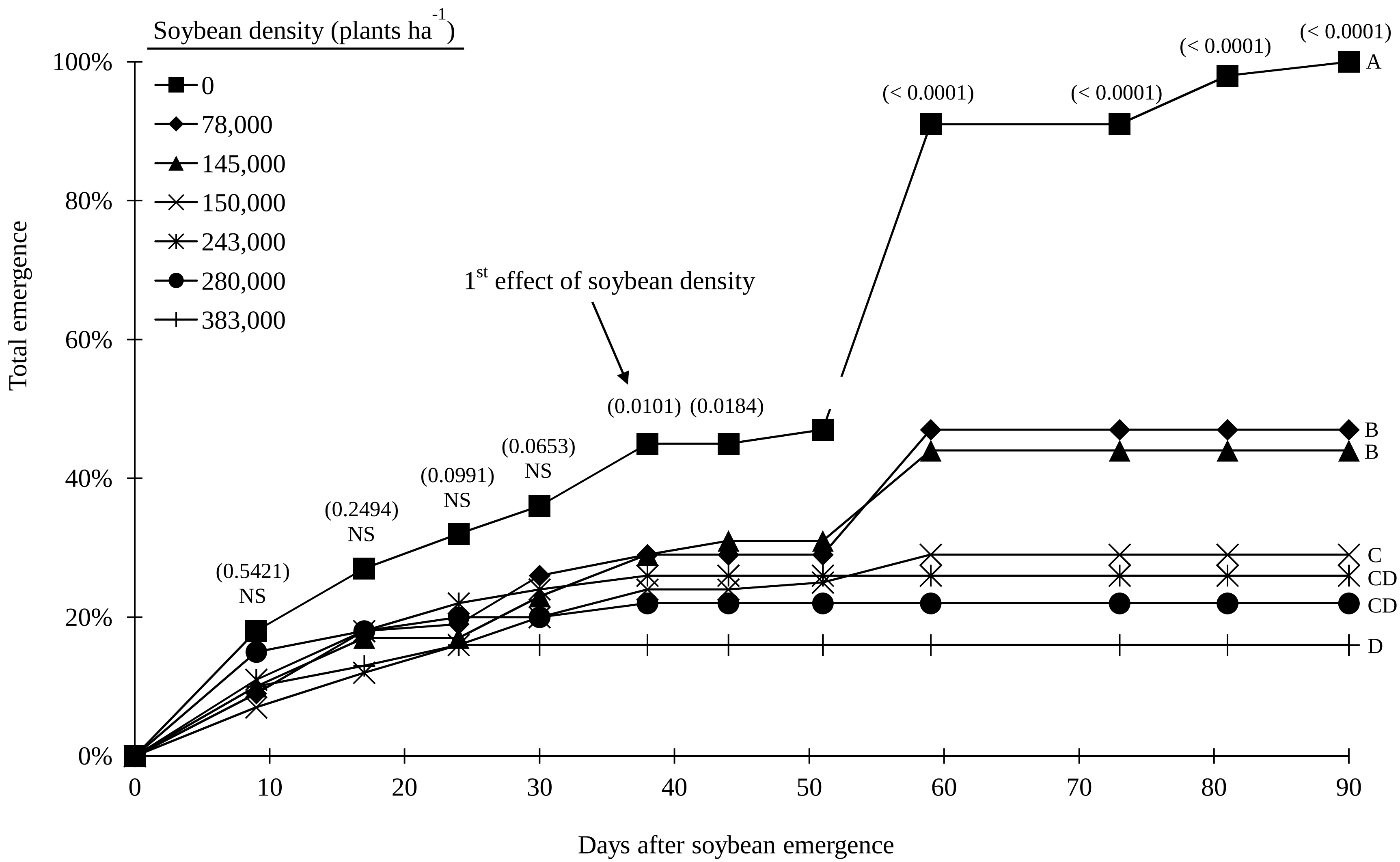

Figure 2. Percentage of total cumulative Palmer amaranth emergence (relative to no soybean, no herbicide treatment) after soybean emergence in the absence of a PRE herbicide at Fayetteville, AR in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at α < 0.05. *F* values for assessing treatment effects at that specific observation timing are represented in parenthesis,

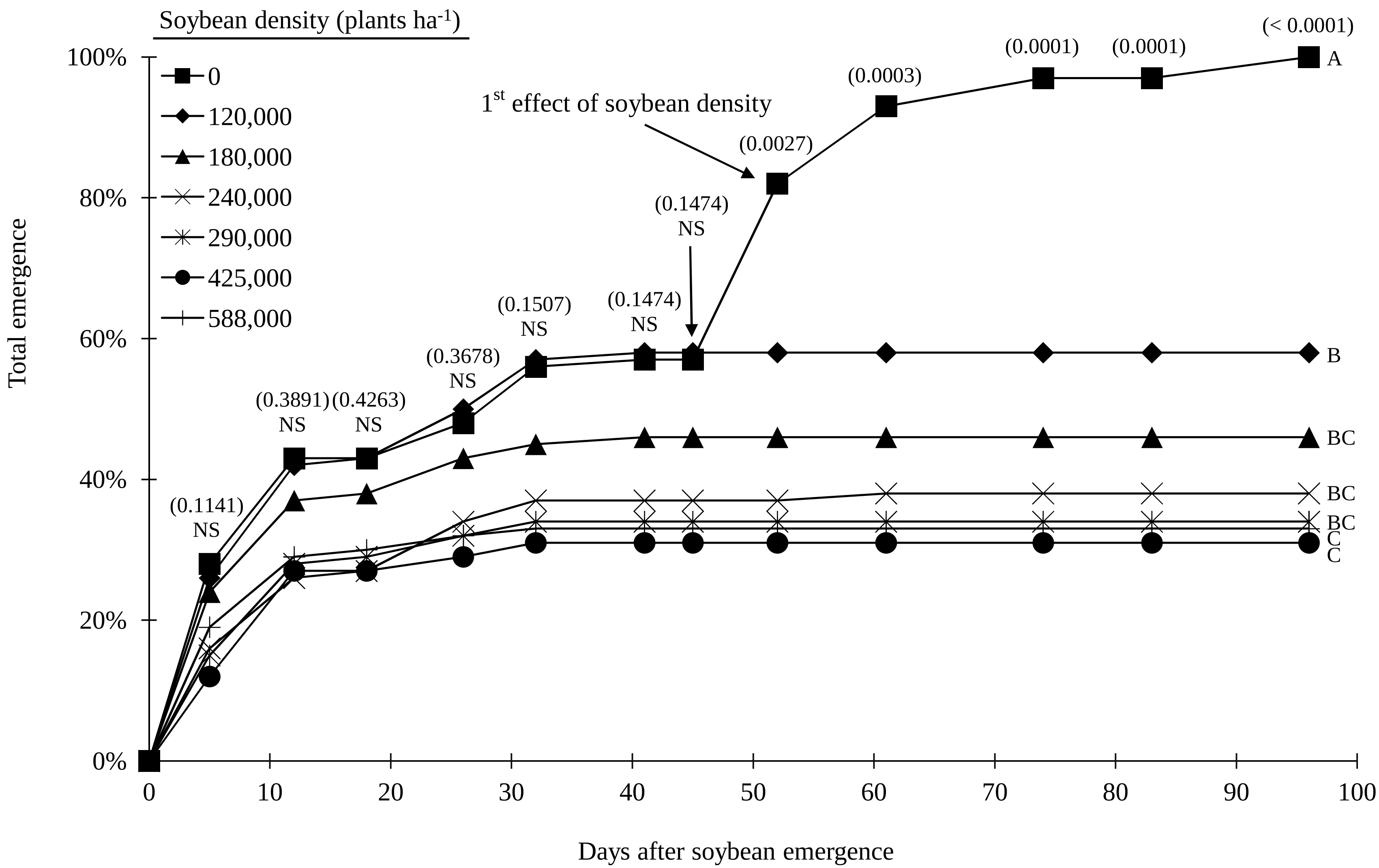

Figure 3. Percentage of total cumulative Palmer amaranth emergence (relative to no soybean, no herbicide treatment) after soybean emergence in the absence of a PRE herbicide at Marianna, AR in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at $\alpha < 0.05$. *F* values for assessing treatment effects at that specific observation timing are represented in parenthesis.

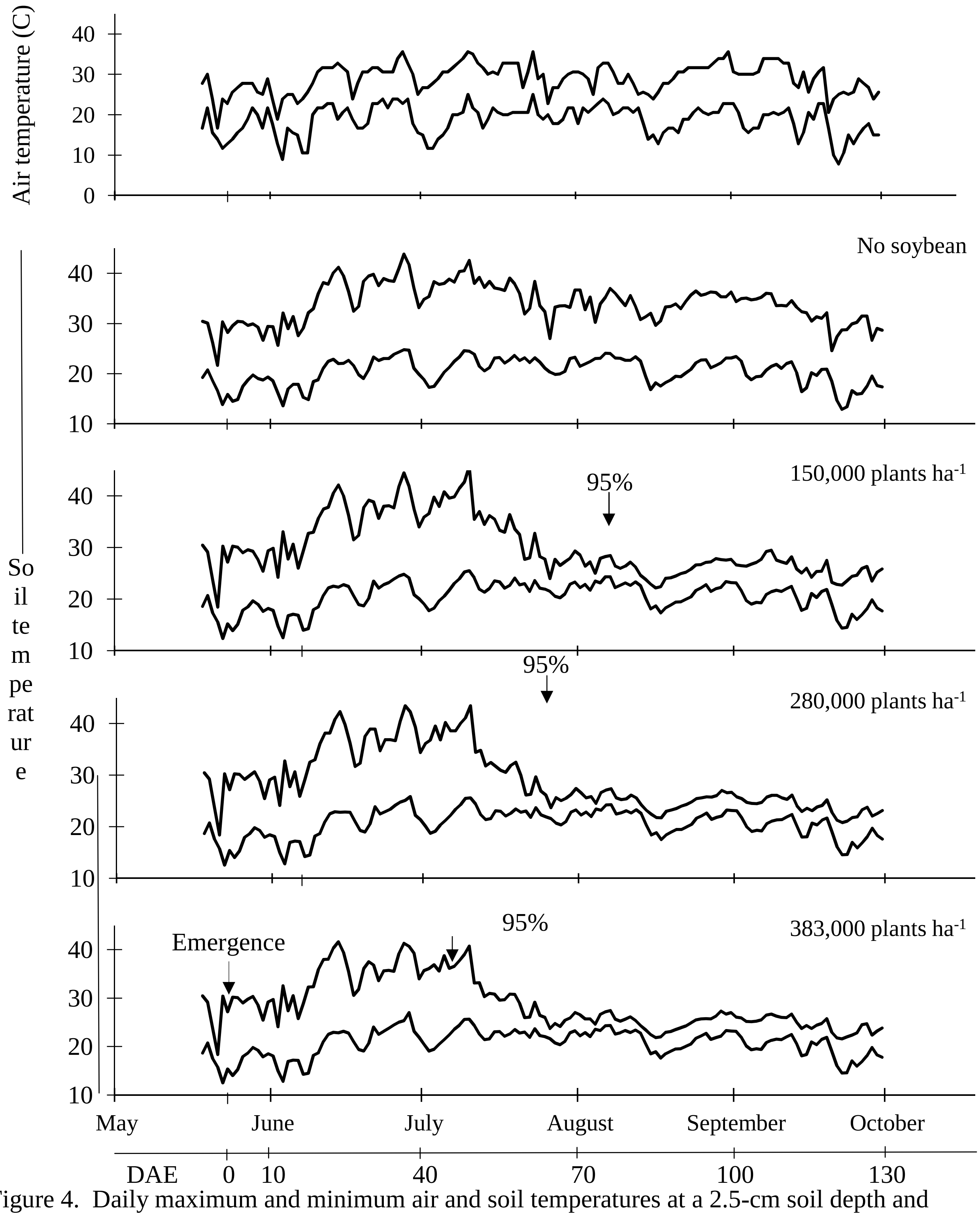

Figure 4. Daily maximum and minimum air and soil temperatures at a 2.5-cm soil depth and onset of 95% soybean canopy formation in 2013 at Fayetteville, AR in plots treated with flumioxazin plus pyroxasulfone at soybean planting.

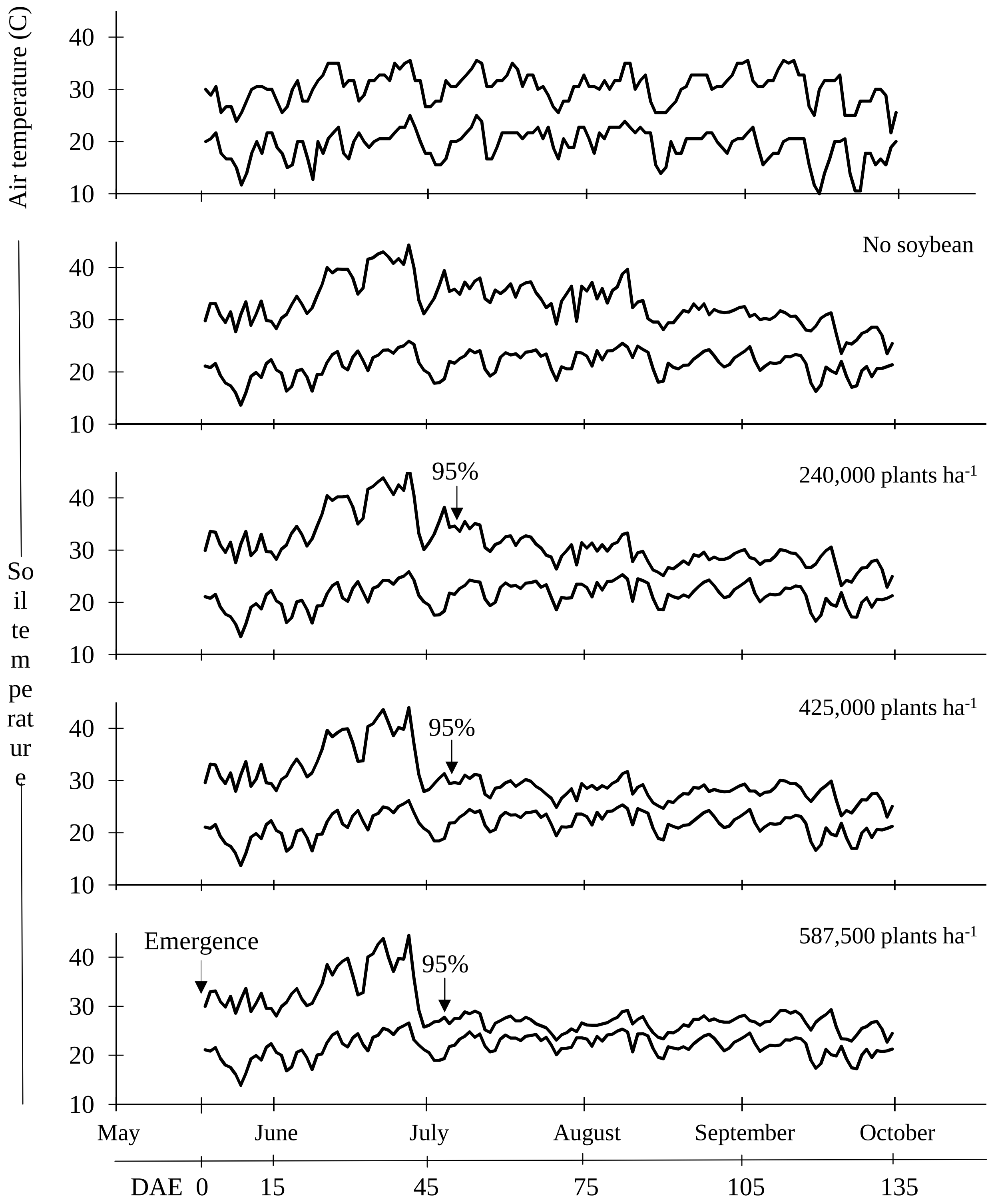

Figure 5. Daily maximum and minimum air and soil temperatures at a 2.5-cm soil depth and onset of 95% soybean canopy formation in 2013 at Marianna, AR in plots treated with flumioxazin plus pyroxasulfone at soybean planting.

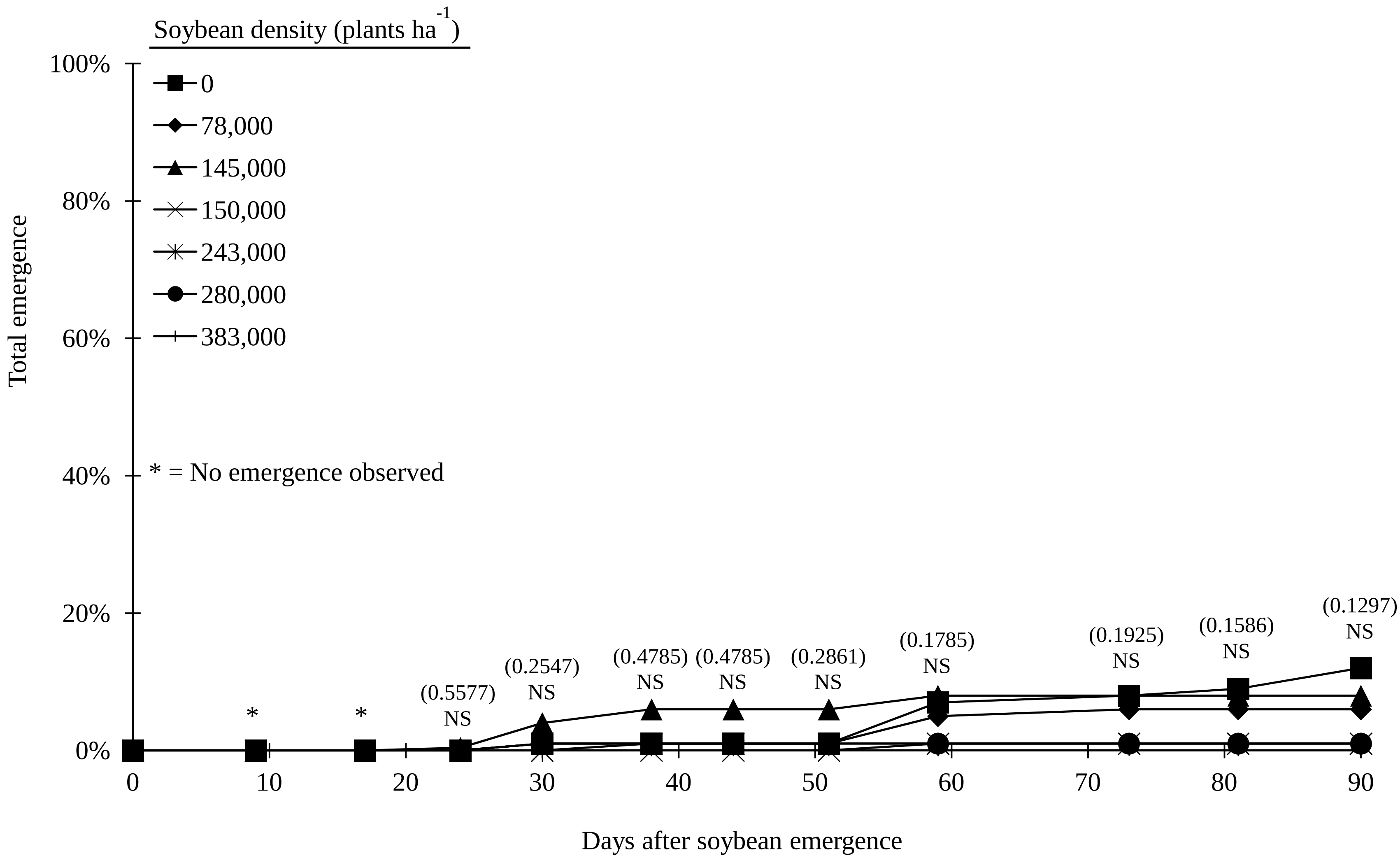

Figure 6. Percentage of total cumulative Palmer amaranth emergence (relative to no soybean, no herbicide treatment) after soybean emergence in the presence of a PRE herbicide at Fayetteville, AR, in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at $\alpha < 0.05$. *F* values for assessing treatment effects at that specific observation timing are represented in parenthesis.

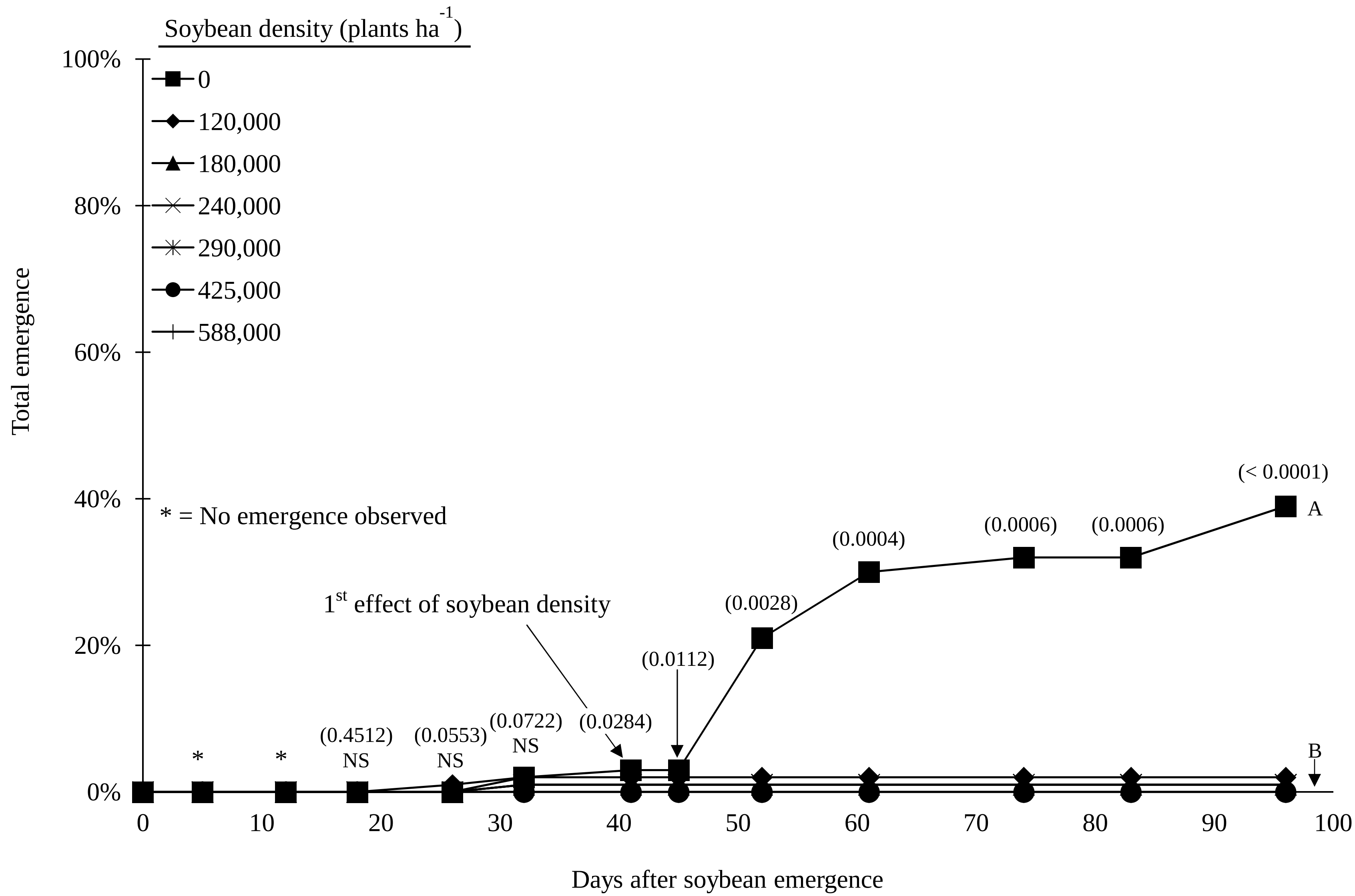

Figure 7. Percentage of total cumulative Palmer amaranth emergence (relative to no soybean, no herbicide treatment) after soybean emergence in the presence of a PRE herbicide at Marianna, AR in 2013. Nonsignificant (NS) indicates cumulative emergence at that specific observation timing was similar in the presence and absence of soybean according to Fisher's protected LSD test at α < 0.05. *F* values for assessing treatment effects at that specific observation timing are represented in parenthesis.

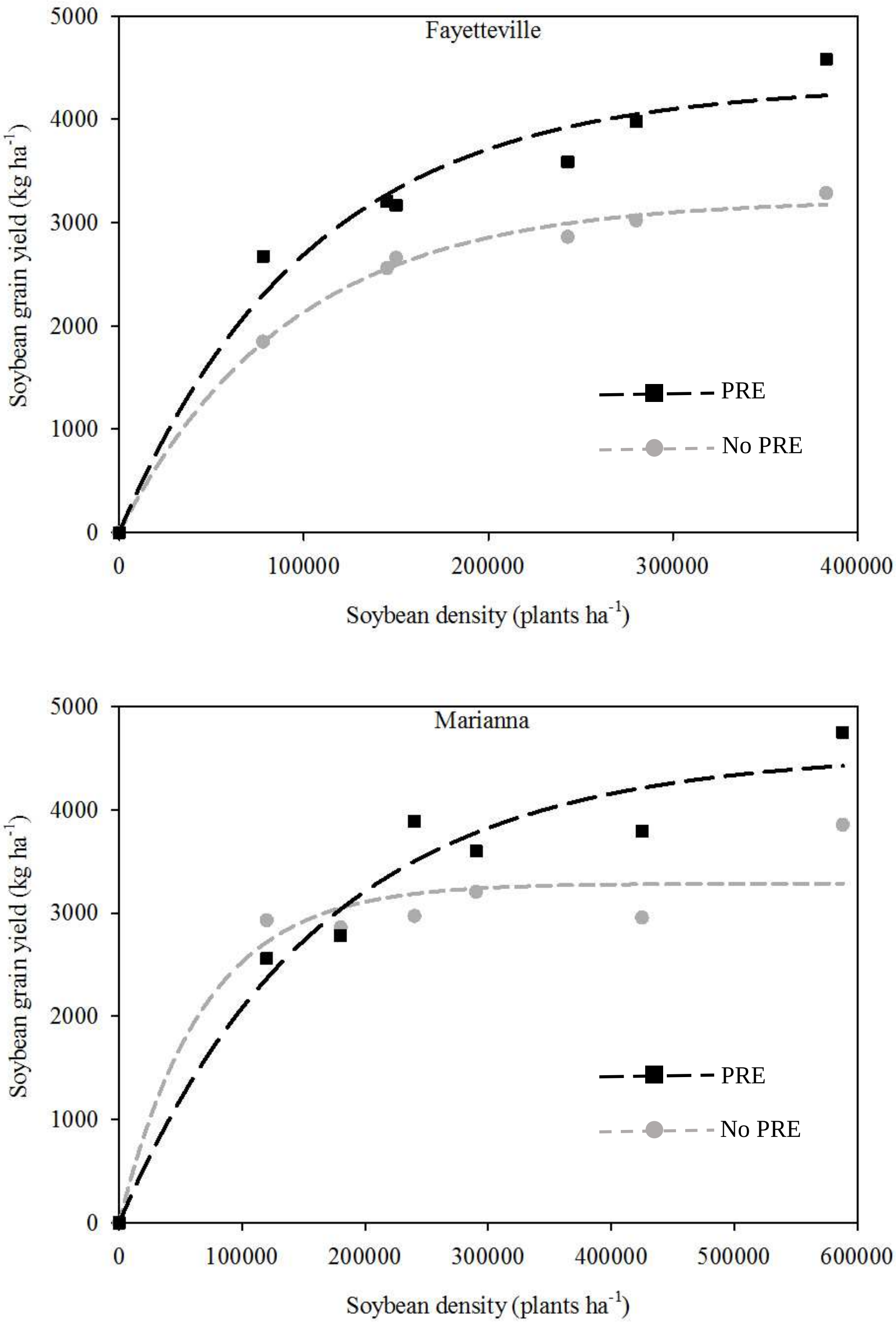

Figure 8. Soybean grain yield as influenced by soybean density in the presence (PRE) or absence (No PRE) of flumioxazin plus pyroxasulfone applied preemergence at Fayetteville and Marianna, AR in 2013 (See Table 2 for model specifics).

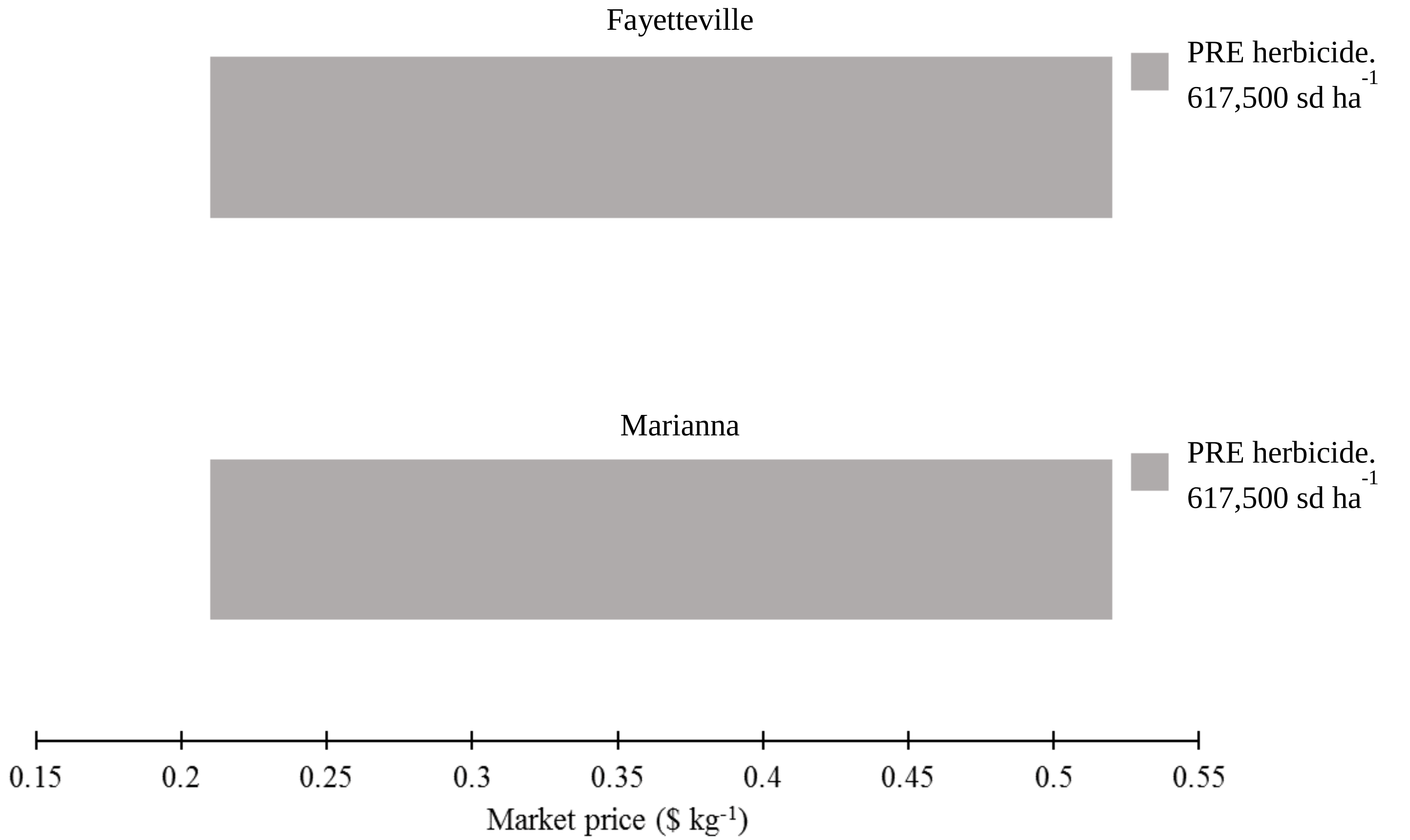

Figure 9. Sensitivity analysis, at Fayetteville and Marianna, AR in 2013, comparing all possible treatment Combinations between soybean seeding rate (0; 123,500; 185,250; 247,000; 308,750; 432,250; 617,500 seed ha^{-1}) and the presence or absence of a PRE applied herbicide for the impact of most dominant treatment with highest partial returns across 10 year high and low soybean market prices.

Literature Cited

Benvenuti S (1995) Soil light penetration and dormancy of jimsonweed (*Datura stramonium*) seeds. Weed Sci 43:389-393

Bryson CT, DeFelice MS (2009) Weeds of the South. Athens, GA: University of Georgia Press Pp. 34

Buhler DD, Werling VL (1989) Weed control from imazaquin and metolachlor in no-till soybeans (*Glyicne max*). Weed Sci 37:392-399

Burnside OC, Wilson RG, Weisberg S, Hubbard KG (1996) Seed longevity of 41 weed species buried 17 years in eastern and western Nebraska. Weed Sci 44:74-86

Cerrato ME, Blackmer AM (1990) Comparison of models for describing corn yield response to nitrogen fertilizer. Agron J 82:138-143

Costea M, Weaver SE, Tardif FJ (2004) The biology of Canadian weeds. 130. *Amaranthus retroflexus* L., *A. powellii* S. Watson and *A. hybridus* L. Canad J Plant Sci 84:631–668

Dalley CD, Kells JJ, Renner KA (2004) Effect of glyphosate application timing and row spacing on weed growth in corn (*Zea mays*) and soybean (*Glycine max*). Weed Technol 18:177-182

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263-270

Edwards JT, Purcell LC (2005) Soybean yield and biomass responses to increasing plant population among diverse maturity groups: I. agronomic characteristics. Crop Sci 45:1770-1777

Edwards JT, Purcell LC, Vories ED (2005) Light interception and yield of short-season maize (*Zea mays* L.) hybrids in the Mid-south. Agron J 97:225-234

Guo P, Al-Khatib K (2003) Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Sci 51:869-875

Horak MJ, Loughlin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347-355

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Jha P, Norsworthy JK, Riley MB, Bridges, Jr. W (2010) Annual changes in temperature and light requirements for germination of Palmer amaranth (*Amaranthus palmeri*) seeds retrieved from soil. Weed Sci 58:426-432

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199-204

Mahoney KJ, Shropshire C, Sikkema PH (2014) Weed management in conventional- and no-till soybean using Flumioxazin/pyroxasulfone. Weed Technol In-press

Miller JH, Keeley PE, Carter CH, Thullen RJ (1975) Soil persistence of trifluralin, benefin, and nitralin. Weed Sci 23:211-214

Molin WT, Hugie JA, Hirase K (2004) Prickly sida (*Sida spinosa* L.) and spurge (*Euphorbia hyssopifolia* L.) response to wide row and ultra narrow row cotton (*Gossypium hirsutum* L.) management systems. Weed Biol Manag 4:222-229

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur E (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: Evidence supporting a zero-threshold strategy. Weed Sci 62:237-249

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci Special Issue Pp. 31-62

Norsworthy JK, Smith KL, Steckel LE, Koger CH (2009) Weed seed contamination of cotton gin trash. Weed Technol 23:574-580

Norsworthy JK, Jha P, Bridges, Jr. W (2007) Sicklepod (*Senna obtusifolia*) survival and fecundity in wide- and narrow-row glyphosate-resistant soybean. Weed Sci 55:252-259

Norsworthy JK (2004) Soybean canopy formation effects on pitted morningglor (*Ipomoea lacunosa*), common cocklebur (*Xanthium strumarium*), and sicklepod (*Senna obtusifolia*) emergence. Weed Sci 52:954-960

Norsworthy JK, Oliver LR (2001) Effect of seeding rate of drilled glyphosate-resistant soybean (*Glycine max*) on seed yield and gross profit margin. Weed Technol 15:284-292

Purcell LC, Ball RA, Reaper JD, Vories ED (2002) Radiation use efficiency and biomass production in soybean at different plant population densities. Crop Sci 42:172-177

Purcell LC (2000) Soybean canopy coverage and light interception measurements using digital imagery. Crop Sci 40:834-837

Renner KA, Mickelson JA (1997) Weed control using reduced rates of post-emergence herbicides in narrow and wide row soybean. J Prod Agric 10:431-437

Riar DS, Norsworthy JK, Steckel LE, Stephenson IV, DO, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the Midsouth United States-soybean: A consultant's perspective. Weed Technol 27:612-622

Richardson MD, Karcher DE, Purcell LC (2001) Quantifying turfgrass cover using digital image analysis. Crop Sci 41:1884-1888

Scott B, Smith K (2011a) A guide to pigweed management for soybean/cotton University of Arkansas Cooperative Extension Service Available http://search.uaex.edu/search?q=a+guide+to+pigweed+management&site=default_collection&client=uaex&proxystylesheet=uaex. Accessed March 4, 2014

Scott B, Smith K (2011b) Prevention and control of glyphosate-resistant pigweed in soybean and cotton. University of Arkansas Cooperative Extension Service Printing Services FSA 2152-PD-3-11RV 4 pp

Sosnoskie LM, Webster TM, Culpepper AS (2013) Glyphosate resistance does not affect Palmer amaranth (*Amaranthus palmeri*) seedbank longevity. Weed Sci 61:283-288

Steckel LE (2007) The dioecious *Amaranthus* spp.: Here to stay. Weed Technol 21:567-570

Steckel LE, Sprague CL, Stoller EW, Wax LM (2004) Temperature effects on germination of nine *Amaranthus* species. Weed Sci 52:217-221

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre- and postemergence herbicide efficacy in soybean. Weed Technol 24:234-243

Vasilakoglou IB, Eleftherohorinos IG (2003) Persistence, efficacy, and selectivity of amide herbicides in corn. Weed Technol 17:381-388

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): A review. Weed Technol 27:12-27

Ware GO, Ohki K, Moon LC (1982) The Mitscherlich plant growth model for determining critical nutrient deficiency levels. Agron J 74:88-91

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145-157

Whitaker JR, York AC, Jordan DL, Culpepper AS (2010) Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol 24:403-410

CHAPTER IV

Effect of Row Spacing, Seeding Rate, and Herbicide Program in Glufosinate-Resistant Soybean on Palmer Amaranth Management

Abstract: A field experiment was conducted in Fayetteville, AR, in 2012 and 2013 to determine the influence of soybean row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth control, survival, and seed production; soybean groundcover and grain yield; and economic returns. Soybean groundcover was > 80% by 79 days after soybean emergence (DAE) for all row spacing and seeding rates in 2012 and in 2013 all soybean row spacings and soybean seeding rates had achieved > 90% groundcover by 50 DAE. Differences in groundcover between years was due to lack of precipitation in 2012. Palmer amaranth control at 21 days after soybean planting (DAP) was 99 to 100% for both years when a PRE application of *S*-metolachlor plus metribuzin was made at planting. At 42 DAP, Palmer amaranth control following PRE-applied *S*-metolachlor plus metribuzin was ≥ 98% and ≥ 88% in 2012 and 2013, respectively. When relying on a postemergence (POST)-only herbicide program initiated at 21 DAP, Palmer amaranth control ranged from 52 to 84% across row spacings at 42 DAP. At soybean harvest, Palmer amaranth control was ≥ 95% and ≥ 86% regardless of row spacing or seeding rate when *S*-metolachlor plus metribuzin was applied at planting. Conversely, total-POST programs had no more than 50% and 85% Palmer amaranth control in 2012 and 2013, respectively. In both years, Palmer amaranth density and seed production at soybean harvest were generally lower in the PRE herbicide programs compared to POST-only programs. Use of a PRE herbicide at planting also improved soybean grain yield and economic returns over programs that relied on a POST-only program. Overall, the impact of soybean row spacing and seeding rate on Palmer amaranth control, density, or seed production were less apparent than the influence of herbicide programs.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* (S.) Wats; soybean, *Glycine max* (L.) Merr.

Key words: glufosinate-resistant, Palmer amaranth, post-only, preemergence, row spacing, seeding rate.

Introduction

Soybean production is a major economic contributor to the U.S. economy, accounting for more than US$41.8 billion of production on 31.5 million ha^{-1} planted in 2013 (USDA-NASS 2013a). Of the soybean planted by U.S. producers, 93% had some type of herbicide-resistant (HR) trait in 2013. Most of the soybean hectares planted to an HR trait are in the form of glyphosate resistance [Roundup Ready (RR), Monsanto], as evident by glyphosate use on 89% of the planted U.S. soybean hectares in 2013 (USDA-NASS 2013b) and glyphosate accounting for 83% of all herbicide active ingredient applied in soybean in 2012 ((USDA-NASS 2014a).

Arkansas ranks tenth among U.S. states in hectarage and accounted for more than US$1.8 billion in production on 1.3 million ha^{-1} of soybean in 2013 (USDA-NASS 2014b). In 2013, 97% of Arkansas soybean acreage had an HR trait, which was 4% greater than the national average (USDA-NASS 2013a).

The increased use and applications [1 glyphosate application $year^{-1}$ in 1995 to 1.4 glyphosate applications $year^{-1}$ in 2002 (Young 2006)] of glyphosate was rational because of the adoption of RR soybean started in 1996. However, the overreliance of glyphosate in RR crops, especially soybean and cotton (*Gossypium hirsutum* L.), led to an increased number of glyphosate-resistant (GR) weed species [1 in 1996 to 28 in 2014 (Heap 2014)], globally. Currently, the United States has 14 weed species that have been confirmed resistant to glyphosate (Heap 2014) and an increase in GR weed species is probable if appropriate practices are not soon incorporated for resistance management.

One of the most important GR weed species in Arkansas, and through much of the Southern U.S. cropping region, is Palmer amaranth. Palmer amaranth was first confirmed resistant to glyphosate in Georgia in 2005, followed by Arkansas in 2006, and currently is reported in 28 states in the U.S. alone (Heap 2014; Norsworthy, personal communication). Palmer amaranth's prolific seed production [≥ 250,000 seed per female plant (Keeley et al. 1987; Scott and Smith 2011; Sellers et al. 2003)], extended emergence period [early April until the first killing frost (DeVore et al. 2013; Jha and Norsworthy 2009)], and rapid erect growth (Klingaman and Oliver 1994; Monks and Oliver 1988; Norsworthy et al. 2008b) make it one of the most troublesome weeds in crop production.

Palmer amaranth can be viewed as a chief example of what happens when the efficacy of an herbicide is lost. In just 14 years, Palmer amaranth went from being the 23rd most troublesome weed in soybean to the 2nd most troublesome weed in the Southern states of Alabama, Arkansas, Florida, Georgia, Kentucky, Missouri, North Carolina, Oklahoma, South Carolina, and Virginia (Webster and Nichols 2012). The same holds true, although to a lesser extent, in cotton. In 1995, Palmer amaranth ranked 10th among troublesome weeds, but by 2009, it was the most troublesome weed in nine Southern states (Alabama, Arkansas, Florida, Georgia, Missouri, North Carolina, Oklahoma, South Carolina, and Virginia) (Webster and Nichols 2012). More recently, a survey conducted by Riar et al. (2013) reported that Palmer amaranth was the most problematic weed of soybean in Arkansas, Louisiana, Mississippi, and Tennessee.

The problems posed by GR Palmer amaranth are of great importance to producers because of the rapid spread and the abundant seed production of this plant. Norsworthy et al. (2014) reported the introduction of 20,000 GR Palmer amaranth seed into a 1 m^2 circle within four cotton fields resulted in 95 to 100% of the field being infested within three years of introduction. In 2009, Arkansas was estimated to have 88,000 soybean hectares infested with GR Palmer amaranth (Nichols et al. 2009), but by 2011, 99% of soybean consultants surveyed in

Arkansas, Mississippi, and Tennessee suspected they had fields infested with GR Palmer amaranth (Riar et al. 2013).

Soybean growers in the Midsouth have limited, effective, over-the-top herbicide options for Palmer amaranth control because of the evolution of herbicide resistance [glyphosate and acetolactate synthase (ALS)-inhibiting herbicides] (Riar et al. 2013). Current options for over-the-top control of Palmer amaranth in soybean include several protoporphyrinogen oxidase (PPO)-inhibiting herbicides and glufosinate in glufosinate-resistant [LibertyLink® (LL), Bayer CropScience] soybean (Scott et al. 2014). Hectares planted to glufosinate-resistant soybean in the Midsouth are greater than that in other areas of the U.S. partially as a result of the effectiveness of glufosinate on Palmer amaranth resistant to glyphosate and ALS-inhibiting herbicides (Barnett et al. 2013; Norsworthy et al. 2008a). However, for glufosinate to provide consistent, effective control of Palmer amaranth, it must be applied when the plants are small, generally ≤ 10 cm in height (Anonymous 2014; Norsworthy et al. 2012; Riar et al. 2013). Because of environmental conditions, applicator scheduling, and timing of on-farm operations, it is difficult for producers to effectively time glufosinate applications and whenever Palmer amaranth escapes control because of it’s large size at application, producers have to hand weed portions of fields, costing as much as \$371 ha^{-1} for dense infestations of Palmer amaranth (Riar et al. 2013).

The introduction of GR crops enabled producers to use one effective herbicide (i.e. glyphosate) mechanism of action (MOA) for broad-spectrum weed control and reduced the number of MOAs used during the growing season, resulting in primarily a glyphosate monoculture weed control program (Young 2006). Relying on repeated applications of effective herbicides, with the same MOA, increases the risk of herbicide-resistant weeds evolving (Beckie

2006; Norsworthy et al. 2012; Powles et al. 1997). Therefore, multiple herbicides with different MOAs are needed throughout the growing season and in subsequent seasons (i.e. crop rotations, trait rotations, etc.) to delay the evolution of herbicide resistance in weed species.

The use of soil residual herbicides not only can increase the number of MOAs used in an herbicide program, but can also offer extended weed control compared to postemergence (POST) herbicides (i.e. glyphosate or glufosinate) that lack residual activity (Ellis and Griffin 2002; Taylor-Lovell et al. 2002; Weisbrook et al. 2001). The efficacy of soil residual herbicides is highly dependent on either rainfall or irrigation shortly after application, which places the herbicide molecules into soil solution where they can be taken up as weeds germinate and emerge (Johnson et al. 2012; Krausz et al. 2001; Stewart et al. 2010).

The incorporation of a soil residual herbicide into herbicide programs has been reported to effectively control Palmer amaranth (Barnes and Oliver 2004; Everman et al. 2009; Riar et al. 2011). In soybean, *S*-metolachlor in combination with either flumioxazin, fomesafen, or metribuzin plus chlorimuron applied preemergence (PRE) followed by (fb) a POST application of fomesafen controlled GR Palmer amaranth ≥ 97%, ≥97%, and ≥94%, respectively, 30 days after the POST herbicide application (Whitaker et al. 2010). Similar results were observed by Norsworthy (2004) where the combination of *S*-metolachlor and either flumetsulam, flumioxazin, chlorimuron plus sulfentrazone, or metribuzin applied PRE controlled Palmer amaranth ≥ 99% in soybean for 5 weeks after planting.

Herbicides are the principal tool and foundation of most effective weed control programs (Harker and O’Donovan 2013; Norsworthy et al. 2012). Since the occurrence of HR weeds, there has been a need for research on the effectiveness of non-herbicidal management practices that could potentially increase weed control, as evidenced by consultants describing their top priority of weed management research being that of cultural weed control practices (Riar et al. 2013). Examples of cultural management practices that could impact weed control include tillage intensity, crop row widths and seeding rates, herbicide trait selection, and crop rotations, as well as others.

The positive benefits of a narrow soybean row spacing and increased seeding rate on weed control are numerous (Hock et al. 2005; Mickelson and Renner 1997; Nice et al. 2001; Place et al. 2009; Rich and Renner 2007). Harder et al. (2007) reported less weed emergence in 19 cm than in 76 cm width soybean rows and also weed biomass was greater at a soybean density of 124,000 plants ha^{-1} compared to 445,000 plants ha^{-1}. End-of-season weed biomass decreased (Hock et al. 2006), weed control increased (Young et al. 2001), and weed survival decreased (Norsworthy et al. 2007) in narrow-row (19 cm) versus wide-row ($\geq$ 76 cm) soybean. A soybean density of at least 478,000 plants ha^{-1} in combination with narrow-rows ($\leq$ 38 cm) increased mid- and late-season control of sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] compared to a density of 269,000 plants ha^{-1} and a 76-cm row spacing (Buehring et al. 2002). Increasing soybean population from 217,000 plants ha^{-1} to 521,000 plants ha^{-1} reduced pitted morningglory (*Ipomea lacunosa* L.) seed production by 41% (Norsworthy and Oliver 2002). Although there are numerous reports on how soybean row spacing and seeding rate influence control of various weeds, there is minimal research on how soybean row spacing and seeding rate affect Palmer amaranth (Jha et al. 2008).

Hence, the objective of this research was to determine the effect of soybean row spacing, seeding rate, and herbicide program on Palmer amaranth emergence, survival, and seed production, as well as, grain yield and economic partial returns.

Materials and Methods

Field experiments were conducted at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR during the summer of 2012 and 2013. The soil type was a Leaf silt loam (Fine, mixed, active, thermic Typic Albaquults) with 34% sand, 53% silt, 13% clay, 1.5% organic matter, with a pH of 6.9.

The experiment consisted of plots that were 2 to 4 m wide (depending on row spacing) by 9 m in length and organized as a split-split plot design replicated four times. The main plot factor was row spacing (19-, 45-, and 90-cm), the sub-plot factor was soybean seeding rate (247,000 and 432,000 seed ha^{-1}), and the sub-sub-plot factor was herbicide program (6). Herbicide programs consisted of: 1) non-treated control; 2) a premix of *S*-metolachlor at 1545 g ai ha^{-1} plus metribuzin at 368 g ai ha^{-1} (Boundary® 6.5 EC, Syngenta Crop Protection, Greensboro, NC 27419) applied PRE; 3) *S*-metolachlor at 1545 g ha^{-1} plus metribuzin at 368 g ha^{-1} applied PRE fb glufosinate (Liberty® 280 SL, Bayer CropScience LP, Research Triangle Park, NC 27709) at 595 g ai ha^{-1} plus a premix of *S*-metolachlor at 1217 g ha^{-1} plus fomesafen at 266 g ai ha^{-1} (Prefix®, Syngenta Crop Protection, Greensboro, NC 27419) applied at 21 days after soybean planting (DAP); 4) *S*-metolachlor at 1545 g ha^{-1} plus metribuzin at 368 g ha^{-1} applied PRE fb glufosinate at 595 g ha^{-1} plus *S*-metolachlor at 1217 g ha^{-1} plus fomesafen at 266 g ha^{-1} applied 21 DAP fb glufosinate at 738 g ha^{-1} plus acetochlor at 1260 g ai ha^{-1} (Warrant®, Monsanto Company, St. Louis, MO 63167) applied 42 DAP; 5) *S*-metolachlor at 1545 g ha^{-1} plus metribuzin at 368 g ha^{-1} applied PRE fb glufosinate at 738 g ha^{-1} plus acetochlor at 1260 g ha^{-1} applied 42 DAP; and 6) glufosinate at 595 g ha^{-1} plus *S*-metolachlor at 1217 g ha^{-1} plus fomesafen at 266 g ha^{-1} applied 21 DAP fb glufosinate at 738 g ha^{-1} plus acetochlor at 1260 g ha^{-1} applied 42 DAP (POST-only). Treatments were applied with a CO_2-pressurized backpack sprayer consisting of a handheld boom that contained four 110015 flat-fan nozzles (Teejet Technologies, Springfield, IL 62703) on 48 cm spacing calibrated to deliver 140 L ha^{-1} at 276 kPa.

Soybean seed were counted with a Seedburo 801 Count-A-Pak® (Seedburo Equipment Co., Des Plaines, IL 60018) for each seeding rate to determine the correct number of seed to be planted in each sub-sub-plot. Prior to planting, the seedbed was prepared by disking the field and using a field cultivator (Kongskilde Industries Inc., Hudson, IL 61748) to obtain a uniform seedbed. Halomax 494, a late maturity group IV glufosinate-resistant soybean cultivar, was either drill-seeded with a 10-row Almaco (ALMACO, Nevada, IA 50201) cone-type drill on a 19 cm row spacing or seeded with a four-row John Deere 6403 (Deere and Company, Moline, IL 61265) planter set to either a 45 or 90 cm row spacing. Soybean were planted on May 16 in 2012 and on June 14 in 2013 and irrigated with an overhead sprinkler.

After soybean planting, two 0.5 m^2 areas were marked with flags (Gempler's, Janesville, WI 53547) in the center of each plot to provide an area to assess Palmer amaranth emergence, survival, and seed production as well as soybean densities. Palmer amaranth density and weed control (visually estimated on a 0 to 100% scale, where 0 was equal to no control and 100 was complete control) were recorded at the 21 and 42 DAP applications and at soybean harvest, and Palmer amaranth survival and seed production were recorded prior to soybean harvest in the two quadrats in each sub-sub-plot.

A digital camera (Sony Cyber-shot®, Sony Electronics, San Diego, CA 92127) was mounted on a 5-cm diameter pipe at a height of 1.5 m and at a 70° downward facing angle. Weekly photographs were taken from a marked position in the center of each sub-sub-plot, starting when soybean reached cotyledon stage (VC). Photographs were taken throughout the growing season and then transferred to a computer, sorted, and individually analyzed by SigmaScan® Pro 5.0 (Systat Software, Inc., San Jose, CA 95110) to determine the soybean canopy formation in days after soybean emergence using the procedures described by Purcell (2000). The output values from SigmaScan were exported to Excel (Microsoft®, Redmond, WA 98052) and sorted. Data from Excel were entered in SigmaPlot® 12.5 (Systat Software, Inc., San Jose, CA 95110) and fit to a non-linear regression and tested for normality by Shapiro-Wilk's test (Table 1).

Economic partial returns were calculated by using the average chemical and seed costs from two distributors in Northeast Arkansas (Helena Chemical Co., Hughes, AR 72348 and Crop Production Services Inc., Crawfordsville, AR 72327) (Table 2). Chemical application costs were obtained from the University of Arkansas Division of Agriculture Research and Extension 2014 Crop Enterprise Budgets available at http://www.uaex.edu/farm-ranch/economics-marketing/farm-planning/enterprise-budgets.aspx. Current soybean market price from http://www.themiraclebean.com/markets was used to determine the value associated with soybean grain yield, and from these data economic partial returns were calculated. Partial returns were used to compare production alternatives where only the revenue and cost items that change across production alternatives were tracked. Hence, the alternative with the greatst partial returns would be most profitable (Kay et al. 2008).

A sensitivity analysis on soybean market price, holding all other costs constant, was conducted to determine whether the dominant production alternative with the greatest partial returns, was consistent over a range of soybean prices. Soybean market prices was based on the range of 10-year low and high soybean prices as reported by the National Agricultural Statistics Service (http://www.nass.usda.gov/Statistics_by_Subject/idex/php?sector=CROPS).

Due to the different environmental conditions between 2012 and 2013, years were analyzed separately. Data were analyzed using ANOVA with the MIXED procedure in JMP to test the significance of main effects and interactions. Soybean row spacing, soybean density, herbicide program, and any interactions containing these effects were fixed effects and replication and its interactions were random effects. Fisher's protected LSD values were calculated and used to separate means when *F* values were statistically significant ($\alpha \leq 0.05$).

Results and Discussion

Soybean Density and Canopy Formation. Soybean densities in 2012 for the soybean seeding rate of 247,000 seed ha^{-1} were 18, 21, and 22 plants m^{-2} for a row spacing of 19-, 45-, and 90-cm, respectively, and for the seeding rate of 432,000 seed ha^{-1} densities were 25, 38, and 41 plants m^{-2} for a row spacing of 19-, 45-, and 90-cm, respectively. In 2013, soybean densities for the seeding rate of 247,000 seed ha^{-1} averaged 23, 19, and 22 plants m^{-2} for the row spacings of 19-, 45-, and 90-cm, respectively, and for the seeding rate of 432,000 seed ha^{-1} densities were 38, 32, and 39 plants m^{-2} for the row spacings of 19-, 45-, and 90-cm, respectively.

Growing conditions differed between the 2012 and 2013 seasons. The growing season of 2012 was characterized as a dry, hot year, having less rainfall compared to the growing season of 2013 (Figure 1a and 1b). Although the experiment was positioned where overhead sprinkler irrigation was accessible, the irrigation system malfunctioned in 2012 during the month of June, resulting in no irrigation for this period. The lack of rainfall or irrigation in June of 2012 hampered soybean growth and resulted in drought stress to the Palmer amaranth which lowered herbicide efficacy. Additionally, the lack of soybean growth during June may have contributed to low efficacy as a result of slow soybean canopy formation and less interference of soybean with Palmer amaranth compared to 2013. Furthermore, there was little residual activity from the *S*-metolachlor plus fomesafen applied at 21 DAP due to the lack of precipitation following application.

Due to the dry environment, the narrow-row soybean (19-cm spacing) needed 79 days after soybean emergence (DAE) to achieve 90% groundcover whereas the 90-cm spacing never achieved 90% groundcover in 2012 (Figure 2). Conversely in 2013, soybean plants had adequate moisture and plant growth was not hindered. In 2013, the 19-cm row spacing achieved > 90% groundcover by 40 DAE, regardless of soybean seeding rate, and all soybean row spacings achieved > 90% groundcover by 50 DAE, regardless of soybean seeding rate. The benefit of the narrow row spacing and/or increased seeding rate on soybean groundcover was not as apparent in 2012 compared to 2013 due to the dry conditions.

Palmer Amaranth Control. Immediately following soybean planting, sufficient irrigation was provided to activate the PRE herbicide in both years. As a result, all PRE herbicide treatments provided ≥ 99% Palmer amaranth control through 21 DAP for both years (data not shown). In 2012, a row spacing by herbicide program interaction occurred at 42 DAP and at soybean harvest.

At 42 DAP, treatments including a PRE herbicide had ≥ 98% Palmer amaranth control, regardless of row spacing or seeding rate in 2012. However, Palmer amaranth control for the POST-only program ranged from 52 to 69% over row spacings (Table 3). The low control in the POST-only treatments is because Palmer amaranth heights (≥ 15 cm) at treatment were in excess of the maximum size (≤ 10 cm) for effective control with glufosinate and fomesafen. Furthermore, the lack of rainfall and irrigation prevented activation of the residual herbicides that were applied at 21 DAP.

Palmer amaranth control in all treatments that contained a PRE herbicide in 2012 was ≥ 95%, regardless of row spacing and seeding rate, at soybean harvest (Table 3). Similarly in other research improved control of *Amaranthus* spp. was reported when glufosinate was applied POST following a PRE residual herbicide (Gardner et al. 2006). When *S*-metolachlor plus metribuzin were applied PRE, no differences were noted in Palmer amaranth control among row spacings at harvest. Conversely, Palmer amaranth control with the POST-only treatments was 26, 50, and 18% for the 19-, 45-, and 90-cm row spacings, further evidence for the need for PRE herbicides in glufosinate-resistant soybean.

In 2013, all treatments containing a PRE herbicide had ≥ 98% control at 42 DAP, except for the 19-cm row spacing that did not receive a POST treatment until 42 DAP (Table 3). Tank-mixing glufosinate with residual herbicides has been shown to provide effective control of *Amaranthus* spp. (Hamill et al. 2000) and use of residual herbicides when non-residual POST herbicides are applied is recommended for managing against evolution of resistant weeds (Norsworthy et al. 2012). The POST-only treatments at 42 DAP with a 45- or 90-cm row spacing had less Palmer amaranth control than the 19-cm row spacing likely because of increased competitiveness and earlier canopy formation in the narrow row spacing.

Similar to the 42 DAP ratings, Palmer amaranth control at harvest in 2013 was generally greatest when a PRE herbicide had been applied. In the absence of a soil-residual herbicide, several glufosinate applications may be needed for effective weed management (Beyers et al. 2002). The POST-only herbicide treatments once again had less control of Palmer amaranth compared to the herbicide programs that included a PRE application. The POST-only applications for the 19-cm row spacing had comparable control to most PRE herbicide treatments; however, the wider row spacings of 45- and 90-cm had less control than the narrow spacing. The main factor contributing to the control of Palmer amaranth was a PRE herbicide application and/or multiple herbicide applications. Coetzer et al. (2002) reported multiple applications of glufosinate provided greater control of Palmer amaranth than a single application.

In both years, there were minimal differences, if any, among the soybean row spacings for Palmer amaranth control when *S*-metolachlor plus metribuzin was applied PRE. It should be noted that the PRE application was activated via rainfall or irrigation both years; hence, the high level of control. If rainfall or irrigation did not occur soon after application, most of the weed control would be supplied by the POST herbicide, similar to the POST-only program that was evaluated in this research. In such instance where PRE herbicides fail or are not applied, value of the 19-cm row spacing over wider row spacings became evident.

Approximately 80% of the soybean fields in Arkansas are irrigated (J.K. Norsworthy; personal communication); however, furrow or flood irrigation is the most common means of irrigating soybean, and these types of irrigation are often not initiated until several weeks after crop emergence. Therefore, PRE herbicides applied in most soybean fields would be solely dependent upon rainfall for activation. By planting glufosinate-resistant soybean in fields containing glyphosate- and ALS-resistant Palmer amaranth both glufosinate and PPO-inhibiting herbicides such as fomesafen can be applied to provide multiple effective mechanisms of action for POST control of Palmer amaranth - a strategy that is recommended for reducing the risk of herbicide resistance evolving (Norsworthy et al. 2012). Differences among row spacings which had a PRE herbicide were minimal. However, in the instance whenever a PRE herbicide was not included (i.e. not activated), the benefit of a narrow row spacing (19 cm) would be evident as a result of some Palmer amaranth control being provided by earlier soybean canopy formation, which may allow a Palmer amaranth infested field to be salvaged.

Palmer Amaranth Density. Palmer amaranth densities were solely influenced by herbicide programs at 21 and 42 DAP for both years and at soybean harvest in 2012 (Table 4). At soybean harvest in 2013, interactions between soybean row spacing and herbicide program and between soybean seeding rate and herbicide program occurred. At 21 DAP, herbicide programs which included a PRE herbicide had less Palmer amaranth in both years than the nontreated control and the POST-only herbicide program for which no treatment had yet been applied (Table 4).

At 42 DAP, no more than 3.6 plants m^{-2} in 2012 and 3.9 plants m^{-2} in 2013 were observed for the treatments containing a PRE application of *S*-metolachlor plus metribuzin whereas the nontreated control had 437 plants m^{-2} in 2012 and 38 plants m^{-2} in 2013 (Table 4). Palmer amaranth densities in the POST-only program in 2012 and 2013 were comparable to the nontreated control at 42 DAP.

At soybean harvest in 2012, Palmer amaranth densities were ≤ 1.9 plants m^{-2} with the inclusion of *S*-metolachlor plus metribuzin PRE (Table 4). In comparison, Palmer amaranth densities were 270 plants m^{-2} in the POST-only treatment, and 516 plants m^{-2} in the nontreated control. No differences between Palmer amaranth densities occurred at soybean harvest in 2013 in the presence of herbicides, either PRE or POST. Furthermore in 2013, when *S*-metolachlor plus metribuzin were applied PRE fb a POST application at 21 DAP, no Palmer amaranth was found in quadrats regardless of row spacing or soybean density.

Although the POST-only treatment had less Palmer amaranth than the nontreated control at harvest for both years, this should not be considered an effective herbicide program because of the large amounts of Palmer amaranth present at harvest. Increasing Palmer amaranth densities have been reported to decrease yield in cotton, grain sorghum (*Sorgum bicolor* L.), corn (*Zea mays* L.), peanut (*Arachis hypogaea* L.), and soybean (Morgan et al. 2001; Moore et al. 2004;

Massinga et al. 2001; Burke et al. 2007; Bensch et al. 2003), especially as a result of early-season interference.

Palmer Amaranth Seed Production. Reductions in the soil seedbank have become a central focus of herbicide resistance management in recent years (Bagavathiannan et al. 2011; Gallandt 2006; Norsworthy et al. 2012; Sosnoskie et al. 2013). For a weed like Palmer amaranth, a prolific seed producer, it is vital to control the weed before seed can be produced.

Herbicide programs impacted Palmer amaranth seed production in 2012 and 2013. Greater seed production was mainly seen in the dry, drought-like growing season of 2012 (Table 5), partly due to the greater Palmer amaranth densities and the fact that Palmer amaranth thrives in dry conditions at the expense of most crops (Ehleringer 1983; Gibson 1998). Treatments containing *S*-metolachlor plus metribuzin applied at planting had less Palmer amaranth seed production in comparison to the nontreated control and POST-only program in 2012 (Table 5); yet, it should be noted that some seed production occurred in at least one of two years for all herbicide programs, except when *S*-metolachlor plus metribuzin were applied PRE and followed with two glufosinate applications, both of which contained residual herbicides.

Soybean Grain Yield. Main effects of soybean row spacing and herbicide program in 2012 and seeding rate, row spacing, and herbicide program in 2013 influenced soybean grain yield (Table 6). The inclusion of *S*-metolachlor plus metribuzin applied PRE increased grain yield over the POST-only program in 2012. Furthermore, grain yield was greater for the 45-cm row spacing compared to the 19- and 90-cm row spacings in 2012.

Averaged over row spacing and seeding rates, a PRE application of *S*-metolachlor + metribuzin increased soybean grain yield at least 1,150 kg ha^{-1} over the nontreated control in 2013 (Table 6). The 45-cm row spacing had greater grain yield (3,070 kg ha^{-1}) than both the 19-

and 90-cm spacing (2,100 and 2,120 kg ha^{-1}, respectively). Yield reductions up to 79% from Palmer amaranth have previously been reported (Bensch et al. 2003; Monks and Oliver 1988; Klingaman and Oliver 1994); however, with the occurrence of GR Palmer amaranth, producers have experienced complete crop loss in some fields (personal observation).

Economic Partial Returns and Sensitivity Analyses. Partial returns were calculated for both 2012 (Table 7) and 2013 (Table 8). For both 2012 and 2013, the inclusion of *S*-metolachlor plus metribuzin applied PRE generally had greater monetary returns. Partial returns were greater for the 45-cm row spacing, due to the higher grain yields, when compared across individual seeding rates and the remaining row spacings for both years. The POST-only herbicide program had partial returns comparable to the nontreated control in 2012 (Table 7), due to yield loss from Palmer amaranth interference, and were comparable to herbicide programs containing PRE herbicides, due to the increased efficacy of the POST herbicides in 2013 (Table 8).

Although partial returns were not always greatest for the herbicide program that had a PRE, 21 DAP, and 42 DAP herbicide application, no Palmer amaranth seed production occurred in this treatment either year. Therefore, a producer could possibly benefit more in the long-term, in regards to the soil seedbank, by reducing the soil seedbank and in turn the risk of herbicide resistance while sacrificing a minimal loss in partial returns for the short-term.

Sensitivity analyses were conducted for 2012 and 2013 to determine the most profitable treatment combination across varying soybean market prices (Figure 3). For both years, the 45-cm row spacing was the most profitable compared to the 19- and 90-cm row spacings. In 2012, the lower seeding rate of 247,000 seed ha^{-1} was most profitable while in 2013 the higher seeding rate of 432,000 seed ha^{-1} was most profitable. The inclusion of solely *S*-metolachlor plus metribuzin applied PRE was the most profitable herbicide program in 2012 and in 2013 at soybean market prices ranging between \$0.21 to \$0.23 kg^{-1}. The addition of POST-applied residual herbicides in 2013 resulted in the most profitable partial returns when market prices were \$0.24 to \$0.52 kg^{-1}.

Practical Implications

The use of a herbicide had more impact on Palmer amaranth management than either row spacing or seeding rate for both years. However, the use of a narrow-row spacing (19-cm) allows soybean to achieve canopy faster compared to wide rows (90-cm), which can aid in suppressing late-season Palmer amaranth emergence and limit biomass and seed production of Palmer amaranth growing in conjunction with the crop. Achieving rapid canopy can be useful when POST residual herbicides are not effective or not activated.

Furthermore, greater control of Palmer amaranth occurred when *S*-metolachlor plus metribuzin were applied PRE followed by POST residual herbicides compared to a POST-only program, regardless of seeding rate or row spacing. This is important since approximately 20% of glufosinate-resistant soybean hectares in Arkansas are treated with POST-only programs (J.K. Norsworthy, personal communication).

In conclusion, Palmer amaranth management in glufosinate-resistant soybean is influenced mainly by herbicide selection and/or application timing and to a lesser extent by soybean seeding rate and row spacing. Applications of effective PRE herbicides strongly dictate the success of early-season Palmer amaranth management, thus leading to less selection pressure on POST herbicides. The combination of a PRE fb POST residual herbicide program as used in this research increases MOA diversity, which lessens the risk of herbicide resistance and/or slows the spread of herbicide resistance due to reduced seed production. Also, greater season-long efficacy often occurred whenever a PRE fb POST (residual) herbicide program was employed. Therefore, producers have more to gain, both in returns and Palmer amaranth management, whenever PRE fb POST (residual) herbicide programs are administered in a timely manner.

Table 1. Nonlinear regression models for determining the number of days after emergence for 95% soybean groundcover at Fayetteville, AR in 2012 and 2013.[a]

		Nonlinear regression groundcover model			
		2012		2013	
Row spacing	Seeding rate	Model	R^2	Model	R^2
cm	1,000 seed ha^{-1}	$y = y0 + ax + bx^2 + cx^3$		$y = \frac{a}{(1 + e^{(\frac{x0-x}{b})})}$	
19	247	$y = -6.005 + 2.929x - 0.0432x^2 + 0.0003x^3$	0.9633	$y = \frac{100}{(1 + e^{(\frac{29.21-x}{5.71})})}$	0.9882
45	247	$y = -12.73 + 3.652x - 0.0606x^2 + 0.0004x^3$	0.9937	$y = \frac{100}{(1 + e^{(\frac{31.54-x}{4.108})})}$	0.9704
90	247	$y = -3.352 + 2.667x - 0.0477x^2 + 0.0003x^3$	0.9891	$y = \frac{100}{(1 + e^{(\frac{30.17-x}{5.327})})}$	0.9095
19	432	$y = -19.48 + 4.042x - 0.0654x^2 + 0.0004x^3$	0.9572	$y = \frac{100}{(1 + e^{(\frac{21.9-x}{5.918})})}$	0.9952
45	432	$y = -11.19 + 3.279x - 0.0473x^2 + 0.0003x^3$	0.9935	$y = \frac{100}{(1 + e^{(\frac{25.48-x}{4.27})})}$	0.9721
90	432	$y = 1.802 + 2.409x - 0.0327x^2 + 0.0002x^3$	0.9794	$y = \frac{100}{(1 + e^{(\frac{23.05-x}{7.91})})}$	0.9964

[a] y is the percentage of soybean groundcover, e is the constant 2.718, *x* is days after soybean emergence, and *y*0, *a*, *b*, and *c* are parameter estimates.

Table 2. Cost associated with chemical, soybean seed, application, and market price for calculating partial returns in 2012 and 2013.

	Partial return costs	
Chemical[a]	Unit	Price unit^{-1} ($)
Boundary (*S*-metolachlor + metribuzin)	L	20.69
Prefix (*S*-metolachlor + fomesafen)	L	13.22
Warrant (acetochlor)	L	8.52
Liberty (glufosinate)	L	20.84
Soybean seed[a]		
glufosinate-resistant	140,000	57.75
Custom chemical application[b]		
Ground application	ha	14.82
Market price[c]		
Soybean	kg	0.43

[a] Chemical and seed costs were averaged from prices given by Helena Chemical Co., Hughes, AR 72348 and Crop Production Services Inc., Crawfordsville, AR 72327 during the summer of 2014.

[b] Application cost was determined from the University of Arkansas Division of Agriculture Research and Extension's 2014 Crop Enterprise Budgets, which can be found at: www.uaex.edu/farm-ranch/economics-marketing/farm-planning/enterprise-budgets.aspx.

[c] Soybean market price was based off the August 2014 price accessed from the Arkansas Soybean Promotion Board, which can be found at: http://www.themiraclebean.com/markets.

Table 3. Palmer amaranth control at 42 days after soybean planting and at soybean harvest as influenced by soybean row spacing and herbicide program, averaged over soybean seeding rate at Fayetteville, AR in 2012 and 2013.

			Control											
			2012						2013					
			42 DAP			Harvest			42 DAP			Harvest		
			Row spacing (cm)											
Herbicide program	Rate	Application timing	19	45	90	19	45	90	19	45	90	19	45	90
	g ai ha^{-1}		%											
S-metolachlor	1545	PRE[a]												
+ metribuzin	368	PRE	99 aA[b]	99 aA	100 aA	98 aA	97 aA	97 aA	98 abA	99 aA	96 aA	98 abA	99 aA	96 aA
S-metolachlor	1545	PRE												
+ metribuzin	368	PRE												
Glufosinate	595	21 DAP[a]												
+ *S*-metolachlor	1217	21 DAP												
+ fomesafen	266	21 DAP	99 aA	100 aA	99 aA	96 aA	99 aA	96 aA	99 abA	99 aA	100 aA	99 abA	99 aA	100 aA
S-metolachlor	1545	PRE												
+ metribuzin	368	PRE												
Glufosinate	595	21 DAP												
+ *S*-metolachlor	1217	21 DAP												
+ fomesafen	266	21 DAP												
Glufosinate	738	42 DAP												
+ acetochlor	1260	42 DAP	100 aA	98 aA	99 aA	98 aA	96 aA	96 aA	100 aA	100 aA	99 aA	100 aA	100 aA	100 aA
S-metolachlor	1545	PRE												
+ metribuzin	368	PRE												
Glufosinate	738	42 DAP												
+ acetochlor	1260	42 DAP	100 aA	100 aA	99 aA	98 aA	98 aA	95 aB	88 abA	98 aA	96 aA	86 abA	99 aA	98 aA
Glufosinate	595	21 DAP												
+ *S*-metolachlor	1217	21 DAP												
+ fomesafen	266	21 DAP												
Glufosinate	738	42 DAP												
+ acetochlor	1260	42 DAP	63 bA	69 bA	52 bA	26 bA	50 bA	18 bA	84 bA	68 bAB	55 bB	85 bA	68 bAB	53 bB

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.

[b] Lowercase letters are used to compare herbicide programs within a soybean row spacing and uppercase letters are used to compare soybean row spacing within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

Table 4. Palmer amaranth density at 21 and 42 days after soybean planting and at soybean harvest as influenced by herbicide program, averaged over soybean row spacing and seeding rate at Fayetteville, AR in 2012. Palmer amaranth density at 21 and 42 days after soybean planting as influenced by herbicide program, averaged over soybean row spacing and seeding rate and at soybean harvest as influenced by soybean row spacing and herbicide program, averaged over seeding rate and as influenced by soybean seeding rate and herbicide program, averaged over row spacing at Fayetteville, AR in 2013.

			Density									
			Observation timing									
			2012			2013						
								Harvest				
								Row spacing			Seed rate	
Herbicide program	Rate	Application timing	21 DAP	42 DAP	Harvest	21 DAP	42 DAP	19 cm	45 cm	90 cm	247,000	432,000
	g ai ha^{-1}		plants m^{-2}									
Nontreated	——	———	438 a[b]	437 a	516 a	59 a	38 a	19 aB[b]	26 aB	41 aA	36 aA	22 aB
S-metolachlor	1545	PRE[a]										
+ metribuzin	368	PRE	0.0 b	3.6 c	1.9 c	0.0 b	0.4 c	0.0 bA	0.1 bA	0.0 bA	0.1 bA	0.0 bA
S-metolachlor	1545	PRE										
+ metribuzin	368	PRE										
Glufosinate	595	21 DAP[a]										
+ *S*-metolachlor	1217	21 DAP										
+ fomesafen	266	21 DAP	0.0 b	0.5 c	0.5 c	0.0 b	0.2 c	0.0 bA	0.0 bA	0.0 bA	0.0 bA	0.0 bA
S-metolachlor	1545	PRE										
+ metribuzin	368	PRE										
Glufosinate	595	21 DAP										
+ *S*-metolachlor	1217	21 DAP										
+ fomesafen	266	21 DAP										
Glufosinate	738	42 DAP										
+ acetochlor	1260	42 DAP	0.0 b	0.0 c	0.0 c	0.0 b	0.2 c	0.0 bA	0.0 bA	0.0 bA	0.0 bA	0.0 bA
S-metolachlor	1545	PRE										
+ metribuzin	368	PRE										
Glufosinate	738	42 DAP										
+ acetochlor	1260	42 DAP	0.0 b	0.8 c	0.1 c	1.8 b	3.9 c	2.1 bA	0.0 bA	0.0 bA	1.4 bA	0.0 bA

Glufosinate	595	21 DAP										
+ *S*-metolachlor	1217	21 DAP										
+ fomesafen	266	21 DAP										
Glufosinate	738	42 DAP										
+ acetochlor	1260	42 DAP	478 a	329 b	270 b	59 a	23 b	4.8 bA	3.5 bA	2.6 bA	4.4 bA	2.8 bA

[a] Abbreviations: PRE, preemergence; DAP, days after soybean planting.

[b] Lowercase letters are used to compare herbicide programs within a soybean row spacing and uppercase letters are used to compare soybean row spacing within an herbicide program for each year. Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher’s protected LSD test at $\alpha \leq 0.05$.

Table 5. Palmer amaranth seed production at soybean harvest as influenced by herbicide program, averaged over soybean row spacing and soybean seeding rate at Fayetteville, AR in 2012 and 2013.

Herbicide program	Rate	Application timing	Seed production 2012		Seed production 2013	
	g ai ha^{-1}		seed m^{-2}			
Nontreated	——	———	247,300	a[b]	96,800	a
S-metolachlor + metribuzin	1545 368	PRE[a] PRE	10,800	c	2,700	b
S-metolachlor + metribuzin Glufosinate + *S*-metolachlor + fomesafen	1545 368 595 1217 266	PRE PRE 21 DAP[a] 21 DAP 21 DAP	3,600	c	0	b
S-metolachlor + metribuzin Glufosinate + *S*-metolachlor + fomesafen Glufosinate + acetochlor	1545 368 595 1217 266 738 1260	PRE PRE 21 DAP 21 DAP 21 DAP 42 DAP 42 DAP	0	c	0	b
S-metolachlor + metribuzin Glufosinate + acetochlor	1545 368 738 1260	PRE PRE 42 DAP 42 DAP	4,100	c	10,700	b
Glufosinate + *S*-metolachlor + fomesafen Glufosinate + acetochlor	595 1217 266 738 1260	21 DAP 21 DAP 21 DAP 42 DAP 42 DAP	167,500	b	7,700	b

[a] Abbreviation: PRE, preemergence; DAP, days after soybean planting.

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

Table 6. Soybean grain yield as influenced by herbicide program, averaged over soybean row spacing and seeding rate, soybean row spacing, averaged over herbicide program and soybean seeding rate, and soybean seeding rate, averaged over herbicide program and soybean row spacing at Fayetteville, AR in 2012 and 2013.

Treatment	Rate	Application timing	Grain yield 2012	Grain yield 2013
Herbicide program	g ai ha^{-1}		kg ha^{-1}	
Nontreated	——	——	490 c[b]	1,280 c
S-metolachlor	1545	PRE[a]		
+ metribuzin	368	PRE	2,420 a	2,430 b
S-metolachlor	1545	PRE		
+ metribuzin	368	PRE		
Glufosinate	595	21 DAP[a]		
+ *S*-metolachlor	1217	21 DAP		
+ fomesafen	266	21 DAP	2,490 a	2,790 a
S-metolachlor	1545	PRE		
+ metribuzin	368	PRE		
Glufosinate	595	21 DAP		
+ *S*-metolachlor	1217	21 DAP		
+ fomesafen	266	21 DAP		
Glufosinate	738	42 DAP		
+ acetochlor	1260	42 DAP	2,310 a	2,850 a
S-metolachlor	1545	PRE		
+ metribuzin	368	PRE		
Glufosinate	738	42 DAP		
+ acetochlor	1260	42 DAP	2,180 a	2,680 ab
Glufosinate	595	21 DAP		
+ *S*-metolachlor	1217	21 DAP		
+ fomesafen	266	21 DAP		
Glufosinate	738	42 DAP		
+ acetochlor	1260	42 DAP	1,160 b	2,570 ab
Row spacing (cm)			kg ha^{-1}	
19 cm			1,730 b	2,100 b
45 cm			2,240 a	3,070 a
90 cm			1,550 b	2,120 b
Seeding rate[c,d] (seed ha^{-1})			kg ha^{-1}	
247,000			——	2,260 b
432,000			——	2,610 a

[a] Abbreviation: PRE, preemergence; DAP, days after soybean planting.

[b] Means within a column for either herbicide program, soybean row spacing, or soybean seeding rate, for both years, followed by the same lowercase letter are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

[c] Soybean seeding rate in 2012 was not significant at $\alpha = 0.05$.

[d] Average soybean density in 2012 for the seeding rate of 247,000 seed ha^{-1} was 200,000 plants ha^{-1} (20 plants m^{-2}) and for the seeding rate of 432,000 seed ha^{-1} was 350,000 plants ha^{-1} (35 plants m^{-2}). Average soybean density in 2013 for the seeding rate of 247,000 seed ha^{-1} was 210,000 plants ha^{-1} (21 plants m^{-2}) and for the seeding rate of 432,000 seed ha^{-1} was 360,000 plants ha^{-1} (36 plants m^{-2}).

Table 7. Partial returns as influenced by soybean row spacing, soybean seeding rate, and herbicide program at Fayetteville, AR in 2012.

			Partial returns[a]					
			Row spacing					
			19 cm		45 cm		90 cm	
			Seeding rate (seed ha^{-1})					
Herbicide program	Rate	Application timing	247,000	432,000	247,000	432,000	247,000	432,000
	g ai ha^{-1}		$ ha^{-1}					
Nontreated	——	——	7.50	64.06	-19.55[c]	328.07	37.37	3.14
S-metolachlor	1545	PRE[b]						
+ metribuzin	368	PRE	881.18	833.98	1,063.61	791.35	727.76	751.75
S-metolachlor	1545	PRE						
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP[b]						
+ *S*-metolachlor	1217	21 DAP						
+ fomesafen	266	21 DAP	834.17	592.42	940.32	950.24	797.60	581.17
S-metolachlor	1545	PRE						
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP						
+ *S*-metolachlor	1217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1260	42 DAP	410.95	702.30	561.99	945.64	432.59	563.80
S-metolachlor	1545	PRE						
+ metribuzin	368	PRE						
Glufosinate	738	42 DAP						
+ acetochlor	1260	42 DAP	597.86	546.11	966.06	821.80	548.85	352.54
Glufosinate	595	21 DAP						
+ *S*-metolachlor	1217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1260	42 DAP	-55.90	221.38	611.58	340.08	-97.67	-0.54

[a] *Partial returns* = (*soybean grain yield* * *market price*) – (*chemical cost* + *application cost* + *soybean seed cost*). Market price was assumed to be \$0.43 kg^{-1}. Chemical cost was determined from the average of two chemical companies (refer to Table 2 for complete description). Application cost was assumed to be \$14.82 ha^{-1} $application^{-1}$. Soybean seed cost was assumed to be \$0.41 per 1,000 seed.

[b] Abbreviation: PRE, preemergence; DAP, days after soybean planting.

[c] Negative value denoted by (-).

Table 8. Partial returns as influenced by soybean row spacing, soybean seeding rate, and herbicide program at Fayetteville, AR in 2013.

			Partial returns[a]					
			Row spacing					
			19 cm		45 cm		90 cm	
			Seeding rate (seed ha^{-1})					
Herbicide program	Rate	Application timing	247,000	432,000	247,000	432,000	247,000	432,000
	g ai ha^{-1}		$ ha^{-1}					
Nontreated	——	——	401.46	432.48	473.63	665.98	244.14	274.62
S-metolachlor	1545	PRE[b]						
+ metribuzin	368	PRE	623.45	756.72	1,086.01	1,206.51	848.07	543.78
S-metolachlor	1545	PRE						
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP[b]						
+ *S*-metolachlor	1217	21 DAP						
+ fomesafen	266	21 DAP	690.81	861.19	1,096.77	1,262.94	822.16	729.30
S-metolachlor	1545	PRE						
+ metribuzin	368	PRE						
Glufosinate	595	21 DAP						
+ *S*-metolachlor	1217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1260	42 DAP	598.24	669.62	886.05	1,371.62	729.49	763.97
S-metolachlor	1545	PRE						
+ metribuzin	368	PRE						
Glufosinate	738	42 DAP						
+ acetochlor	1260	42 DAP	631.94	688.72	1,191.12	1,261.64	736.90	611.35
Glufosinate	595	21 DAP						
+ *S*-metolachlor	1217	21 DAP						
+ fomesafen	266	21 DAP						
Glufosinate	738	42 DAP						
+ acetochlor	1260	42 DAP	594.70	606.90	1,008.24	1,102.46	595.68	784.46

[a] *Partial returns* = (*soybean grain yield* * *market price*) – (*chemical cost* + *application cost* + *soybean seed cost*). Market price was assumed to be $0.43 kg^{-1}. Chemical cost was determined from the average of two chemical companies (refer to Table 2 for complete description). Application cost was assumed to be $14.82 ha^{-1} application^{-1}. Soybean seed cost was assumed to be $0.41 per 1,000 seed.

[b] Abbreviation: PRE, preemergence; DAP, days after soybean planting.

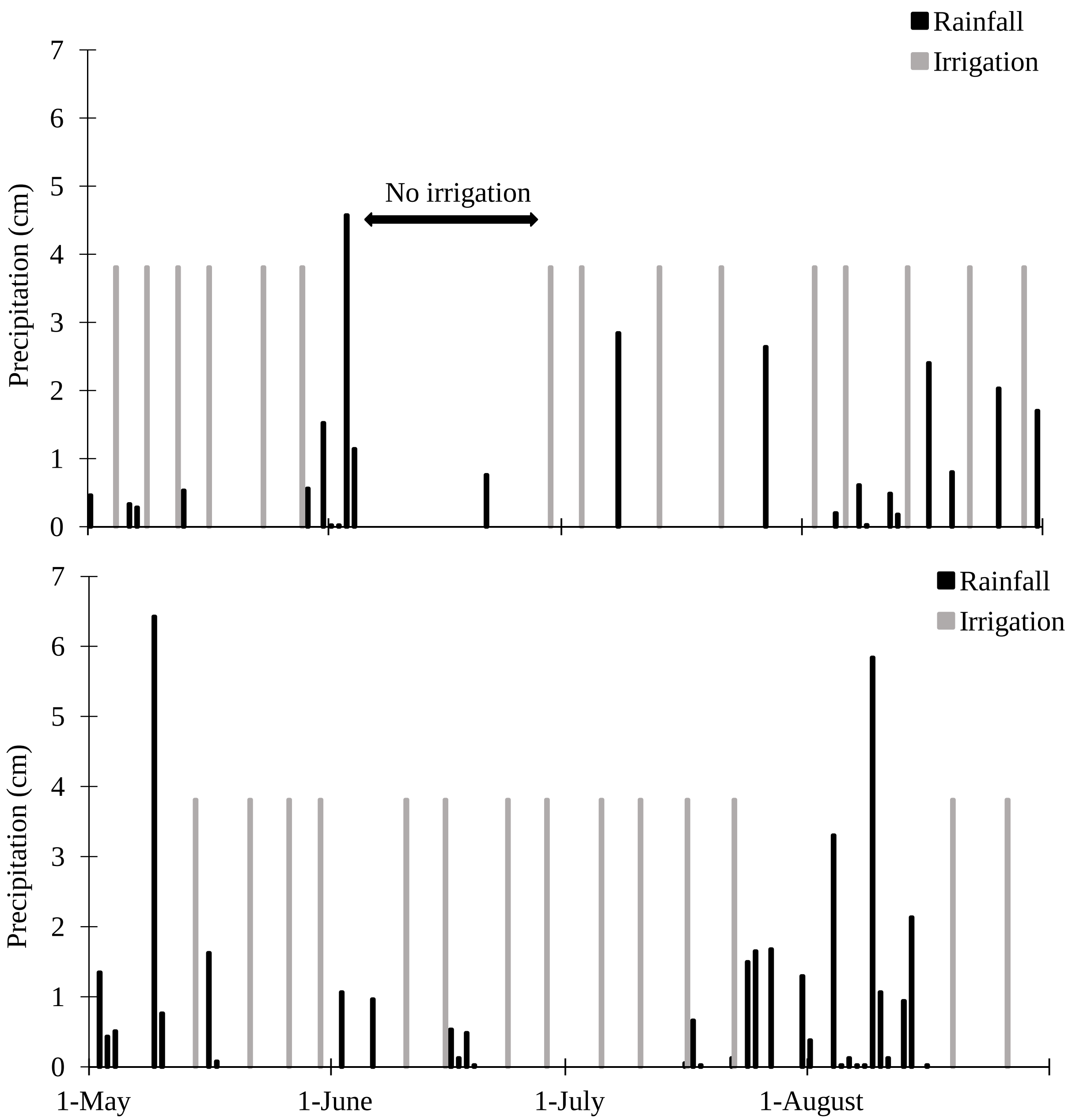

Figure 1. Rainfall and irrigation distribution at Fayetteville, AR in 2012 (a) and 2013 (b).

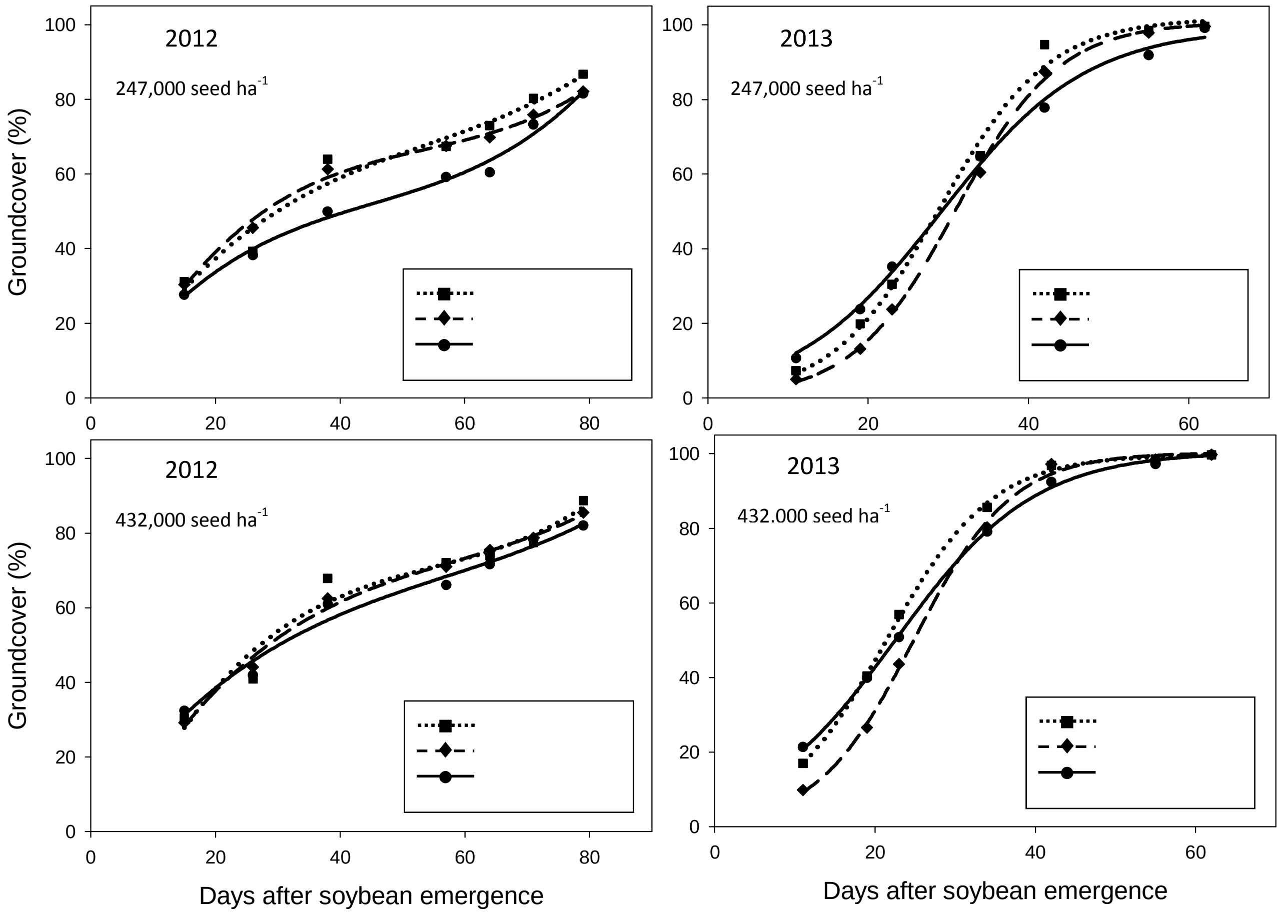

Figure 2. Effect of soybean row spacing on soybean groundcover at two different seeding rates at Fayetteville, AR in 2012 and 2013.

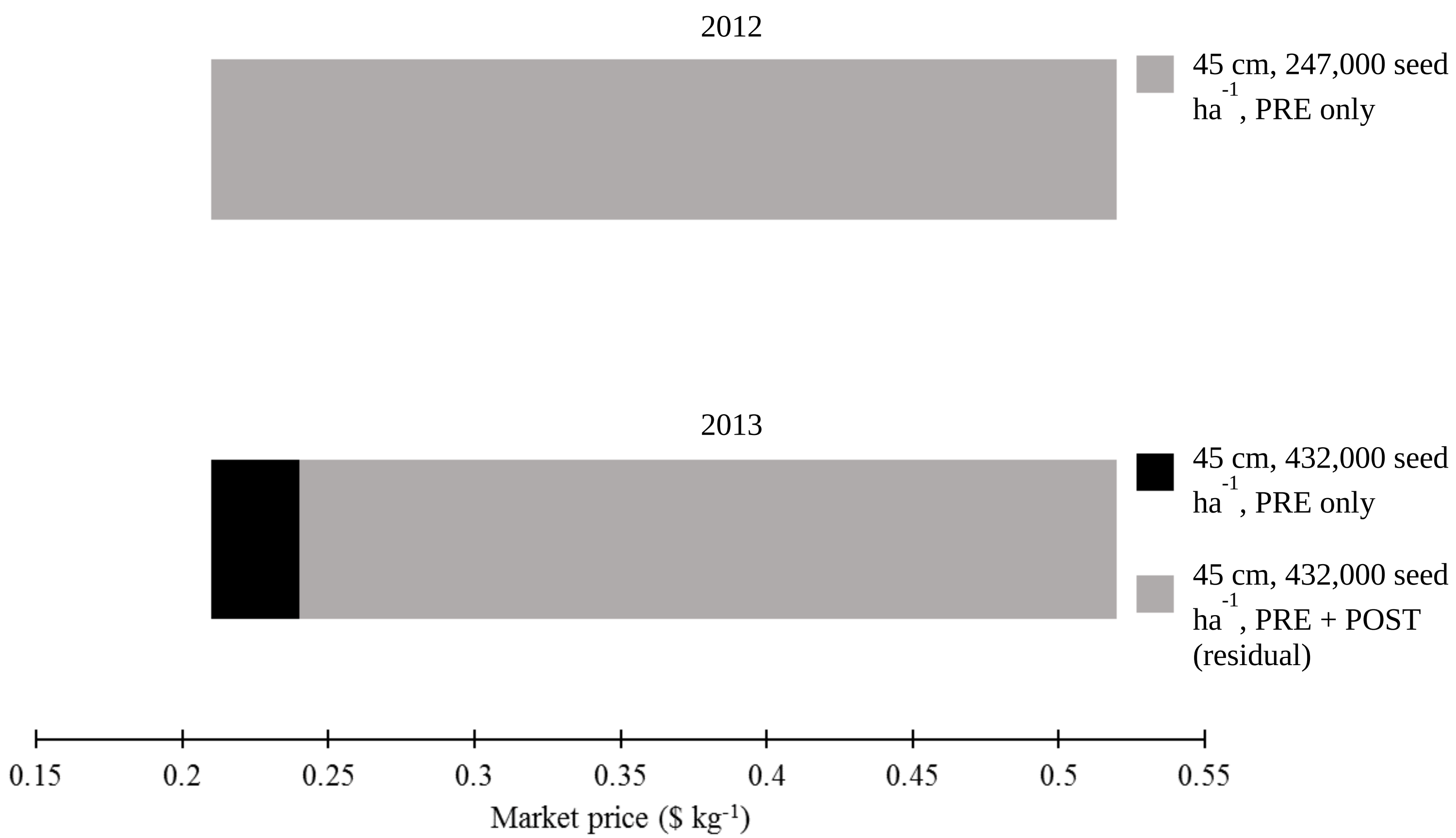

Figure 3. Sensitivity analysis, at Fayetteville, AR in 2012 and 2013, comparing all possible treatment combinations between soybean row spacings (19, 45, and 90 cm), soybean seeding rate (247,000 and 432,000 seed ha^{-1}), and herbicide programs (6) for the impact of most dominant treatment with highest partial returns across 10 year high and low soybean market prices. For specific herbicide programs (see materials and methods for complete description).

Literature Cited

Anonymous (2014) Liberty 280 SL herbicide label. http://www.cdms.net/LDat/IdUA5004.pdf. Accessed: April 26, 2014 Research Triangle Park, NC: Bayer CropScience

Bagavathiannan MV, Norsworthy JK, Smith KL, Burgos N (2011) Seedbank size and emergence pattern of barnyardgrass (*Echinochloa crus-galli*) in Arkansas. Weed Sci 59:359-365

Barnes JW, Oliver LR (2004) Preemergence weed control in soybean with cloransulam. Weed Technol 18:1077-1090

Barnett KA, Culpepper AS, York AC, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*) control by glufosinate plus fluometuron applied postemergence to WideStrike® cotton. Weed Technol 27:291-297

Beckie HJ (2006) Herbicide-resistant weeds: management tactics and practices. Weed Technol 20:793-814

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*Amaranthus palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37-43

Beyers JT, Smeda RJ, Johnson WG (2002) Weed management programs in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:267-273

Buehring NW, Nice GRW, Shaw DR (2002) Sicklepod (*Senna obtusifolia*) control in soybean (*Glycine max*) response to soybean row spacing and population in three weed management systems. Weed Technol 16:131-141

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technol 21:367-371

Coetzer E, Al-Khatib K, Peterson DE (2002) Glufosinate efficacy on *Amaranthus* species in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:326-331

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263-270

Ehleringer J (1983) Ecophysiology of *Amaranthus palmeri*, a Sonoran Desert summer annual. Oecologia 57:107-112

Ellis JM, Griffin JL (2002) Benefits of soil-applied herbicides in glyphosate-resistant soybean (*Glycine max*). Weed Technol 16:541-547

Everman WJ, Clewis SB, York AC, Wilcut JW (2009) Weed control and yield with flumioxazin, fomesafen, and *S*-metolachlor systems for glufosinate-resistant cotton residual weed management. Weed Technol 23:391-397

Gallandt ER (2006) Symposium: How can we target the weed seedbank? Weed Sci 54:588-596

Gardner AP, York AC, Jordan DL, Monks DW (2006) Management of annual grasses and *Amaranthus* spp. in glufosinate-resistant cotton. J Cotton Sci 10:328-338

Gibson AC (1998) Photosynthetic organs of desert plants. Bioscience 48:914

Hamill AS, Knezevic SZ, Chandler K, Sikkema PH, Tardif FJ, Shrestha A, Swanton CJ (2000) Weed control in glufosinate-resistant corn (*Zea mays*). Weed Technol 14:578-585

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744-752

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1-11

Heap I (2014) The Internation Survey of Herbicide Resistant Weeds. http://www.weedscience.org/summary/home.aspx. Accessed: April 26, 2014

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2005) Influence of soybean row width and velvetleaf emergence time on velvetleaf (*Abutilon theophrasti*). Weed Sci 53:160-165

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci 54:38-46

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Jha P, Norsworthy JK, Bridges, Jr. W, Riley MB (2008) Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) and Pusley (*Richardia* spp.) demographics in glyphosate-resistant soybean. Weed Sci 56:408-415

Johnson WG, Chahal GS, Regehr DL (2012) Efficacy of various corn herbicides applied preplant incorporated and preemergence. Weed Technol 26:220-229

Kay RD, Edwards WM, Duffy PA (2008) Farm Management 6th edition. New York, NY: McGraw-Hill. Pp 175-185

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199-204

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523-527

Krausz RF, Young BG, Kapusta G, Matthews JL (2001) Influence of weed competition and herbicides on glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:530-534

Massinga RA, Curie RS, Horak MJ, Boyer Jr. J (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202-208

Mickelson JA, Renner KA (1997) Weed control using reduced rates of postemergence herbicides in narrow and wide row soybean. J Prod Agric 10:431-437

Monks DW, Oliver LR (1988) Interactions between soybean (*Glycine max*) cultivars and selected weeds. Weed Sci 36:770-774

Moore JW, Murray DS, Westerman RB (2004) Palmer amaranth (*Amaranthus palmeri*) effects on the harvest and yield of grain sorghum (*Sorghum bicolor*). Weed Technol 18:23-29

Morgan GD, Baumann PA, Chandler JM (2001) Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol 15:408-412

Nice GRW, Buehring NW, Shaw DR (2001) Sicklepod (*Senna obtusifolia*) response to shading, soybean (*Glycine max*) row spacing, and population in three management systems. Weed Technol 15:155-162

Nichols RL, Bond J, Culpepper AS, Dodds D, Nandula V, Main CL, Marshall MW, Mueller TC, Norsworthy JK, Price A, Patterson M, Scott RC, Smith KL, Steckel LE, Stephenson D, Wright D, York AC (2009) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) spreads in the Southern United States. Resist Pest Manag Newsl 18:8-10

Norsworthy JK (2004) Soil-applied herbicide use in wide- and narrow-row glyphosate-resistant soybean (*Glycine max*). Crop Prot 23:1237-1244

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur EE (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Sci 62:237-249

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008a) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK, Jha P, Bridges Jr. W (2007) Sicklepod (*Senna obtusifolia*) survival and fecundity in wide- and narrow-row glyphosate-resistant soybean. Weed Sci 55:252-259

Norsworthy JK, Oliver LR (2002) Pitted morningglory interference in drill-seeded glyphosate-resistant soybean. Weed Sci 50:26-33

Norsworthy JK, Oliveria MJ, Jha P, Malik M, Buckelew JK, Jennings KM, Monks DW (2008b) Palmer amaranth and large crabgrass growth with plasticulture-grown bell pepper. Weed Technol 22:296-302

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci Special Issue Pp. 31-62

Place GT, Reberg-Horton SC, Dunphy JE, Smith AN (2009) Seeding rate effects on weed control and yield for organic soybean production. Weed Technol 23:497-502

Powles SB, Preston C, Bryan IB, Jutsum AR (1997) Herbicide resistance: impact and management. Adv Agron 58:57-93

Purcell LC (2000) Soybean canopy coverage and light interception measurements using digital imagery. Crop Sci 40:834-837

Riar DS, Norsworthy JK, Griffith GM (2011) Herbicide programs for enhanced glyphosate-resistant and glufosinate-resistant cotton (*Gossypium hirsutum*). Weed Technol 25:526-534

Riar DS, Norsworthy JK, Steckel LE, Stephenson IV DO, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the Midsouth United States-soybean: A consultant's perspective. Weed Technol 27:612-622

Rich AM, Renner KA (2007) Row spacing and seeding rate effects on eastern black nightshade (*Solanum ptychanthum*) and soybean. Weed Technol 21:124-130

Scott B, Smith K (2011) Prevention and control of glyphosate-resistant pigweed in soybean and cotton. University of Arkansas Cooperative Extension Service Printing Services FSA 2152-PD-3-11RV 4 pp

Scott RC, Barber LT, Boyd JW, Norsworthy JK, Burgos N (2014) Recommended Chemicals for Weed and Brush Control. Little Rock, AR: The University of Arkansas Division of Agriculture Cooperative Extension Service Miscellaneous Publication 44 Pp 38

Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329-333

Sosnoskie LM, Webster TM, Culpepper AS (2013) Glyphosate resistance does not affect Palmer amaranth (*Amaranthus palmeri*) seedbank longevity. Weed Sci 61:283-288

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre- and postemergence herbicide efficacy in soybean. Weed Technol 24:234-243

Taylor-Lovell S, Wax LM, Bollero G (2002) Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol 16:502-511

[USDA-NASS] United States Department of Agriculture, National Agricultural Statistics Service (2013a) Acreage: http://usda.mannlib.cornell.edu/usda/current/Acre/Acre-06-28-2013.pdf. Accessed: May 17, 2014

[USDA-NASS] United States Department of Agriculture, National Agricultural Statistics Service (2013b) Soybeans: http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/2012_Soyb Soyb_Highlights/index.asp. Accessed: May 15, 2014

[USDA-NASS] United States Department of Agriculture, National Agricultural Statistics Service (2014a) U.S. Soybean Industry: http://nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Ag_Resource_Management/AR AR_Soybeans_Factsheet/index.asp. Accessed: May 15, 2014

[USDA-NASS] United States Department of Agriculture, National Agricultural Statistics Service (2014b) Quick Stats: http://quickstats.nass.usda.gov/data/printable/2F1C1A7D-096A-3D99-B18F-CB82E5C06117. Accessed: May 16, 2014

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the Southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145-157

Whitaker JR, York AC, Jordan DL, Culpepper AS (2010) Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol 24:403-410

Wiesbrook ML, Johnson WG, Hart SE, Bradley PR, Wax LM (2001) Comparison of weed management systems in narrow-row, glyphosate- and glufosinate-resistant soybean (*Glycine max*). Weed Technol 15:122-128

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307

Young BG, Young JM, Gonzini LC, Hart SE, Wax LM, Kapusta G (2001) Weed management in narrow- and wide-row glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:112-121

CHAPTER V

Conclusions

This research shows that successful weed management is highly dependent on highly efficacious herbicide programs. The use of a PRE-applied residual herbicide, either *S*-metolachlor plus metribuzin or flumioxazin plus pyroxasulfone, effectively controlled Palmer amaranth early in the growing season and when these PRE herbicides were followed by a POST-residual herbicide program Palmer amaranth control was optimized. The POST-only herbicide programs did not provide adequate control of Palmer amaranth and should not be considered an effective herbicide program when dealing with Palmer amaranth.

Increasing the soybean seeding rate was costly due to the increased seed costs and had only a slight benefit in regards to suppression of late-season Palmer amaranth emergence. Decreasing the soybean row spacing resulted in faster soybean canopy formation, which reduced the diurnal soil temperature fluctuations, in turn reducing late-season Palmer amaranth emergence. Strategies that aid canopy formation such as reducing the row spacing will reduce the selection for resistance to POST herbicides by limiting the number of Palmer amaranth plants exposed to a herbicide. The use of rye or wheat plus deep tillage also reduced Palmer amaranth emergence in soybean. This research provides several examples of how non-chemical management practices can reduce Palmer amaranth emergence and reduce the selection pressure on both PRE and POST herbicides, but it should be noted that none of these tactics alone were effective.

In conclusion, producers should take a multi-faceted approach to manage Palmer amaranth. By incorporating cultural and mechanical practices with a highly efficacious PRE plus POST-residual herbicide program, Palmer amaranth can be properly managed. Furthermore, complete control of Palmer amaranth will result in a reduced soil seedbank, reducing Palmer amaranth emergence in subsequent years along with the spread of herbicide resistance. The key to a long-term sustainable weed management program is the use of diverse tactics, both chemical and non-chemical, along with paying attention to lowering the soil seedbank. A value on reducing the seedbank remains a research priority for future work.