2014

Control Options for Rhizome Johnsongrass (Sorghum halepense L. Pers.) in Glufosinate-Resistant Cotton (Gossypium hirsutum L.) and Soybean (Glycine max L. Merr.)

Randall Lee Landry
Louisiana State University and Agricultural and Mechanical College

CONTROL OPTIONS FOR RHIZOME JOHNSONGRASS (*Sorghum halepense* L. Pers.) IN GLUFOSINATE-RESISTANT COTTON (*Gossypium hirsutum* L.) AND SOYBEAN (*Glycine max* L. Merr.)

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Plant, Environmental, and Soil Sciences

by
Randall Lee Landry
B. S., Louisiana State University at Alexandria, 2008
December 2014

ACKNOWLEDGEMENTS

I would like to thank God for giving me the ability and knowledge to pursue this degree. He gave me the strength and perseverance to handle a full time job and school simultaneously. I owe everything to Him.

My family has always been my rock. The sacrifices by my parents, Charles and Rebecca Landry, are too many to count. Mom, thanks for the constant encouragement and making sure I always did my best no matter what. Dad, thanks for making sure I always took care of things, and teaching me to use my hands as well as my head. I will always respect and love you. The constant calls of encouragement and support I will always cherish. The overflow of love and support you have shown has taught me more than school ever will. My sister, Tamara, thanks for always being there and taking care of little 'big' brother. Thank you for giving me the chance to be Dylan and Logan's uncle, they are my world.

Thanks to my committee members, Dr. Daniel O. Stephenson, IV, Dr. James L Griffin, and Dr. Donnie K. Miller. Your support and guidance were paramount to this work. Thank you for always taking the time and energy to teach me. Your advice and assistance guided me the entire way.

Thank you to my fellow graduate students, Matthew Bauerle, Caleb Fish, Matthew Foster, Ben McKnight, and Brandi Woolam. Working with each one of you is an experience I will not soon forget. Thank you for your help in this project. Thank you to all the student workers that helped collect data; your help and diligence will always be remembered. A special thanks to the farm crew and staff at Dean Lee Research and Extension Center.

TABLE OF CONTENTS

ABSTRACT

Field studies were conducted in 2011, 2012, and 2013 near Alexandria, LA to determine glufosinate rates and timings for control of rhizome johnsongrass [*Sorghum halepense* (L.) Pers.] in glufosinate-resistant soybean [*Glycine max* (L.)Merr.]. Johnsongrass control (75%) and height reduction (63%) throughout the season were greatest when glufosinate was applied at 0.7 kg ai ha^{-1} followed by (fb) 0.6 kg ha^{-1}. Furthermore, following initial applications of glufosinate at 0.7 kg ha^{-1} (2670 kg ha^{-1}) increased soybean yields were observed compared to 0.5 kg ha^{-1} (2400 kg ha^{-1}), and soybean yields were greater following sequential glufosinate applications of 0.6 kg ha^{-1} followed by 0.5 kg ha^{-1}. These data suggest that sequential applications of glufosinate is an option to control rhizomatous johnsongrass in glufosinate-resistant soybean. Additionally, field trials were conducted in 2011 and 2012 to assess control of johnsongrass in soybean with sequences of chlorimuron, clethodim, and fomesafen applied at early-post-emergence (EPOST), mid-postemergence (MPOST), and late-postemergence (LPOST). Sequential applications of glufosinate was added as a comparison treatment at all three timings. Clethodim applied EPOST was similar in johnsongrass control to sequentially applied glufosinate 35 days after LPOST. Johnsongrass control at harvest following sequential glufosinate applications (90%) or clethodim fb chlorimuron fb fomesafen (82%) did not differ. At harvest, differences in johnsongrass heights were not observed between treatments. Following sequentially applied glufosinate soybean yields were similar where clethodim was applied LPOST. Furthermore, trials were conducted to assess johnsongrass control in cotton [*Gossypium hirsutum* L.] in 2011, 2012, and 2013 following glufosinate applied two or three times sequentially, initiated 2, 3, or 4 wk after planting and sequential applications timed 2 or 3 wk apart. Johnsongrass control was maximized when three applications were applied at least 3 wk apart. However, johnsongrass control and

reduction in heights was greatest when timing the initial application 4 WAP. Additionally, cotton yield was comparable to three total applications when two applications were made initiated 4 WAP.

CHAPTER 1
INTRODUCTION

Johnsongrass [*Sorghum halepense* (L.) Pers.] is an erect perennial grass present in many crop production areas of the world and its rapid growth and capacity to reproduce infers a competitive distinction (Anderson et al. 1960; Holm et al. 1977; McWhorter 1961). Johnsongrass can reach heights of 3.5 m, has a prominent white midrib, large panicle inflorescence, and reproduces by both seeds and rhizomes (Holm et al. 1977; Ingle and Rogers 1961; McWhorter 1971a; 1971b; Oyer et al. 1959). Rhizomatous and seedling johnsongrass are capable of producing rhizomes soon after emergence; however, greatest rhizome development was reported from mature seed stage to just before dormancy (Aldrich 1984; Anderson et al. 1960; Keeley and Thullen 1979; McWhorter 1961; 1972). Experiments by Talbot (1928) and Anderson et al. (1960) suggest that johnsongrass rhizomes function in a reproductive capacity in the year following development. Warwick and Black (1983) suggested johnsongrass spread to colder climates is limited to rhizome tolerance to freezing temperatures. Lab experiments suggest rhizome tolerance to -3°C, but field conditions in Illinois suggest -9°C (Hull 1970; Stoller 1977).

Johnsongrass is native to the Mediterranean region, specifically Syria and Turkey (Holm et al. 1977; Spencer 1974; Haragan 1991). Johnsongrass range has been expanded by environment (i.e., animals, wind, water), human (i.e., sowing as a forage), and mechanical means (i.e., combine harvester, cultivator). In the United States, McWhorter (1971a) reported johnsongrass was planted in the southeast in the 1830's. Current range of johnsongrass is from latitude 55° N to latitude 45° S, where it infests six continents, excluding Antarctica (Holm et al. 1977). The date of introduction in Louisiana is unknown; however, johnsongrass was found in

59 of the 64 parishes in 1964 (Allen 1975). Considered as one of the world's worst weeds, johnsongrass is detrimental to crop yield (Holm et al. 1977; McWhorter and Hartwig 1965; McWhorter 1972).

McWhorter (1993) reported that johnsongrass was present in 90% of soybean fields in Arkansas, Louisiana, and Mississippi in 1991 and was estimated to reduce average annual value of soybean by $23.7 ± 0.6 million. In cotton, johnsongrass was present in 55 to 90% of fields surveyed in Arkansas, Louisiana, and Mississippi and reduction in average annual value of harvested cotton was estimated to be $5.8 ± 1.9 million (McWhorter 1993). Johnsongrass can influence commodity yields negatively by competition, allelopathic effects, and hosting diseases or insects (Warwick and Black 1983; Bendixon 1986). Bridges and Chandler (1987) reported full season competition of johnsongrass at densities of 1, 2, 4, 8, 16, and 32 plants 9.8 m^{-1} of row reduced average seed cotton yield 1, 4, 14, 40, 65, and 70% respectively. In soybean, full season johnsongrass competition reduced soybean yields 59 to 88% (Williams and Hayes 1984). Johnsongrass competition can also influence harvest efficiency and quality of product. In Oklahoma, johnsongrass reduced stripper-harvest efficiency in cotton 0.3 and 0.6% per weed in 15 m of row in 1996-97 (Wood et al. 2002). McWhorter and Anderson (1981) found close to 6% of foreign material in soybean seed samples when johnsongrass is not controlled.

Cultural weed control practices were used for control of johnsongrass before herbicides were introduced (Nalewaja 1999). Cultural and mechanical weed control strategies include: crop row spacing and plant population, crop cultivar selection, crop rotation, tillage, and use of cover crops (Anderson 1996; Nalewaja 1999). However, controlling weeds effectively is a multi-faceted approach. Keeley and Thullen (1981) found that cultivation alone was not sufficient to prevent johnsongrass from impacting seed cotton yields. Gebhardt (1981) found that PRE and

POST herbicide applications in conjugation with cultivation improved weed control and soybean yield. Frans et al. (1991) reported that crop rotations with high herbicide rates were needed to control johnsongrass. Bendixon (1988) observed less johnsongrass at harvest in soybean seeded in 25 cm rows compared with 76 cm. In corn, foliar application of trichloroacetate (TCA) and plowing in fall and spring provided 75 to 95% johnsongrass control (Burt and Willard 1959). A combination of disking, followed by herbicide application of dalapon, significantly decreased rhizomatous johnsongrass populations and increased corn yield (Hicks and Fletchall 1967). Preplant application of butylate or EPTC provided 79 to 93% early season control in corn and was highly correlated with increased corn yields (Roeth 1973).

Trifluralin applied preplant in cotton reduced number of MSMA applications needed for johnsongrass control (Kleifield 1970). Trifluralin, in addition to other dinitroaniline herbicides, is effective for johnsongrass control in soybean (McWhorter 1977). Dale and Chandler (1979) found that yearly rotations of corn and cotton and use of herbicides with different modes of action improved control of johnsongrass. In the 1980's, utilization of acetyl coenzyme A carboxylase (ACCase)- and acetolactate synthase (ALS)-inhibiting herbicides provided an effective POST option for control of johnsongrass in cotton and soybean (Banks and Tripp 1983; Tranel and Wright 2002). Johnson et al. (1991) found that johnsongrass was controlled 70 to 90% when the ACCase-inhibiting herbicides clethodim, sethoxydim, fluazifop-P, haloxyfop, or quizalofop were applied POST as split applications in soybean. Likewise, Banks and Tripp (1983) found similar results when applying sequential applications of ACCase-inhibiting herbicides at lower rates when compared to a single application at a higher rate. In corn, POST application of the ALS-inhibiting herbicides nicosulfuron and primisulfuron controlled rhizome johnsongrass 50 to 80% resulting in corn yield greater than other herbicide programs (Camacho et al. 1991).

Glyphosate-resistant soybean was introduced in 1996, allowing flexibility to make POST applications of the non-selective herbicide glyphosate without crop injury (Delannay et al. 1995). Glyphosate inhibits 5-enolpyruvyl-shikimate-3-phosphate synthase, thus preventing production of the essential amino acids tryptophan, phenylalanine, and tyrosine (Duke 1990; Jaworski 1972). Johnsongrass control with glyphosate can be attributed to extensive translocation throughout the plant and into the rhizomes (McWhorter et al. 1980) and 90-100% control has been reported at 840 + g ai ha^{-1} (Culpepper et al. 2000; Griffin et al. 2006; Lanie et al. 1994; Parochetti et al. 1975).

In the U. S., 18% of corn, 60% of cotton, and 80% of soybean acres were planted using glyphosate-resistant cultivars/hybrids in 2004 (Duke 2005; Dill 2005). Furthermore, 40, 82, and 88% of glyphosate-resistant corn, cotton, and soybean, respectively, were treated with glyphosate in the U. S. in 2005 (Xiu 2012). However, excessive herbicide use of a single mode of action can result in weeds resistant to that mode of action (Owen and Green 2011). Currently, 14 weed species have been documented as resistant to glyphosate in the U. S. and 30 species have been documented worldwide (Heap 2014). Excessive use of glyphosate in Argentina, Arkansas, and Louisiana has led to the presence of glyphosate-resistant johnsongrass (Heap 2014; Johnson et al. 2014; Riar et al. 2011; Vial-Aiub et al. 2007). Johnson et al. (2014) reported that glyphosate-resistant johnsongrass is not widespread in Arkansas, but the lethal dose to kill 50% of the resistant population was 8.5X the labeled use rate of glyphosate.

The introduction of glufosinate-resistant soybean in 1996 provided another weed management option (Rasche and Gadsby 1997). Glufosinate is a nonselective POST herbicide that inhibits glutamine synthetase, which causes lethal levels of ammonia to accumulate in the plant tissues resulting in rapid cellular damage (Duke 1990). Unlike glyphosate, translocation is limited and glufosinate is considered a contact-type herbicide (Bromilow et al. 1993). Utilization of glufosinate-resistant soybean is low in the midsouthern United States, which was determined by a 2011 survey of Arkansas, Louisiana, Mississippi, and Tennessee crop consultants which reported that 12, <1, 2, and 4% of soybean hectares, respectively, were planted in glufosinate-resistant soybean (Riar et al. 2013). Furthermore, the survey reported that a glyphosate-resistant soybean system herbicide costs were lower than glufosinate-resistant soybean herbicide system with costs of US \$78 and US \$91 ha^{-1}, respectively (Riar et al. 2013). Effective control of johnsongrass was reported with single (89%) and sequential (93%)applications of glufosinate 8 WAT by Culpepper et al. (2000), but different combinations of glufosinate rates and timings need to be investigated, as sequential timing varied 16-28 d after initial treatment and treatments were based on soybean growth stage. Glufosinate alone is not adequate for control of some weeds in cotton and more research is needed to determine its fit in weed management programs (Culpepper and York 1999; Gardner et al. 2006).

Prior to the advent of glyphosate-resistant soybean and cotton, growers controlled grasses with soil-applied herbicides, cultivation, hand removal, and graminicides (Vidrine et al. 1995). Following the introduction of glyphosate-resistant crops, glyphosate applications POST provided excellent control of johnsongrass, which decreased the need for other chemical and physical control measures. However with the discovery of glyphosate-resistant johnsongrass in Louisiana, efforts in cotton and soybean have concentrated on developing control programs without glyphosate. This research project will address control of rhizome and seedling johnsongrass using glufosinate-resistant cotton and soybean. Little information is available concerning glufosinate application rate and timing for control of johnsongrass. In addition, research will investigate POST herbicides other than glyphosate and glufosinate for control of johnsongrass. The overall objective is to develop effective alternative programs for mitigation and management of glyphosate-resistant johnsongrass in cotton and soybean.

Literature Cited

Aldrich R J (1984) Weed-Crop Ecology. Breton Publ, North Scituate, MA. Pp 93-117.

Allen CM (1975) Grasses of Louisiana. Lafayette, LA: Univ of SW Louisiana. 276 p.

Anderson L E, Appleby AP, Weseloh JW (1960) Characteristics of johnsongrass rhizomes Weeds 8:402-406.

Anderson W P (1996) Weed Science Principles and Applications. 3rd edn. West Publ. Co. St. Paul, MN. Pp. 43-51.

Banks PA, Tripp TN (1983) Control of johnsongrass (*Sorghum halepense*) in soybeans (*Glycine max*) with foliar-applied herbicides. Weed Sci 31:628-633.

Bendixon LE (1986) Corn (*Zea mays*) yield in relationship to johnsongrass (*Sorghum halepense*) population. Weed Sci 34:449-451.

Bendixon LE (1988) Soybean (*Glycine max*) competition helps herbicides control johnsongrass (*Sorghum halepense*). Weed Technol 2:46-48.

Bridges DC, Chandler JM (1987) Influence of johnsongrass (*Sorghum halepense*) density and period of competition on cotton yield. Weed Sci 35:63-67.

Bromilow RH, Chamberlain K, Evans AA (1993) Phloem translocation of strong acids- glyphosate, substituted phosphoric and sulfonic acids- in *Ricinus communis* L. Pest Sci 37:39-47.

Burt EO, Willard CJ (1959) Control of johnsongrass (*Sorghum halepense* L. Pers.) in Ohio by herbicides and cultural practices. Weeds 7:162-166.

Camacho RF, Moshier L J, Morishita DW, Devlin DL (1991) Rhizome johnsongrass (*Sorghum halepense*) control in corn (*Zea mays*) with primisulfuron and nicosulfuron. Weed Technol 5:789-794.

Culpepper AS, York AC (1999) Weed management in glufosinate-resistant corn (*Zea mays*). Weed Technol 13:324-333.

Culpepper AS, York AC, Batts RB, Jennings KM (2000) Weed management in glufosinate and glyphosate-resistant soybean (*Glycine max*). Weed Technol 14:77-88.

Dale JE, Chandler JM (1979) Herbicide-crop rotation for johnsongrass (*Sorghum halepense*) control. Weed Sci 27:479-485.

Delannay X, Bauman TT, Beighley DH, Buettner MJ, Coble HD, DeFelice MS, Derting CW, Diedrick TJ, Griffin JL, Hagood ES, Hancock FG, Hart SE, LaVallee BJ, Loux MM, Lueschen WE, Matson KW, Moots CK, Murdock E, Nickell AD, Owen MDK, Paschal II EH, Prochaska LM, Raymond PJ, Reynolds DB, Rhodes WK, Roeth FW, Sprankle PL, Tarochione LJ, Tinius CN, Walker RH, Wax LM, Weigelt HD, Padgette SR (1995) Yield evaluation of a glyphosate- tolerant soybean line after treatment with glyphosate. Crop Sci 35:1461-1467.

Dill GM (2005) Glyphosate-resistant crops: history, status and future. Pest Mgnt Sci 61:219-224.

Duke SO (1990) Overview of herbicide mechanisms of action. Environ Health Perspect 87:263-271.

Duke SO (2005) Taking stock of herbicide-resistant crops ten years after introduction. Pest Mgmt Sci 61:211-218.

Frans RE, McClelland MR, Horton DK, Corbin, Jr. BR, Talbert RE (1991) Crop and herbicide rotations for johnsongrass (*Sorghum halepense*) control. Weed Sci 39:660-666.

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

Gebhardt MR (1981) Cultural and chemical weed control systems in soybeans (*Glycine max*). Weed Sci 29:133-138.

Griffin JL, Miller DK, Salassi ME (2006) Johnsongrass (*Sorghum halepense*) control and economics of using glyphosate- resistant soybean in fallowed sugarcane fields. Weed Technol 20:980-985.

Haragan PD (1991) Weeds of Kentucky and adjacent states. The Univ. Press of Kentucky. Pp 194-195.

Heap I. The International Survey of Herbicide Resistant Weeds. Online. Internet. September 3, 2014. Available www.weedscience.com.

Hicks RD, Fletchall OH (1967) Control of johnsongrass in corn. Weeds 15:16-20.

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The World’s Worst Weeds Distribution and Biology. Honolulu, HI: The University Press of Hawaii. Pp 54-61.

Hull RJ (1970) Germination control of johnsongrass rhizome buds. Weed Sci. 18:118-121.

Ingle M, Rogers BJ (1961) The growth of mid-western strain of *Sorghum halepense* under controlled conditions. Amer J Bot 48:392-396.

Johnson DB, Norsworthy JK, Scott RC (2014). Distribution of herbicide-resistant johnsongrass (*Sorghum halepense*) in Arkansas. Weed Technol 28:111-121.

Johnson WG, Frans RE, Parsch LD (1991) Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence herbicides. Weed Technol 5:87-91.

Jaworski EG (1972) Mode of action of N-phosphonomethyl-glycine: inhibition of aromatic amino acid biosynthesis. J Agric Food Chem 20:1195–1198.

Keeley PE, Thullen RJ (1979) Influence on planting date on the growth of johnsongrass (*Sorghum halepense*) from seed. Weed Sci 27:554-558.

Keeley PE, Thullen RJ (1981) Control and competitiveness of johnsongrass (*Sorghum halepense*) in cotton (*Gossypium hirsutum*). Weed Sci 29:356-359.

Kleifeld Y (1970) Combined effect of trifluralin and MSMA on johnsongrass control in cotton. Weed Sci 18:16-18.

Lanie AJ, Griffin JL, Vidrine PR, Reynolds DB (1994) Herbicide combinations for soybean (*Glycine max*) planted in stale seedbed. Weed Technol 8:17-22.

McWhorter CG (1961) Morphology and development of johnsongrass plants from seeds and rhizomes. Weeds 9:558-562.

McWhorter CG (1971a) Anatomy of johnsongrass. Weed Sci 19:385-393.

McWhorter CG (1971b) Growth and development of johnsongrass ecotypes. Weed Sci 19:141-147.

McWhorter CG (1972) Factors affecting johnsongrass rhizome production and germination. Weed Sci 20:41-45.

McWhorter CG (1977) Johnsongrass control in soybeans with soil-incorporated dinitroaniline herbicides. Weed Sci 25:264-267.

McWhorter CG (1993) A 16 year survey on levels of johnsongrass (*Sorghum halepense*) in Arkansas, Louisiana, and Mississippi. Weed Sci 41:669-677.

McWhorter CG, Anderson JM (1981) The technical and economic effects of johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*). Weed Sci 29:245-253.

McWhorter CG, Hartwig EE (1965) Effectiveness of preplanting tillage in relation to herbicides in controlling johnsongrass for soybeans production. Agron J 57:385-389.

McWhorter CG, Jordan TN, Wills GD (1980) Translocation of ^{14}C-glyphosate in soybeans (*Glycine max*) and johnsongrass (*Sorghum halepense*). Weed Sci 28:113-118.

Nalewaja JD (1999) Cultural practices for weed resistance management. Weed Technol 13:643-646.

Owen MDK, Green JM (2011) Herbicide resistant crops: Utilities and limitations for herbicide resistant weed management. Agri Food Chem 59:5819-5829.

Oyer EB, Gries GA, Rogers BJ (1959) The seasonal development of johnsongrass plants. Weeds 7:13-19.

Parochetti JV, Wilson HP, Burt GW (1975) Activity of glyphosate on johnsongrass. Weed Sci 23:395-400.

Rasche E, Gadsby M (1997) Glufosinate ammonium tolerant crops-international commercial developments and experiences. Pages 941-946 *in* Proceedings of the Brighton Crop Protection Conference-Weeds. Brighton, UK: British Crop Protection Council.

Riar DS, Norsworthy JK, Johnson DB, Scott RC, Bagavathiannan M (2011) Glyphosate resistance in a johnsongrass (*Sorghum halepense*) biotype from Arkansas. Weed Sci 59:299-304.

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.

Roeth, FW (1973) Johnsongrass control in corn with soil incorporated herbicides. Weed Sci 21:474-476.

Spencer ER (1974) All About Weeds. New York, NY: Dover Publications. Pp 24-27.

Stoller EW (1977) Differential cold tolerance of quackgrass *Agropyron repens* and johnsongrass *Sorghum halepense* rhizomes Weed Sci 25:348-351.

Talbot MW (1928) Johnsongrass as a weed. U.S. Dept Agr Farmer's Bul 1537.

Tranel PJ, Wright TR (2002) Resistance of weeds to ALS-inhibiting herbicides: What have we learned? Weed Sci 50:700-712.

Vial-Aiub MM, Balbi MC, Gundel PE, Ghersa CB, Powles SB (2007) Evolution of glyphosate-resistant johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. Weed Sci 55:566-571.

Vidrine PR, Reynolds DB, Blouin DC (1995) Grass control in soybean (*Glycine max* L.) with graminicides applied alone and in mixtures. Weed Technol 9:68-72.

Warwick SI, Black LD (1983) The biology of Canadian weeds.61. *Sorghum halepense* (L.) Pers. Can J Plant Sci 63:997-1014.

Williams CS, Hayes RM (1984) Johnsongrass (*Sorghum halepense*) competition in soybeans (*Glycine max*). Weed Sci 32:498-501.

Wood ML, Murray DS, Banks JC, Verhalen LM, Westerman RB, Anderson KB (2002) Johnsongrass (*Sorghum halepense*) density effects on cotton (*Gossypium hirsutum*) harvest and economic value. Weed Technol 16:495-501.

Xiu Y (2012) National Agricultural Statistics Service (NASS): *Agricultural Chemical Use Database*. http://www.pestmanagement.info/nass/ Accessed August 16, 2012.

CHAPTER 2
GLUFOSINATE RATE AND APPLICATION TIMING FOR CONTROL OF RHIZOMATOUS JOHNSONGRASS (*Sorghum halepense* L. Pers.) IN SOYBEAN (*Glycine max* L. Merr.)

Introduction

Johnsongrass [*Sorghum halepense* (L.) Pers.] is a perennial monocot present in many arable parts of the world (Holm et al. 1977). It can reach a height up to 3.5 m, has a prominent white midrib, and is able to reproduce vegetatively and by seeds (Holm et al. 1977; Ingle and Rogers 1961; McWhorter 1971; Oyer et al. 1959), giving it a competitive advantage over many native species. Holm et al. (1977) lists johnsongrass as one of the world's worst weeds. Introduced into North America from the Mediterranean region in the 1830's, johnsongrass was planted as forage (Holm et al. 1977; Spencer 1974; Haragan 1991). By 1964, johnsongrass was found in 60 of 64 parishes in Louisiana (Allen 1975).

Louisiana growers planted 413,000, 457,000, and 453,000 ha of soybean [*Glycine max* (L.) Merr.] in 2011, 2012, and 2013, respectively (Anonymous 2014). Weeds in soybean can cause up to 37% of the losses incurred by growers (Oerke 2006). Johnsongrass competes with soybean for light, moisture, and nutrients, which extends time needed for seed drying and slows mechanical harvest (McWhorter and Hartwig 1972). In addition, johnsongrass infestations in soybean can reduce yields up to 42% (McWhorter and Hartwig 1972), and can serve as a host for insects and diseases (McWhorter 1989).

Early johnsongrass control in soybean was accomplished through combinations of cultural and mechanical methods (Nalewaja 1999; Anderson 1996). McWhorter (1974, 1977) reported acceptable johnsongrass control after two successive years of soil-incorporated dinitroaniline herbicides. Johnsongrass was controlled 70 to 90% by sequential POST applications of sethoxydim, fluazifop-P, haloxyfop, quizalofop, or clethodim (Johnson and Frans 1991). Similarly, Winton-Daniels et al. (1990) reported greater johnsongrass control following sequential POST applications of fenoxaprop, fluazifop-p, haloxyfop, quizalofop, and sethoxydim than a single application.

POST applications of glyphosate in glyphosate-resistant (GR) soybean allows a producer to effectively manage many broadleaf and grass weeds (Ateh and Harvey 1999; Delannay et al. 1995; Nelson and Renner 2013; Webster et al. 1999). As a consequence, 88% of all GR soybean acres were treated with glyphosate in 2005 in the United States (Xiu 2012). In glyphosate-resistant (GR) soybean, glyphosate controlled johnsongrass >90% at least 50 days after treatment (DAT) (Culpepper et al. 2000; Griffin et al. 2006). Owen and Green (2011) reported that excessive use of a single herbicide mode of action over an extended period of time could result in weeds that are resistant to that herbicide. Currently, there are 30 species of plants worldwide that are resistant to glyphosate. Glyphosate-resistant johnsongrass has been reported in Argentina, Arkansas, Mississippi, and Louisiana (Heap 2014; Johnson et al. 2014b; Riar et al. 2011; Vila-Aiub et al. 2007). With the continued planting of GR soybean in the United States and the increasing number of documented GR weeds, alternative control measures are needed to mitigate and manage GR weeds (Duke 2005; Dill 2005).

Introduction of glufosinate-resistant soybean in 1996 provided growers the opportunity to apply glufosinate POST to weeds without injury to the soybean (Rasche and Gadsby 1997). Glufosinate interrupts essential amino acid biosynthesis by inhibiting the glutamine synthetase enzyme, which is responsible for converting glutamate and ammonia to glutamine (Duke 1990). This inhibition causes a buildup of ammonia in susceptible plants that rapidly destroys cells and tissue (Tachibana 1986; Sauer 1987). Glufosinate provides broad-spectrum control of grass and broadleaf weeds (Corbett et al. 2004; Tharp et al. 1999). Johnson et al. (2014a) has reported effective johnsongrass control with sequential applications of glufosinate or herbicide combinations with glufosinate (80% or greater 10 WAE), but sequential applications were made at the same rate (ex. 590 g ai ha^{-1} followed by (fb) 590 g ai ha^{-1}) and timing (3 and 6 wk after emergence) (Johnson et al. 2014a).

Preliminary research was conducted to investigate glufosinate efficacy on rhizomatous johnsongrass when applied to johnsongrass at differing heights. Data indicated that 0.7 kg ha^{-1} of glufosinate controlled 15, 31, and 46 cm johnsongrass 69%, 57%, and 96% 14 d after treatment (DAT) (RL Landry, unpublished data; Appendix A). This is in contrast to Johnson and Norsworthy (2014) who observed 96, 91, and 78% control of 15, 31, and 46 cm johnsongrass with the same glufosinate rate. The disagreement in findings may be attributed to increased coverage with glufosinate due to greater johnsongrass leaf number present when applications were made in our experiment. Also, rhizomatous johnsongrass emergence historically begins in late February to early March in Louisiana and reaches a height of 10 to 20 cm in mid-April, which coincides with the typical time of soybean planting in Louisiana, indicating a need to determine early-season control strategies in soybean (DO Stephenson, IV, personal communication).

Little research has been conducted with glufosinate to determine rates and application timings most effective for control of johnsongrass. Therefore, the objective of this research was to evaluate rhizome johnsongrass control as effected by glufosinate rates and application timings in glufosinate-resistant soybean.

Materials and Methods

Field experiments were conducted 2011, 2012, and 2013 at Louisiana State University Agricultural Center Dean Lee Research and Extension Center near Alexandria, LA. Soil was a Coushatta silt loam (fine-silty, mixed, superactive, thermic Fluventic Eutrudepts) with a pH of 8.0 and 1.5% organic matter. An augmented three factor factorial arranged in a randomized complete block replicated four times was used in all experiments. Based upon the observations from the preliminary research and to mimic scenarios observed in Louisiana producer's soybean fields, the initial glufosinate application was applied to 46 cm johnsongrass in all experiments. Treatments include an initial application of glufosinate (Liberty 280 SL, herbicide, Bayer CropScience LP 2 T.W. Alexander Drive Research Triangle Park, North Carolina 27709) to 46 cm johnsongrass at 0.5, 0.6, or 0.7 kg ai ha^{-1} later followed by a sequential application of glufosinate at 0.5 or 0.6 kg ai ha^{-1} 3 or 4 wk after the initial application, with a nontreated control included for comparison. Rhizomatous johnsongrass was 122 cm tall when both the 3 and 4 wk sequential applications were applied, but johnsongrass leaf number was greater at the 4 wk timing (5 leaves versus 7 leaves). Corresponding soybean growth stages at the initial and sequential glufosinate applications were 0-4 trifoliates (0.6 - 20 cm tall) and 6-8 trifoliates (15 - 91 cm tall), respectively, in all years.

All treatments were applied with a tractor-mounted, compressed-air sprayer calibrated to deliver 187 L ha^{-1} at 145 kPa using Teejet 11002, flat fan nozzles (Spraying Systems Co., P.O. Box 7900 Wheaton, IL 60189). Plot size was 9 m long with four, 0.97 m rows. 'Merschman Miami 949', 'Halo 494', and 'HBK 4950'glufosinate-resistant soybean were planted in 2011, 2012, and 2013, respectively. Soybean was seeded at 282,400 seeds ha^{-1} on April 27 in 2011 and 305,900 seeds ha^{-1} on May 3, 2012 and May 8, 2013. All studies were conducted using conventional-tillage methods and standard soybean production practices.

Soybean injury, johnsongrass control (0% no control/ injury to 100% complete control/ injury) and heights were assessed 20 and 28 days after sequential treatment (DAT) and at harvest. Johnsongrass heights were determined by measuring five plants per plot. Prior to analysis, johnsongrass heights were converted to a percentage of the nontreated. Yield was determined by harvesting the center two rows of plots using conventional harvesting equipment. Johnsongrass densities in the nontreated plots averaged 200 plants m^{-2} prohibiting machine harvest of these plots; thus the nontreated yields were excluded from analysis. Yield was adjusted to 13% moisture before analysis.

All data were subjected to analysis of variance using PROC GLIMMIX in SAS (release 9.3, SAS Institute, Cary, NC). Type III statistics were used to test all possible fixed effects (initial and sequential glufosinate application rates and sequential application timing) or interactions among the fixed effects. Random effects were years and replications nested within in years (Blouin et al. 2011). Considering year a random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Least square means were calculated and means were separated ($P \leq 0.05$) using Tukey's honest significant difference test. All data were subject to arcsine square root transformation to test for normality (Ahrens et al. 1990), but nontransformed means are presented.

Results and Discussion

Soybean Injury. Injury to soybean from glufosinate was not observed at any evaluation date (data not shown, Appendix B). Others have reported excellent tolerance of glufosinate-resistant soybean to glufosinate (Pline et al. 2000). Beyers et al. (2002) however, observed injury as high as 11% 2 WAT, but injury was no more than 1 % 4 WAT.

Rhizomatous Johnsongrass Control. For johnsongrass control 20 DAT analysis of variance indicated significance for initial glufosinate application rate (Table 2.1). Johnsongrass control 20 DAT was equivalent for initial glufosinate rates of 0.7 kg ha^{-1}(85%) and 0.6 kg ha^{-1} (83%) and greater than for 0.5 kg ha^{-1} (79%) (Table 2.2). At 28 DAT johnsongrass control remained greatest when glufosinate was applied at the two higher rates (Tables 2.1 and 2.2). Additionally at 28 DAT johnsongrass control was also affected by timing of sequential application (Table 2.1) and control was greater when the sequential application was delayed until 4 WAT compared with 3 WAT (83 vs 76%). Johnson and Norsworthy (2014) reported no difference in glufosinate rate (0.5, 0.6, or 0.7 kg ha^{-1}) on johnsongrass control when applied to 45 cm johnsongrass 14 (71, 75, and 78 %) and 28 (58, 61, and 68 %) DAT, respectively.

At harvest, greater rhizomatous johnsongrass control was observed following an initial glufosinate application of 0.6 and 0.7 kg ha^{-1} (74% and 77%, respectively) (Table 2.2). Control at harvest for glufosinate was greater for 0.7 compared with 0.5 (64%), but control was equivalent for 0.6 and 0.5. Johnson et al. (2014a), Culpepper et al. (2000), and Wiesbrook et al. (2001) also observed an increase in johnsongrass control following increased rates of glufosinate. Johnsongrass control in the present study was also affected by timing of the sequential application (Table 2.1) and at harvest johnsongrass control was greater when the sequential application was applied 3 WAT (76%) compared with 4 WAT (63%) (Table 2.3).

Table 2.1. Significance of the main effects of initial glufosinate application rate, sequential glufosinate application rate, and sequential glufosinate application timing and interactions among main effects pooled across environments for johnsongrass control and height at each evaluation date and soybean grain yield.[a,b]

Parameter[c]	Data collection	IR	SR	ST	IR x SR	IR x ST	SR x ST	IR x SR x ST
		---------- P-value ----------						
Johnsongrass control	20 DAT	0.0002	0.3073	0.2284	0.1628	0.0853	0.4139	0.6861
	28 DAT	0.0541	0.0575	0.0094	0.2399	0.4606	0.3473	0.6594
	Harvest	0.0107	0.5275	0.0014	0.2678	0.7232	0.1330	0.4546
Johnsongrass height	20 DAT	0.0397	0.4905	0.0041	0.5300	0.3473	0.1703	0.0931
	28 DAT	0.2998	0.0358	0.0253	0.1106	0.3439	0.7247	0.6855
	Harvest	0.4725	0.0042	0.0191	0.8517	0.6954	0.9213	0.9310
Soybean grain yield		0.0076	0.0346	0.5869	0.2337	0.2896	0.7770	0.7820

[a] Abbreviations: DAT, d after treatment; IR, initial glufosinate application rate; SR, sequential glufosinate application rate; ST, sequential glufosinate application timing.
[b] Main effects and interactions considered significant for Type III error if $P \leq 0.05$.

Prostko et al. (2001), Wiesbrook et al. (2001), and Johnson et al. (2014a) suggested that sequential applications of herbicides are more effective at controlling weeds. Although no difference in johnsongrass control was observed 20 DAT between the 3 and 4 wk sequential glufosinate application timings (Table 2.1; data not shown, Appendix C), delaying the sequential application from 3 to 4 wk after the initial glufosinate application increased johnsongrass control 7 and 13 percentage points 28 DAT and at harvest, respectively (Table 2.3). This observation may be due to increased johnsongrass leaf number (5 leaves versus 7 leaves) providing greater interception of glufosinate when applied 4 wk after the initial glufosinate application (Table 2.1, 2.2).

Table 2.2. Johnsongrass control and heights (% of nontreated), and soybean yield as influenced by initial rate.[a,b]

	Johnsongrass control		Johnsongrass heights	Soybean yield
Initial rate	20 DAT	At harvest	20 DAT.	
kg ai ha^{-1}	-----------------------------------%-----------------------------			kg ha^{-1}
0.5	79b	64b	48a	2400b
0.6	83a	74ab	42ab	2600ab
0.7	85a	77a	41b	2670a

[a] Abbreviations: DAT, d after treatment.
[b] Means followed by the same letter in each column are not significantly different based on Tukey's HSD at P ≤ 0.05.

Table 2.3. Johnsongrass control and heights (% of nontreated) in soybean as influenced by sequential timing.[a,b]

	Johnsongrass control		Johnsongrass heights		
Sequential timing	28 DAT	At harvest	20 DAT	28 DAT	At harvest
	---%--				
3 WAT	76b	65b	47a	49a	76a
4 WAT	83a	78a	40b	36b	63b

[a] Abbreviations: DAT, d after treatment.
[b] Means followed by the same letter in each column are not significantly different based on Tukey's HSD at P ≤ 0.05.

Rhizomatous Johnsongrass Heights. Analysis indicated that initial and sequential glufosinate application rate and sequential application timing were significant for johnsongrass heights (Table 2.1). Johnsongrass heights were 48, 42, and 41% of the nontreated for 0.5, 0.6, and 0.7 kg ha^{-1}, respectively, with differences observed between the 0.5 and 0.7 kg ha^{-1} glufosinate rates 20 DAT (Table 2.2), but these differences were not observed 28 DAT (38 to 48%) (Table 2.1; data not shown, Appendix D). Conversely, the sequential glufosinate application rate did not influence johnsongrass heights as a percent of the nontreated 20 DAT (Table 2.1; data not shown), but increasing the glufosinate rate from 0.5 to 0.6 kg ha^{-1} decreased johnsongrass heights 11 and 15 percentage points 28 DAT and at harvest, respectively (Table 2.4). Additionally, delaying the sequential glufosinate application timing from 3 to 4 wk after the initial application decreased johnsongrass heights as a percent of the nontreated 7 to 13percentage points at all evaluation dates (Table 2.3). Johnson and Norsworthy (2014) reported johnsongrass stand reductions following applications of glufosinate (65-73%), but no differences were detected between rates 28 DAT.

Table 2.4. Johnsongrass heights (% of nontreated) and soybean yield as influenced by sequential rate.[a,b]

	Johnsongrass heights		Soybean yield
Sequential rate	28 DAT	At harvest	
kg ai ha^{-1}	---------------------------%-------------------------		kg ha^{-1}
0.5	48a	77a	2490b
0.6	37b	62b	2620a

[a] Abbreviations: DAT, d after treatment.
[b] Means followed by the same letter in each column are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Glufosinate-resistant Soybean Yield. For soybean yield analysis indicated that initial and sequential glufosinate rates were significant (Table 2.1). Soybean yields following the initial glufosinate application of 0.5, 0.6, and 0.7 kg ha^{-1} were 2400, 2600, and 2670 kg ha^{-1}, respectively, and that yield following the 0.5 kg ha^{-1} was 10% less compared with 0.7 kg ha^{-1} (Table 2.2). Similarly, increasing the sequential glufosinate rate from 0.5 to 0.6 kg ha^{-1} increased soybean yield 130 kg ha^{-1} (5%) (Table 2.4). Timing the sequential application 3 or 4 wk after the initial glufosinate application (Table 2.1) did not influence soybean yield with yield averaging 2488 kg ha^{-1}(data not shown, Appendix D). Johnson et al. (2014a) observed no differences in glufosinate-resistant soybean yields following herbicide programs for johnsongrass control (2,690 to 3,160 kg ha^{-1}); however, differences might have been observed if the test area had not been sprayed with clethodim 10 WAE.

These data show that based on johnsongrass control at harvest glufosinate rates of 0.6 or 0.7 kg ha^{-1} followed by either 0.5 or 0.6 kg ha^{-1} glufosinate can provide around 75% control. Soybean yield was maximized with an initial glufosinate application of 0.6 to 0.7 kg ha^{-1} followed either 3 or 4 wk later with glufosinate at 0.6 kg ha^{-1}. Data show that a sequential application of glufosinate in glufosinate-resistant soybean would be an option for management of glyphosate-resistant rhizomatous johnsongrass but that control level obtained and subsequent yield may not be equivalent to 75% control at harvest.

Literature Cited

Ahrens WH, Cox DJ, Budhwar G (1990) Use of the arcsine and square root transformations for subjectively determined percentage data. Weed Sci 38:452-458.

Allen CM (1975) Grasses of Louisiana. Lafayette, LA: Univ of SW Louisiana. 276 p.

Anderson WP (1996) Weed Science Principles and Applications. 3rd edn. West Publ. Co. St. Paul, MN. Pp. 43-51.

Anonymous (2014) USDA-NASS Quick Stats Lite. http://www.nass.usda.gov/Quick_Stats/Lite/ Accessed August 11, 2014.

Ateh CM, Harvey RG (1999) Annual weed control by glyphosate in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:394-398.

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

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol. 25:165-169.

Carmer SG, Nyquist WE, Walker WM (1989) Least significant differences in combined analyses of experiments with two- or three-factor treatment designs. Agron J 81:655-672.

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, sulfosate. Weed Technol. 18:443-453.

Culpepper AS, York AC, Batts RB, Jennings KM (2000) Weed management in glufosinate and glyphosate-resistant soybean (*Glycine max*). Weed Technol 14:77-88.

Delannay X, Bauman TT, Beighley DH, Buettner MJ, Coble HD, DeFelice MS, Derting CW, Diedrick TJ, Griffin JL, Hagood ES, Hancock FG, Hart SE, LaVallee BJ, Loux MM, Lueschen WE, Matson KW, Moots CK, Murdock E, Nickell AD, Owen MDK, Paschal II EH, Prochaska LM, Raymond PJ, Reynolds DB, Rhodes WK, Roeth FW, Sprankle PL, Tarochione LJ, Tinius CN, Walker RH, Wax LM, Weigelt HD, Padgette SR (1995) Yield evaluation of a glyphosate- tolerant soybean line after treatment with glyphosate. Crop Sci 35:1461-1467.

Dill GM (2005) Glyphosate-resistant crops: history, status and future. Pest Manage Sci 61:219-224.

Duke SO (1990) Overview of herbicide mechanisms of action. Environ. Health Perspect. 87:263 -271.

Duke SO (2005) Taking stock of herbicide-resistant crops ten years after introduction. Pest Mgmt Sci 61:211-218.

Griffin JL, Miller DK, Salassi ME (2006) Johnsongrass (*Sorghum halepense*) control and economics of using glyphosate- resistant soybean in fallowed sugarcane fields. Weed Technol 20:980-985.

Haragan PD (1991) Weeds of Kentucky and adjacent states. The Univ. Press of Kentucky. Pp 194-195.

Heap I. The International Survey of Herbicide Resistant Weeds. Online. Internet. July 12, 2014. Available www.weedscience.com.

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The world's worst weeds distribution and biology. Honolulu, HI: The University Press of Hawaii. Pp 54-61.

Ingle M, Rogers BJ (1961) The growth of mid-western strain of *Sorghum halepense* under controlled conditions. Amer J Bot 48:392-396.

Johnson DB, Norsworthy JK (2014) Johnsongrass (*Sorghum halepense*) management as influenced by herbicide selection and application timing. Weed Technol. 28:142-150.

Johnson DB, Norsworthy JK, Scott RC (2014a) Herbicide programs for controlling glyphosate resistant johnsongrass (*Sorghum halepense*) in glufosinate-resistant soybean. Weed Technol 28:10-18.

Johnson DB, Norsworthy JK, Scott RC (2014b). Distribution of herbicide-resistant johnsongrass (*Sorghum halepense*) in Arkansas. Weed Technol 28:111-121.

Johnson WG, Frans RE (1991) Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence herbicides Weed Technol. 5:87-91.

McWhorter CG (1971) Anatomy of johnsongrass. Weed Sci 19:385-393.

McWhorter CG (1974) Johnsongrass control in soybeans with trifluralin and nitralin. Weed Sci. 22:111-115.

McWhorter CG (1977) Johnsongrass control in soybeans with soil-incorporated dinitroaniline herbicides. Weed Sci 25:264-267.

McWhorter CG (1989) History, biology, and control of johnsongrass Rev. Weed Sci 4:85-121.

McWhorter CG, Hartwig EE (1972) Competition of johnsongrass and cocklebur with six soybean varieties. Weed Sci 20:56-59.

Nalewaja JD (1999) Cultural practices for weed resistance management. Weed Technol 13:643-646.

Nelson KA, Renner KA (2013) Weed management in wide- and narrow- row glyphosate resistant soybean. Journal of Prod Ag 12:460-465.

Oerke EC (2006) Crop losses to pests. Journal of Agric Sci 144:31-43.

Oyer EB, Gries GA, Rogers BJ (1959) The seasonal development of johnsongrass plants. Weeds 7:13-19.

Owen MDK, Green JM (2011) Herbicide resistant crops: utilities and limitations for herbicide resistant weed management. Agri Food Chem 59:5819-5829.

Pline WA, Hatzios KK, Hagood ES (2000) Weed and herbicide-resistant soybean (*Glycine max*) response to glufosinate and glyphosate plus ammonium sulfate and pelargonic acid. Weed Technol. 14:667-674.

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

Rasche E, Gadsby M (1997) Glufosinate ammonium tolerant crops-international commercial developments and experiences. Pages 941-946 *in* Proceedings of the Brighton Crop Protection Conference-Weeds. Brighton, UK: British Crop Protection Council.

Riar DS, Norsworthy JK, Johnson DB, Scott RC, Bagavathiannan M (2011) Glyphosate resistance in a johnsongrass (*Sorghum halepense*) biotype from Arkansas. Weed Sci 59:299-304.

Sauer H, Wild A, Rühle W (1987) The effect of phosphinothricin (glufosinate) on photosynthesis—II. The causes of inhibition of photosynthesis. Z Naturforsch 42c (Biosciences 42): 270–278.

Spencer ER (1974) All About Weeds. New York, NY: Dover Publications. Pp 24-27.

Tachibana K, Watanabe T, Sekizuwa Y, Takematsu T (1986) Accumulation of ammonia in plants treated with bialaphos Journal of Pest Sci 11:33-37.

Tharp BE, Schabenberger O, Kells JJ (1999) Response of annual weed species to glufosiante and glyphosate Weed Technol. 13:542-547.

Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CB, Powles SB (2007) Evolution of glyphosate-resistant johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. Weed Sci 55:566-571.

Webster EP, Bryant KJ, Earnest LD (1999) Weed control and economics in nontransgenic and glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:586-593.

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.

Winton-Daniels K, Frans R, McClelland M (1990) Herbicide systems for johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*). Weed Technol 4:115-122.

Xiu Y (2012) National Agricultural Statistics Service (NASS): *Agricultural Chemical Use Database*. http://www.pestmanagement.info/nass/ Accessed July 14, 2012.

CHAPTER 3
RHIZOME JOHNSONGRASS (*Sorghum halepense* L. Pers.) CONTROL WITH CHLORIMURON, CLETHODIM, AND FOMESAFEN IN SOYBEAN (*Glycine max* L. Merr.)

Introduction

Johnsongrass [*Sorghum halepense* (L.) Pers.] is one of the world's worst weeds (Holm et al. 1977). It can reach heights up to 3.5 meters, has a prominent white midrib, and a large panicle inflorescence (Holm et al. 1977; Ingle and Rogers 1961; McWhorter 1971a; 1971b; Oyer et al. 1959). In addition, johnsongrass can reproduce by seeds and rhizomes, with rhizomes functioning as reproductive tissues for up to one growing season and has a cold tolerance of -3°C or more if buried deeper (Anderson et al. 1960; Hull 1970; Talbot 1928; Stoller 1977; Warwick and Black 1983).

Johnsongrass is a member of the Poaceae family, a large perennial grass that is native to lands east of the Mediterranean Sea, specifically the political boundaries between Syria and Turkey (Holm et al. 1977; Spencer 1974; Haragan 1991). Johnsongrass range has expanded to include six continents only excluding Antarctica (Holm et al. 1977). North American introduction of johnsongrass has varying historical accounts; however by 1830 it was widely documented as being planted as forage (McWhorter 1971). Inevitably, johnsongrass expansion has caused it to become a major pest in agronomic crops (Holm et al. 1977). Johnsongrass competes with crops for nutrients, space, water, and sunlight; additionally johnsongrass exhibits allelopathy, and host disease or insects (Warwick and Black 1983; Bendixon 1986).

Louisiana growers planted 413,000, 457,000, and 453,000 ha of soybean [*Glycine max* (L.) Merr.] in 2011, 2012, and 2013, respectively (Anonymous 2014). However, despite current production practices of soybean, 37% of losses can be attributed to weeds (Oerke 2006).

McWhorter reported johnsongrass was present in 55-90% of cotton [*Gossypium hirsutum* (L.)] and soybean acres surveyed in Arkansas, Louisiana, and Mississippi in 1991 and, as a result, johnsongrass has the potential to cause detrimental yield losses (McWhorter and Hartwig 1965; McWhorter 1972, McWhorter 1993). Johnsongrass has been reported to reduce soybean yields 14%; however, other studies have shown 59-88% yield reduction following season-long competition (Sims and Oliver 1990; Williams and Hayes 1984). Furthermore, johnsongrass presence late-season can reduce harvest efficiency and increase presence of foreign matter in soybean up to 6 % (McWhorter and Anderson 1981).

Controlling johnsongrass in soybean has been reported with preemergence (PRE) and postemergence (POST) herbicides split with cultivation (Gebhardt 1981). Furthermore, use of dinitoraniline herbicides in soybean is effective for johnsongrass control (McWhorter 1977). Introduced in the late 20th century, acetyl coenzyme A carboxylase (ACCase)- and acetolactate synthase (ALS)- inhibiting herbicides proved effective in cotton and soybean for johnsongrass control (Banks and Tripp 1983; Tranel and Wright 2002). ACCase inhibiting herbicides inhibit the *de novo* fatty acid synthesis in susceptible monocots all while not affecting insensitive dicot plants (Ishikawa et al. 1985; Iwataki et al. 1979; Burgstahler et al. 1984, 1986; Hatzios 1982). ALS inhibiting herbicides inhibit the amino acid biosynthesis of leucine, isoleucine, and valine, requirements for cell growth (Ray 1982a, 1982b, Rost 1984). Use of ACCase- and ALS-inhibiting herbicides was reported to control johnsongrass 70-90% and 50-80% when applied POST in soybean and corn respectively (Johnson et al. 1991; Camacho et al. 1991).

The introduction of glyphosate-resistant (GR) crops in 1996, allowed POST applications of glyphosate to crops without injury (Delannay et al. 1995). Glyphosate inhibits 5-enolpyruvyl-shikimate-3-phosphate synthase, preventing production of the essential amino acids tryptophan, phenylalanine, and tyrosine needed for growth in the plant (Duke 1990; Jaworski 1972). Glyphosate applications in GR soybean can manage numerous broadleaf and grass weeds (Ateh and Harvey 1999; Delannay et al. 1995; Nelson and Renner 2013; Webster et al. 1999). Extensive johnsongrass control has been reported using glyphosate POST (90-100%) at least 50 days after treatment (DAT) (Culpepper et al. 2000; Griffin et al. 2006; Lanie et al. 1994; Parochetti et al. 1975).

In 2005, 88, 82, and 40% of GR soybean, cotton, and corn acres, were treated with glyphosate in the U. S., respectively (Xiu 2012). However, reliance on a single mode of action can result in herbicide resistant weeds overtime (Owen and Green 2011). Excessive use of glyphosate in Argentina, Arkansas, and Louisiana has led to the presence of GR johnsongrass (Vila-Aiub et al. 2007; Riar et al. 2011; Heap 2014).

This research evaluated the effectiveness of controlling johnsongrass in soybean without non-selective herbicides. These experiments aim to assess effectiveness of herbicides commonly used in central Louisiana for weed control and to determine if these combinations provide acceptable control of johnsongrass.

Materials and Methods

Field experiments were conducted 2011 and 2012 at Louisiana State University Agricultural Center Dean Lee Research and Extension Center near Alexandria, LA. Soil was a Coushatta silt loam (fine-silty, mixed, superactive, thermic Fluventic Eutrudepts) with a pH of 8.0 and 1.5% organic matter. The experimental design was a randomized complete block with four replications. All treatments include chlorimuron (Classic, herbicide, E. I. du Pont de Nemours and Company, Delaware 19898) at 9 g ai ha^{-1}, clethodim (Select Max, herbicide, Valent U.S.A., California 94596) at 140 g ai ha^{-1}, and fomesafen (Flexstar, herbicide, Syngenta Crop Protection, North Carolina 27419) at 260 g ai ha^{-1}. Treatments were applied at early-postemergence (EPOST), mid-postemergence (MPOST), and late-postemergence (LPOST), which corresponded to two-, five-, and eight-trifoliate soybean, respectively. Treatment structure is given in Table 3.1. A non-ionic surfactant at 0.25% v/v was added to all chlorimuron and fomesafen applications and a crop oil concentrate at 1% v/v was added to all clethodim applications. Glufosinate (Liberty 280 SL, herbicide, Bayer CropScience LP 2 T.W. Alexander Drive Research Triangle Park, North Carolina 27709) at 450 g ai ha^{-1} applied at all three application timings and a nontreated control were added as comparison treatments. All treatments were applied with a tractor-mounted, compressed-air sprayer calibrated to deliver 187 L ha^{-1} at 145 kPa using Teejet 11002, flat fan nozzles (Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187). Plot size was 9 m long with four, 0.97 m rows. ‘Merschman Miami 949’ and ‘Halo 494’ glufosinate-resistant soybean were seeded in 2011 at 282,400 seeds ha^{-1}, and 2012 at 305,900 seeds ha^{-1}, respectively. All studies were conducted using conventional-tillage methods and standard soybean production practices.

Soybean injury and johnsongrass control and heights (0% no control to 100% complete control) were assessed 35 d after LPOST and at harvest. Johnsongrass heights were determined by measuring five plants per plot, and, prior to analysis, johnsongrass heights were converted to a percentage of the nontreated. Yield was determined by harvesting the center two rows of plots using conventional harvesting equipment. Johnsongrass densities in the nontreated plots averaged 220 plants m^{-2} which prohibited machine harvest of these plots, thus the nontreated yields were excluded from the analysis. Yield was adjusted to 13% moisture before analysis.

Table 3.1. Herbicide treatments evaluated in 2011 and 2012.[a]

Herbicide treatment	Rate	Timing
	g ha^{-1}	
Chlorimuron fb fomesafen fb clethodim	9 fb 260 fb 140	EPOST fb MPOST fb LPOST
Chlorimuron fb clethodim fb fomesafen	9 fb 140 fb 260	EPOST fb MPOST fb LPOST
Clethodim fb chlorimuron fb fomesafen	140 fb 9 fb 260	EPOST fb MPOST fb LPOST
Clethodim fb fomesafen fb chlorimuron	140 fb 260 fb 9	EPOST fb MPOST fb LPOST
Fomesafen fb chlorimuron fb clethodim	260 fb 9 fb 140	EPOST fb MPOST fb LPOST
Fomesafen fb clethodim fb chlorimuron	260 fb 140 fb 9	EPOST fb MPOST fb LPOST
Glufosinate fb glufosinate fb glufosinate	450 fb 450 fb 450	EPOST fb MPOST fb LPOST

[a] Abbreviations: EPOST, early-postemergence; fb, followed by; LPOST, late-postemergence; MPOST, mid-postemergence.

All data were subjected to analysis of variance using PROC GLIMMIX in SAS (release 9.3, SAS Institute, Cary, NC) with years and replications nested within year as random effects (Blouin et al. 2011). Herbicide treatment was considered a fixed effect. Considering replications and years random effects permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Least square means were calculated and means separated ($P \leq 0.05$) using Tukey's honest significance difference test.

Results and Discussion

Glufosinate-resistant Soybean Injury. Soybean foliar injury observed in 2011 was minimal (< 20%) and plants were able to recover within seven days (data not shown, Appendix E). Adcock and Banks (1991) and Minton et al. (1989) observed no adverse effects on soybean after applying chlorimuron and clethodim, respectively. Harris et al. (1991) observed some foliar injury after applying fomesafen to soybean, but plants were able to recover and no yield loss was noted. No soybean injury was observed following applications in 2012 (data not shown, Appendix E)

Rhizomatous Johnsongrass Control. Applying glufosinate at all three application timings provided 90% johnsongrass control 35 d after LPOST and at harvest (Table 3.2). Similarly, both treatments that included clethodim EPOST provided 78 to 89% johnsongrass control 35 d after LPOST, which was equal to the glufosinate only treatment. Only clethodim EPOST followed by (fb) chlorimuron MPOST fb fomesafen LPOST provided johnsongrass control at harvest that was equal to the glufosinate only treatment (Table 3.2). However, no difference in control was observed between both treatments that contained clethodim EPOST at harvest. Regardless of herbicide applied MPOST or LPOST, treatments with chlorimuron EPOST controlled johnsongrass 66 to 74% 35 d after LPOST and 59 to 69% at harvest (Table

Table 3.2. Johnsongrass control and heights 28 d after late-postemergence treatment and at harvest and soybean yield as influenced by herbicide treatment.[a,b]

Herbicide treatment	Johnsongrass control		Johnsongrass heights		Soybean yield
	35 d after LPOST	At harvest	35 d after LPOST	At harvest	
	------------------%------------		-----------------cm---------------		kg ha^{-1}
Chlorimuron fb fomesafen fb clethodim	66 bc	59 de	73 bc	99 a	2490 abc
Chlorimuron fb clethodim fb fomesafen	74 b	69 cd	66 b	118 a	2150 bcd
Clethodim fb chlorimuron fb fomesafen	89 a	82 ab	32 a	106 a	2010 bcd
Clethodim fb fomesafen fb chlorimuron	78 ab	73 bc	59 b	109 a	2220 bcd
Fomesafen fb chlorimuron fb clethodim	76 b	54 e	51 ab	107 a	2620 ab
Fomesafen fb clethodim fb chlorimuron	58 c	49 e	84 bc	115 a	16 10 d
Glufosinate fb glufosinate fb glufosinate	90 a	90 a	46 ab	103 a	3090 a
Nontreated	0[c]	0[c]	130 bc	144 b	0[d]

[a] Abbreviations: fb, followed by; LPOST, late-postemergence.
[b] Data pooled across two experiments. Means followed by the same letter in each column are not significantly different based on Tukey's HSD at $P \leq 0.05$.
[c] Nontreated data was excluded from analysis of johnsongrass control, but was included in analysis of johnsongrass heights.
[d] Nontreated soybean plots were not harvestable; therefore, these data were excluded from soybean yield analysis.

3.2). When fomesafen was applied EPOST, the sequence of chlorimuron and clethodim MPOST or LPOST influenced johnsongrass control 35 d after LPOST. When following fomesafen EPOST, johnsongrass control was increased 18% when clethodim was applied LPOST compared to chlorimuron LPOST 35 d after LPOST (Table 3.2). However, this difference was not observed at harvest with control ranging from 49 to 54% for both treatments that contained fomesafen EPOST. In the absence of a nonselective herbicide such as glufosinate, data indicates that johnsongrass control is greatest when clethodim is applied EPOST regardless of the application sequence of chlorimuron and fomesafen.

Rhizomatous Johnsongrass Heights. Analysis indicated that different sequences of herbicides were significant for johnsongrass heights at 35 DA LPOST (Table 3.2). Clethodim EPOST, chlorimuron MPOST, and fomesafen LPOST is the only treatment that reduced johnsongrass heights greater than the nontreated, but was similar to glufosinate fb glufosinate fb glufosinate and fomesafen fb chlorimuron fb clethodim 35 d after LPOST (Table 3.2). At harvest, no treatment was significantly different when comparing heights, except when comparing all treatments to the nontreated (Table 3.2).

Glufosinate-resistant Soybean Yield. Soybean yields were greatest following sequential applications of glufosinate (3090 kg ha^{-1}), but did not differ from treatments that contained clethodim LPOST (2490 and 2620 kg ha^{-1}) (Table 3.2). Yields following clethodim EPOST fb either chlorimuron MPOST and fomesafen LPOST (2010 kg ha^{-1}) or fomesafen MPOST and chlorimuron LPOST (2220 kg ha^{-1}) were not significantly different than chlorimuron fb clethodim fb fomesafen (2150 kg ha^{-1}) or fomesafen fb clethodim fb chlorimuron (1610 kg ha^{-1}) (Table 3.2).

Johnsongrass control when clethodim was applied EPOST regardless of sequential sequence of chlorimuron or fomesafen, was similar to glufosinate applied sequentially 35 DA LPOST (Table 3.1). Furthermore, johnsongrass control at harvest following glufosinate alone (90%) or clethodim fb chlorimuron fb fomesafen (82%) did not differ (Table 3.1). Johnsongrass heights are reduced similarly following sequential glufosinate applications and clethodim fb chlorimuron fb fomesafen or fomesafen fb chlorimuron fb clethodim 35 DA LPOST (Table 3.2). At harvest, there are no differences between herbicide treatments for reduction of johnsongrass heights (Table 3.2). Soybean yields were similar to the sequential glufosinate compared to herbicide treatments that contained clethodim LPOST (Table 3.2). The data suggests that glufosinate and treatments where clethodim was applied EPOST are good options to control glyphosate-resistant johnsongrass. Chlorimuron and fomesafen did not provide an increase in johnsongrass control regardless of when they were applied.

Literature Cited

Adcock TE, Banks PA (1991) Effects of chlorimuron on soybean (*Glycine max*) and sicklepod (*Cassia obtusifolia*) as influenced by application timing. Weed Sci 39:139-142.

Anderson LE, Appleby AP, Weseloh JW (1960) Characteristics of johnsongrass rhizomes. Weeds 8:402-406.

Anonymous (2014) USDA-ERS. Soybeans and oil crops-backgroundhttp://www.ers.usda.gov/topics/crops/soybeans-oil-crops/background.aspx#.VBBdb_nN8F. Accessed September 9, 2014.

Anonymous (2014) USDA-NASS Quick Stats Lite. http://www.nass.usda.gov/Quick_Stats/Lite/ Accessed August 11, 2014.

Ateh CM, Harvey RG (1999) Annual weed control by glyphosate in glyphosate-resistant soybean (Glycine max). Weed Technol. 13:394-398.

Banks PA, Tripp TN (1983) Control of johnsongrass (*Sorghum halepense*) in soybeans (*Glycine max*) with foliar-applied herbicides. Weed Sci 31:628-633.

Bendixon LE (1986) Corn (*Zea mays*) yield in relationship to johnsongrass (*Sorghum halepense*) population. Weed Sci 34:449-451.

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol. 25:165-169.

Burgstahler RJ, Lichtenthaler HK (1984) Inhibition by sethoxydim of phospho- and galactolipid accumulation in maize seedlings. *In* PA Siegenthaler, W Eichenberger, eds, Structure, Function and Metabolism of Plant Lipids. Elsevier, New York, p. 619-623.

Burgstahler RJ, Retzlaff G, Lichtenthaler HK (1986) Mode of action of sethoxydim: effects on the plant's lipid metabolism. Abstracts of the Sixth International Congress of Pesticide Chemistry, Ottawa, p 3B-11.

Camacho RF, Moshier L J, Morishita DW, Devlin DL(1991) Rhizome johnsongrass (*Sorghum halepense*) control in corn (*Zea mays*) with primisulfuron and nicosulfuron. Weed Technol 5:789-794.

Carmer SG, Nyquist WE, Walker WM (1989) Least significant differences in combined analyses of experiments with two- or three-factor treatment designs. Agron J 81:655-672.

Culpepper AS, York AC, Batts RB, Jennings KM (2000) Weed management in glufosinate and glyphosate-resistant soybean (*Glycine max*). Weed Technol 14:77-88.

Delannay X, Bauman TT, Beighley DH, Buettner MJ, Coble HD, DeFelice MS, Derting CW, Diedrick TJ, Griffin JL, Hagood ES, Hancock FG, Hart SE, LaVallee BJ, Loux MM, Lueschen WE, Matson KW, Moots CK, Murdock E, Nickell AD, Owen MDK, Paschal II EH, Prochaska LM, Raymond PJ, Reynolds DB, Rhodes WK, Roeth FW, Sprankle PL, Tarochione LJ, Tinius CN, Walker RH, Wax LM, Weigelt HD, Padgette SR (1995) Yield evaluation of a glyphosate- tolerant soybean line after treatment with glyphosate. Crop Sci 35:1461-1467.

Duke SO (1990) Overview of herbicide mechanisms of action. Environ Health Perspect 87:263-271.

Gebhardt MR (1981) Cultural and chemical weed control systems in soybeans (*Glycine max*). Weed Sci 29:133-138.

Griffin JL, Miller DK, Salassi ME (2006) Johnsongrass (*Sorghum halepense*) control and economics of using glyphosate- resistant soybean in fallowed sugarcane fields. Weed Technol 20:980-985.

Haragan PD (1991) Weeds of Kentucky and adjacent states. The Univ. Press of Kentucky. Pp 194-195.

Harris JR, Gossett BJ, Murphy TR, Toler JE (1991) Response of broadleaf weeds and soybeans to the diphenyl ether herbicides. J of Prod Agric 4:407-NP.

Hatzios KK (1982) Effects of sethoxydim on the metabolism of isolated leaf cells of soybean [*Glycine max* (L.) Merr.].Plant Cell Rep 1:87-90.

Heap I. The International Survey of Herbicide Resistant Weeds. Online. Internet. September 8, 2014. Available www.weedscience.com.

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The world's worst weeds distribution and biology. Honolulu, HI: The University Press of Hawaii. Pp 54-61.

Hull RJ (1970) Germination control of johnsongrass rhizome buds. Weed Sci. 18:118-121.

Ingle M, Rogers BJ (1961) The growth of mid-western strain of *Sorghum halepense* under controlled conditions. Amer J Bot 48:392-396.

Ishikawa H, Yamada S, Hosaka H, Kawana T, Okunuki S, Kohara K (1985) Herbicidal properties of sethoxydim for the control of gramineous weeds. J Pestic Sci 10:187-193.

Iwataki I, Hirono Y, (1979) The chemical and herbicidal activity of alloxydim-sodium and related compounds. *In* H Geissbuhler, ed, Advances in Pesticide Science, Fourth International Congress on Pesticide Chemicals. Permagon Press, Oxford, p 235-243.

Johnson WG, Frans RE, Parsch LD (1991) Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence herbicides. Weed Technol 5:87-91.

Jaworski EG (1972) Mode of action of N-phosphonomethyl-glycine: inhibition of aromatic amino acid biosynthesis. J Agric Food Chem 20:1195–1198.

Lanie AJ, Griffin JL, Vidrine PR, Reynolds DB (1994) Herbicide combinations for soybean (Glycine max) planted in stale seedbed. Weed Technol 8:17-22.

McWhorter CG, Hartwig EE (1965) Effectiveness of preplanting tillage in relation to herbicides in controlling johnsongrass for soybeans production. Agron J 57:385-389.

McWhorter CG (1971a) Anatomy of johnsongrass. Weed Sci 19:385-393.

McWhorter CG (1971b) Growth and development of johnsongrass ecotypes. Weed Sci 19:141-147.

McWhorter CG (1972) Factors affecting johnsongrass rhizome production and germination. Weed Sci 20:41-45.

McWhorter CG (1977) Johnsongrass control in soybeans with soil-incorporated dinitroaniline herbicides. Weed Sci 25:264-267.

McWhorter CG (1993) A 16 year survey on levels of johnsongrass (*Sorghum halepense*) in Arkansas, Louisiana, and Mississippi. Weed Sci 41:669-677.

McWhorter CG, Anderson JM (1981) The technical and economic effects of johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*). Weed Sci 29:245-253.

Minton BW, Shaw DR, Kurtz ME (1989) Postemergence grass and broadleaf herbicide interactions for red rice (*Oryza sativa*) control in soybeans (*Glycine max*). Weed Technol 3:329-334.

Nelson KA, Renner KA (2013) Weed management in wide- and narrow- row glyphosate resistant soybean. Journal of Prod Ag 12:460-465.

Oerke EC (2006) Crop losses to pests. Journal of Agric Sci 144:31-43.

Owen MDK, Green JM (2011) Herbicide resistant crops: utilities and limitations for herbicide resistant weed management. Agri Food Chem 59:5819-5829.

Oyer EB, Gries GA, Rogers BJ (1959) The seasonal development of johnsongrass plants. Weeds 7:13-19.

Parochetti JV, Wilson HP, Burt GW (1975) Activity of glyphosate on johnsongrass. Weed Sci 23:395-400.

Ray TB (1982a) The mode of action of chlorisulfuron: a new herbicide for cereals. Pestic Biochem Physiol 17:10-17.

Ray TB (1982b) The mode of action of chlorisulfuron: the lack of direct inhibition of plant DNA synthesis. Pestic Biochem Physiol 18:262-266.

Riar DS, Norsworthy JK, Johnson DB, Scott RC, Bagavathiannan M (2011) Glyphosate resistance in a johnsongrass (*Sorghum halepense*) biotype from Arkansas. Weed Sci 59:299-304.

Rost TL (1984) The comparative cell cycle and metabolic effects of chemical treatments on root tip meristems. III. Chlorisulfuron. J Plant Growth Reg 3:51-63.

Sims BD, Oliver LR (1990) Mutual influences of seedling johnsongrass (*Sorghum halepense*), sicklepod (*Cassia obtusifolia*), and soybean (*Glycine max*). Weed Sci 38:139-147.

Spencer ER (1974) All About Weeds. New York, NY: Dover Publications. Pp 24-27.

Stoller EW (1977) Differential cold tolerance of quackgrass and johnsongrass rhizomes. Weed Sci 25:348-351.

Talbot MW (1928) Johnsongrass as a weed. U.S. Dept Agr Farmer's Bul 1537.

Tranel PJ, Wright TR (2002) Resistance of weeds to ALS-inhibiting herbicides: What have we learned? Weed Sci 50:700-712.

Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CB, Powles SB (2007) Evolution of glyphosate resistant johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. Weed Sci 55:566-571.

Warwick SI, Black LD (1983) The biology of Canadian weeds. 61.*Sorghum halepense* (L.)Pers. Can J Plant Sci 63:997-1014.

Webster EP, Bryant KJ, Earnest LD (1999) Weed control and economics in nontransgenic and glyphosate-resistant soybean (Glycine max). Weed Technol. 13:586-593.

Williams CS, Hayes RM (1984) Johnsongrass (*Sorghum halepense*) competition in soybeans (*Glycine max*). Weed Sci 32:498-501.

Xiu Y (2012) National Agricultural Statistics Service (NASS): *Agricultural Chemical Use Database*. http://www.pestmanagement.info/nass/ Accessed August 16, 2012.

CHAPTER 4
GLUFOSINATE RATE AND APPLICATION TIMING FOR CONTROL OF RHIZOMATOUS JOHNSONGRASS (*Sorghum halepense* L. Pers.) IN GLUFOSINATE-RESISTANT COTTON (*Gossypium hirsutum* L.)

Introduction

Surveys conducted in Arkansas, Louisiana, and Mississippi reported 55 to 90 % of cotton [*Gossypium hirsutum* (L.)] fields were infested with johnsongrass [*Sorghum halepense* (L.) Pers.] and reduced the estimated value of harvested cotton was $5.8 ±1.9 million averaged from 1978 to 1991 (McWhorter 1993). Johnsongrass can influence commodity yields negatively by competition with crop, allelopathic effects, and hosting diseases or insects (Warwick and Black 1983; Bendixon 1986). Johnsongrass has an upward growth habit and the reproductive ability can make this perennial grass an issue for growers (Anderson et al. 1960; Holm et al. 1977; McWhorter 1961). Johnsongrass can reach heights of 3.5 m, reproduce by both rhizomes and seeds, and has a prominent white midrib (Holm et al. 1977; Ingle and Rogers 1961; McWhorter 1971a; 1971b; Oyer et al. 1959). Talbot (1928) and Anderson et al. (1960) reported johnsongrass rhizomes produce new plants one year after development.

Johnsongrass is native to the Mediterranean region, specifically the political boundary between Syria and Turkey (Holm et al. 1977; Spencer 1974; Haragan 1991). Johnsongrass range has been expanded by environment (i.e. animals, wind, water), human (i.e. sowing as a forage), and mechanical means (i.e. combine harvester, cultivator). Current range of johnsongrass is from latitude 55° N to latitude 45° S, where it infests six continents, excluding Antarctica (Holm et al. 1977). Colder climate expansion is limited because of rhizome tolerance to freezing temperatures (Warwick and Black 1983). Information is limited on introduction into North America; however, McWhorter (1971a) reported johnsongrass was planted extensively as a forage in the 1830's. By 1975, johnsongrass was reported in 59 of the 64 parishes in Louisiana (Allen 1975).

The United States planted 5.95, 5.98, and 4.21 million ha of cotton in 2011, 2012, and 2013, respectively (Anonymous 2014). Bridges and Chandler (1987) reported full season competition of johnsongrass at densities of 1, 2, 4, 8, 16, and 32 plants 9.8 m^{-1} of row reduced average seed cotton yield 1, 4, 14, 40, 65, and 70% respectively. Furthermore, Keeley and Thullen (1989) found that competition between johnsongrass and cotton for 6, 9, 12, and 25 weeks after emergence reduced cotton yields 20, 60, 80 and 90%, respectively. Johnsongrass competition can also influence harvest efficiency. In Oklahoma, johnsongrass reduced stripper-harvest efficiency in cotton 0.3 and 0.6% per weed in 15 m of row in 1996-97 (Wood et al. 2002).

Controlling weeds in agronomic crops requires use of cultural, mechanical, and herbicidal weed control strategies in conjunction for effective control (Nalewaja 1999; Anderson 1996). Keeley and Thullen (1981) reported cultivation alone was not sufficient to prevent johnsongrass from impacting seed cotton yields. Crop rotations in conjunction with high herbicide rates or herbicides of different modes of action has been reported to control johnsongrass (Frans et al. 1991; Dale and Chandler 1979). Introduction of acetyl coenzyme A carboxylase (ACCase)- and acetolactate synthase (ALS)-inhibiting herbicides provided an effective postemergence (POST) option for control of johnsongrass in cotton and soybean (Banks and Tripp 1983; Tranel and Wright 2002). ACCase inhibiting herbicides inhibit the *de novo* fatty acid synthesis in susceptible monocots and ALS inhibiting herbicides inhibit the amino acid biosynthesis of leucine, isoleucine, and valine, requirements for cell growth (Ishikawa et al. 1985; Iwataki et al. 1979; Burgstahler et al. 1984, 1986; Hatzios 1982; Ray

1982a, 1982b, Rost 1984). Johnson et al. (1991) found that johnsongrass was controlled 70 to 90% when the ACCase-inhibiting herbicides clethodim, sethoxydim, fluazifop-P, haloxyfop, or quizalofop were applied POST as split applications in soybean. Likewise, Banks and Tripp (1983) found similar results when applying sequential applications of ACCase-inhibiting herbicides at lower rates when compared to a single application at a higher rate.

Following introduction of glyphosate, POST-directed applications of glyphosate controlled johnsongrass effectively in cotton (Banks and Santelmann 1977). Glyphosate inhibits 5-enolypruvyl-shikimate-3-phosphate synthase (EPSPS), which results in a reduction of essential amino acids tryptophan, tyrosine, and phenylalanine (Duke and Hoagland 1978; Lee 1980). Rope-wick applications of glyphosate to johnsongrass in cotton achieved a 78% reduction in shoots when compared to cultivation only (Keeley et al. 1984).

Introduction of glyphosate-resistant crops (GR) allowed POST broadcast applications of glyphosate to manage grass and broadleaf weeds without crop injury (Ateh and Harvey 1999; Delannay et al. 1995; Nelson and Renner 2013; Webster et al. 1999). Consequently, 82% of GR cotton in the U. S. was treated with glyphosate in 2005 (Xiu 2012). However, excessive use of a single mode of action for weed control has been the likely cause of documented resistance to that mode of action (Owen and Green 2011). Excessive use of glyphosate in Argentina, Arkansas, and Louisiana has led to the presence of glyphosate-resistant johnsongrass (Heap 2014; Johnson et al. 2014; Riar et al. 2011; Vila-Aiub et al. 2007). With the continued planting of GR cotton in the United States and the increasing number of GR weeds documented, review of weed control practices is needed to mitigate and manage GR weeds (Duke 2005; Dill 2005).

Glufosinate-resistant (GLR) cotton provided growers weed control options with glufosinate POST without injury to the cotton (Blair-Kerth et al. 2001). Glufosinate interrupts essential amino acid biosynthesis by inhibiting the glutamine synthetase enzyme, which is responsible for converting glutamate and ammonia to glutamine (Duke 1990). This inhibition causes a buildup of ammonia in susceptible plants that rapidly destroys cells and tissue (Tachibana 1986; Sauer 1987). Glufosinate alone and in mixtures provides broad-spectrum control of grass and broadleaf weeds (Corbett et al. 2004; Tharp et al. 1999; Everman et al. 2007). In GLR cotton, if more than 0.6 kg ha^{-1} of glufosinate is applied in any single application, the season total may not exceed 1.8 kg ha^{-1}, but if a rate between 0.6 and 0.9 kg ha^{-1} of glufosinate is applied as a single application, then the season total may not exceed 1.5 kg ha^{-1} (Anonymous 2014a); therefore, the maximum amount of glufosinate allowed in-crop can influence application rates and the number of applications available to a cotton producer during a growing season. This issue may influence johnsongrass management decisions for GLR cotton producers and little information is available pertaining to glufosinate rates and application timings for control of johnsongrass in GLR cotton. Therefore, the objective of this research was to evaluate number of glufosinate applications and timings for control of johnsongrass that is within federal labeling restrictions.

Materials and Methods

Field experiments were conducted 2011, 2012, and 2013 at Louisiana State University Agricultural Center Dean Lee Research and Extension Center near Alexandria, LA. Soil was a Coushatta silt loam (fine-silty, mixed, superactive, thermic Fluventic Eutrudepts) with a pH of 8.0 and 1.5% organic matter. An augmented factorial arranged in a randomized complete block design was used in all experiments. Treatment structure is given in Table 4.1. Factor one was either two or three total glufosinate (Liberty 280 SL, herbicide, Bayer CropScience LP 2 T.W. Alexander Drive Research Triangle Park, North Carolina 27709) applications, which dictated glufosinate rate for each treatment where 0.9 followed by (fb) 0.6 kg ha^{-1} was applied in two total applications treatments and a sequential application of glufosinate at 0.6 kg ha^{-1} was applied for the three total applications treatments. The second factor consisted of three timings for the initial glufosinate application (2, 3, or 4 wk after planting) and time between sequential applications (2 or 3 wk) was the third factor. Glufosinate rates (0.6 or 0.9 kg ha^{-1}) utilized in the experiments were based upon the season total limits of 1.5 and 1.8 kg ha^{-1} and the total number of applications allowed by the label (Anonymous 2014a)

Table 4.1. Herbicide treatments evaluated in 2011, 2012, and 2013.[a]

Herbicide	Application rate	Application timing
	kg ai ha^{-1}	wk after planting
Glufosinate fb glufosinate fb glufosinate	0.6 fb 0.6 fb 0.6	2 fb 4 fb 6
Glufosinate fb glufosinate	0.9 fb 0.6	2 fb 4
Glufosinate fb glufosinate fb glufosinate	0.6 fb 0.6 fb 0.6	3 fb 5 fb 7
Glufosinate fb glufosinate	0.9 fb 0.6	3 fb 5
Glufosinate fb glufosinate fb glufosinate	0.6 fb 0.6 fb 0.6	4 fb 6 fb 8
Glufosinate fb glufosinate	0.9 fb 0.6	4 fb 6
Glufosinate fb glufosinate fb glufosinate	0.6 fb 0.6 fb 0.6	2 fb 5 fb 7
Glufosinate fb glufosinate	0.9 fb 0.6	2 fb 5
Glufosinate fb glufosinate fb glufosinate	0.6 fb 0.6 fb 0.6	3 fb 6 fb 9
Glufosinate fb glufosinate	0.9 fb 0.6	3 fb 6
Glufosinate fb glufosinate fb glufosinate	0.6 fb 0.6 fb 0.6	4 fb 7 fb 10
Glufosinate fb glufosinate	0.9 fb 0.6	4 fb 7

[a] Abbreviations: fb, followed by

All treatments were applied with a tractor-mounted, compressed-air sprayer calibrated to deliver 187 L ha^{-1} at 145 kPa using Teejet 11002, flat fan nozzles (Spraying Systems Co., P.O. Box 7900 Wheaton, IL 60189). Plot size was 9 m long with four, 0.97 m rows. ‘Phytogen 375’, ‘Stoneville 5445’, and ‘Fibermax 1944’ glufosinate-resistant cotton were planted in 2011, 2012, and 2013, respectively. Cotton was planted at 102,800, 102,000, and 101,800 seeds ha^{-1} in 2011, 2012, and 2013, respectively. All studies were conducted using conventional-tillage methods and standard cotton production practices.

Cotton injury and johnsongrass control (0% no control to 100% complete control) were assessed 7, 14, and 21 days after the 10 WAP application and at harvest. Johnsongrass heights were determined by measuring five plants per plot 28 d after the 10 WAP application and at harvest. Prior to analysis, johnsongrass heights were converted to a percentage of the nontreated. Yield was determined by harvesting the center two rows of plots using conventional harvesting equipment. Johnsongrass densities in the nontreated plots averaged 200 plants m^{-2} prohibiting machine harvest of these plots, thus the nontreated yields were excluded from analysis. Seed cotton yields were adjusted to 40% lint turnout prior to analysis.

All data were subjected to analysis of variance using PROC GLIMMIX in SAS (release 9.3, SAS Institute, Cary, NC). Type III statistics were used to test all possible fixed effects (total glufosinate applications, initial and sequential glufosinate application timings) or interactions among the fixed effects. Random effects were years and replications nested within in years (Blouin et al. 2011). Considering year and replication an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Least square means were calculated and mean separated ($P \leq 0.05$) using Tukey's honest significant difference test. All data were subject to arcsine square root transformation to test for normality (Ahrens et al. 1990), but nontransformed means are presented. Discussion will focus on mean effects and two-way interactions for johnsongrass control and heights (% on nontreated), and cotton yield.

Results and Discussion

Cotton Injury. No cotton injury was observed following glufosinate applications regardless of rate, number of applications, or interval between sequential applications (data not shown, Appendix F). Similarly, Blair-Kerth et al. (2001) reported excellent tolerance of GLR cotton to applications of glufosinate. Gardner et al. (2006) reported no more than 2% injury on cotton following EPOST application of glufosinate and injury was not reported later in growing season. Data indicates that GLR cotton can tolerate glufosinate applications.

Rhizomatous Johnsongrass Control. Analysis indicated that the interactions between total glufosinate applications and initial application timing, total number of applications and time period between sequential applications, and initial application timing and time period between sequential applications were observed in johnsongrass control 7 DAT (Table 4.2). Regardless of initial glufosinate application timing, johnsongrass control 7 DAT was equivalent (93 to 95%) when sequential glufosinate applications were applied 2 wk apart (Table 4.3). However, when the sequential glufosinate applications were applied 3 wk apart, johnsongrass control was 83% and less than when sequential applications were made either 2 or 4 wk apart (92% control). Furthermore, averaged across sequential glufosinate application timing, all treatments controlled johnsongrass >90% except three glufosinate applications initiated 3 WAP (83%) 7 DAT (Table 4.4). In addition, averaged across initial glufosinate application timings, 86% johnsongrass control was observed following three glufosinate applications applied sequentially 3 wk apart, which was less that all other treatments that provided 92 to 95% control of johnsongrass (Table 4.5). Differences in control when three glufosinate applications were applied initially 3 WAP followed by sequential applications 3 wk apart may be due to 0.66 cm of rainfall that occurred 2 hr following the 10 WAP application in 2013. Glufosinate efficacy is directly related to

Table 4.2. Significance of the main effects of initial glufosinate application rate, sequential glufosinate application rate, and total glufosinate applications and interactions among main effects pooled across environments for johnsongrass control and height at each evaluation date and seed cotton yield.[a,b]

Parameter	Data collection	APP	IAPP	SAPP	APPxIAPP	APPxSAPP	IAPPxSAPP	APPxIAPPxSAPP
		---------- P-value ----------						
Johnsongrass control	7 DAT	0.0440	0.0005	<0.0001	<0.0001	0.0089	<0.0001	<0.0001
	14 DAT	0.0039	0.2191	0.1830	0.2444	0.0360	0.2959	0.0334
	21 DAT	<0.0001	0.4935	0.4157	0.1998	0.0002	0.5205	0.0378
	Harvest	<0.0001	0.8171	0.4974	0.4559	0.5072	0.9214	0.2443
Johnsongrass heights	28 DAT	0.0006	0.0884	0.3377	0.0199	0.5535	0.0042	<0.0001
	Harvest	<0.0001	0.4697	0.7661	0.4508	0.5335	0.2953	0.2007
Cotton lint yield		<0.0001	0.0118	0.0588	0.0022	0.6099	0.0462	0.0211

[a] Abbreviations: APP, total glufosinate applications; DAT, d after treatment; IAPP, initial glufosinate application timing; SAPP, sequential glufosinate application timing.
[b] Main effects and interactions considered significant for Type III error if $P \leq 0.05$.

Table 4.3. Johnsongrass control as influenced by initial glufosinate application timing and sequential glufosinate application timing 7 DAT in 2011, 2012, and 2013.[a,b]

IAPP	2 SAPP	3 SAPP
	-------------------%	-------------------
2	95 a	92 a
3	95 a	83 b
4	93 a	92 a

[a] Abbreviations: DAT, d after treatment; IAPP, initial glufosinate application timing; SAPP, sequential glufosinate application timing
[b] Data pooled over total glufosinate applications. Means followed by the same letter are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Table 4.4. Johnsongrass control as influenced by total glufosinate applications and initial application timing 7 DAT in 2011, 2012, and 2013.[a,b]

APP	2 IAPP	3 IAPP	4 IAPP
	-------------	--------------%--------------	-------------
2	92 a	95 a	93 a
3	96 a	83 b	93 a

[a] Abbreviations: APP, total glufosinate applications; DAT, d after treatment; IAPP, initial glufosinate application timing.
[b] Data pooled over initial glufosinate application timing. Means followed by the same letter are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Table 4.5. Johnsongrass control as influenced by total glufosinate applications and sequential application timing 7, 14, and 21 DAT in 2011, 2012, and 2013.[a,b]

	7 DAT		14 DAT		21 DAT	
APP	2 SAPP	3 SAPP	2 SAPP	3 SAPP	2 SAPP	3 SAPP
	----------	----------	----------	%----------	----------	----------
2	95 a	92 a	92 a	86 b	83 b	74 c
3	92 a	86 b	93 a	94 a	87 ab	94 a

[a] Abbreviations: APP, total glufosinate applications; DAT, d after treatment; SAPP, sequential glufosinate application timing
[b] Data pooled over initial glufosinate application timing. Means followed by the same letter within each rating date are not significantly different based on Tukey's HSD at $P \leq 0.05$.

environmental conditions and the glufosinate label requires a rain free period of 4 hours after application for maximum efficacy (Anonymous 2014a). Everman (2005) reported differential response of weeds to glufosinate following different rain free periods, where maximum efficacy was observed on goosegrass [*Eleusine indica* (L.) Gaertn) and Palmer amaranth (*Amaranthus palmeri* L.) following a 1 and 24 hr rain free period, respectively. In addition to the rain fall shortly after application, cooler temperature associated with cloud cover following the 10 WAP application in 2013 could have attributed to the observed decrease in johnsongrass control.

For johnsongrass control 14 and 21 DAT, the interactions of total number of applications and initial application timing or timing of initial application and timing of sequential applications were not significant (Table 4.2). Averaged across initial glufosinate application timing, johnsongrass control 14 DAT was equivalent and at least 92% when the sequential applications were made 2 wk apart but when sequential applications were made 3 wk apart control was greatest for sequential applications 3 wk compared with 2 wk apart (94% vs 86%) (Table 4.5). This same response was also noted 21 DAT where control for 2 or 3 applications with sequential applications made 2 wk apart were equivalent and averaged 85%. Where sequential applications were made 3 wk apart johnsongrass control was 94% for 3 glufosinate applications compared with 74% for 2 applications. At harvest, johnsongrass control was affected by only the number of total glufosinate applications and control was 89% following 3 glufosinate applications and greater than 2 applications (67%) (data not shown, Appendix F).

Rhizomatous Johnsongrass Heights. Analysis indicated that the interactions of total glufosinate applications and initial glufosinate application timing and the initial and sequential glufosinate application timings, as well as the main effect of total glufosinate applications were significant for johnsongrass heights as a percent of the nontreated (Table 4.2) Averaged across sequential glufosinate application timing, johnsongrass heights were 24% of the nontreated 28 DAT following the first of three glufosinate applications that was applied 4 WAP, which was greater than all other treatments except when the first of three total glufosinate applications were initiated 2 WAP (47%) (Table 4.6). No differences for reduction in johnsongrass heights as a percent of the nontreated was observed among other treatments (47 to 82% reduction). In addition, regardless of the total glufosinate applications, applying the initial glufosinate application 3 WAP following by sequential application(s) 3 wk apart reduced johnsongrass height to only 91% of the nontreated 28 DAT (Table 4.7). Differences observed in heights where the initial application is applied 3 WAP followed by sequential application(s) 3 wk apart or where 3 total glufosinate applications initialized 3 WAP could be attributed to the 0.66 cm rainfall that occurred 2 hours following the 10 WAP application in 2013. All other treatments reduced johnsongrass heights 50 to 78% of the nontreated. At harvest, johnsongrass heights was reduced more following three glufosinate applications (33%) than 2 applications (87%) (data not shown, Appendix G).

Table 4.6. Johnsongrass heights (percent of the nontreated) as influenced by total glufosinate applications and initial application timing 28 DAT in 2011, 2012, and 2013.[a,b]

APP	2 IAPP	3 IAPP	4 IAPP
	--------------------	%	--------------------
2	82 a	72 a	78 a
3	47 ab	74 a	24 b

[a] Abbreviations: APP, total glufosinate applications; DAT, d after treatment; IAPP, initial glufosinate application timing.
[b] Data pooled over initial glufosinate application timing. Means followed by the same letter are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Cotton Lint Yield. The interactions of total glufosinate applications and initial glufosinate application timing and initial glufosinate application timing and sequential application timing were significant for cotton lint yield (Table 4.2). When 3 applications of glufosinate were made with the initial application made 2 or 3 WAP cotton lint yield was greater when compared with 2 total applications (78 and 49%, respectively) (Table 4.7).

Table 4.7. Johnsongrass heights (percent of the nontreated) as influenced by initial application timing and sequential application timing 28 DAT in 2011, 2012, and 2013.[a,b]

IAPP	2 SAPP	3 SAPP
	--------------------%--------------------	
2	78 ab	52 b
3	50 b	91 a
4	50 b	53 ab

[a] Abbreviations: DAT, d after treatment; IAPP, initial glufosinate application timing; SAPP, sequential glufosinate application timing.
[b] Data pooled across total glufosinate applications. Means followed by the same letter are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Cotton lint yield; however, for 2 or 3 glufosinate applications with the initial applications made 4 WAP was equivalent (average of 917 kg ha^{-1}). Cotton lint yield was similar when the initial application for two glufosinate applications was applied 4 WAP and all treatments that received three glufosinate applications (Table 4.8). Averaged across total glufosinate applications, no yield differences were detected when initial application was 4 WAP regardless of sequential glufosinate application timing (909 and 923 kg ha^{-1}) or initial timing at 3 WAP and timing of sequential is 3 wk after initial (1020 kg ha^{-1}) (Table 4.9). Furthermore, cotton yields were not different when initial glufosinate application timing was 2 or 4 WAP regardless of sequential application timing and initial application timing was 3 WAP and sequential was timed 2 wk later (751 to 923 kg ha^{-1}) (Table 4.9).

Table 4.8. Cotton lint yield as influenced by total glufosinate applications and initial application timing in 2011, 2012, and 2013.[a,b]

APP	2 IAPP	3 IAPP	4 IAPP
		----------kg ha^{-1}----------	
2	549 c	719 bc	888 ab
3	976 a	1070 a	944 ab

[a] Abbreviations: APP, total glufosinate applications; IAPP, initial glufosinate application timing.
[b] Data pooled across sequential glufosinate application timing. Means followed by the same letter are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Table 4.9. Cotton lint yield as influenced by initial glufosinate application timing and sequential glufosinate application timing in 2011, 2012, and 2013.[a,b]

IAPP	2 SAPP	3 SAPP
	------------------------------kg ha^{-1}	----------------------------
2	751 b	770 b
3	775 b	1020 a
4	923 ab	909 ab

[a] Abbreviations: IAPP, initial glufosinate application timing; SAPP, sequential glufosinate application timing.
[b] Data pooled across total glufosinate applications. Means followed by the same letter are not significantly different based on Tukey's HSD at $P \leq 0.05$.

Results show that rhizomatous johnsongrass in GLR cotton can be effectively controlled with sequential applications of glufosinate. Johnsongrass control was maximized when three glufosinate applications rather than two were made 3 wk apart rather than 2 wk apart. In regard to initial application timing (2, 3, or 4 WAP) this variable was of importance as an interacting factor at 7 DAT but not at 14, 21 DAT or at harvest. Similarly, paired with johnsongrass control, the greatest reduction in johnsongrass heights as a percent of the nontreated was observed following three glufosinate applications that were initiated 4 WAP. Initiating treatments 4 WAP resulted in greatest johnsongrass control and greatest reduction in johnsongrass heights, additionally, cotton lint yield was maximized following two glufosinate applications when the first application was applied 4 WAP or following three glufosinate applications regardless of application timing. In regard to cotton lint yield, yield was maximized when glufosinate was applied three times with initial application made 2 or 3 WAP. If the initial application is delayed until 4 WAP two glufosinate applications were as effective as three in maximizing cotton lint yield. It is also important that sequential applications of glufosinate be made 3 to 4 wks apart rather than 2. Sequential applications of glufosinate can be effective in managing rhizomatous johnsongrass in GLR cotton.

Literature Cited

Ahrens WH, Cox DJ, Budhwar G (1990) Use of the arcsine and square root transformations for subjectively determined percentage data. Weed Sci 38:452-458.

Allen CM (1975) Grasses of Louisiana. Lafayette, LA: Univ of SW Louisiana. 276 p.

Anderson LE, Appleby AP, Weseloh JW (1960) Characteristics of johnsongrass rhizomes. Weeds 8:402-406.

Anderson WP (1996) Weed Science Principles and Applications. 3rd edn. West Publ. Co. St. Paul, MN. Pp. 43-51.

Anonymous (2014a) Liberty 280 SL herbicide product label. Bayer Crop Science Publication. Research Triangle Park, NC: Bayer Crop Science. 21 p.

Anonymous (2014) USDA-NASS. National statistics for cotton http://www.nass.usda.gov/Statistics_by_Subject/result.php?9705D5AE-AC07-3712 B0A1-FF3D5A7519C8&sector=CROPS&group=FIELD%20CROPS&comm=COTTON. Accessed September 23, 2014.

Ateh CM, Harvey RG (1999) Annual weed control by glyphosate in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:394-398.

Banks PA, Santelmann PW (1977) Glyphosate as a postemergence treatment for johnsongrass control in cotton and soybeans. Agro. Journ. 69:579-582.

Banks PA, Tripp TN (1983) Control of johnsongrass (*Sorghum halepense*) in soybeans (*Glycine max*) with foliar-applied herbicides. Weed Sci 31:628-633.

Bendixon LE (1986) Corn (*Zea mays*) yield in relationship to johnsongrass (*Sorghum halepense*) population. Weed Sci 34:449-451.

Blair-Kerth LK, Dotray PA, Keeling JW, Gannaway JR, Oliver MJ, Quisenberry JE (2001) Tolerance of transformed cotton to glufosinate Weed Sci. 49:375-380.

Bridges DC, Chandler JM (1987) Influence of johnsongrass (*Sorghum halepense*) density and period of competition on cotton yield. Weed Sci 35:63-67.

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol. 25:165-169.

Burgstahler RJ, Lichtenthaler HK (1984) Inhibition by sethoxydim of phospho- and galactolipid accumulation in maize seedlings. *In* PA Siegenthaler, W Eichenberger, eds, Structure, Function and Metabolism of Plant Lipids. Elsevier, New York, p. 619-623.

Burgstahler RJ, Retzlaff G, Lichtenthaler HK (1986) Mode of action of sethoxydim: effects on the plant's lipid metabolism. Abstracts of the Sixth International Congress of Pesticide Chemistry, Ottawa, p 3B-11.

Carmer SG, Nyquist WE, Walker WM (1989) Least significant differences in combined analyses of experiments with two- or three-factor treatment designs. Agron J 81:655-672.

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, sulfosate. Weed Technol. 18:443-453.

Dale JE, Chandler JM (1979) Herbicide-crop rotation for johnsongrass (*Sorghum halepense*) control. Weed Sci 27:479-485.

Delannay X, Bauman TT, Beighley DH, Buettner MJ, Coble HD, DeFelice MS, Derting CW, Diedrick TJ, Griffin JL, Hagood ES, Hancock FG, Hart SE, LaVallee BJ, Loux MM, Lueschen WE, Matson KW, Moots CK, Murdock E, Nickell AD, Owen MDK, Paschal II EH, Prochaska LM, Raymond PJ, Reynolds DB, Rhodes WK, Roeth FW, Sprankle PL, Tarochione LJ, Tinius CN, Walker RH, Wax LM, Weigelt HD, Padgette SR (1995) Yield evaluation of a glyphosate- tolerant soybean line after treatment with glyphosate. Crop Sci 35:1461-1467.

Dill GM (2005) Glyphosate-resistant crops: history, status and future. Pest Manage Sci 61:219-224.

Duke SO, Hoagland RE (1978) Effects of glyphosate on metabolism of phenolic compounds. 1. Induction of phenylalanine ammonia-lyase activity in darkgrown maize roots. Plant Sci Lett 11:185-190.

Duke SO (1990) Overview of herbicide mechanisms of action. Environ Health Perspect 87:263-271.

Duke SO (2005) Taking stock of herbicide-resistant crops ten years after introduction. Pest Mgmt Sci 61:211-218.

Everman WJ, (2007) Influence of environmental and physiological factors on glufosinate and glyphosate weed management. Ph.D dissertation. Raleigh, NC: North Carolina State University. 208 p http://www.lib.ncsu.edu/resolver/1840.16/4809. Accessed: October 1, 2014.

Everman WJ, Burke IC, Allen JR, Collins J, Wilcut JW (2007) Weed control and yield with glufosinate-resistant cotton weed management systems Weed Technol 21:695-701.

Frans RE, McClelland MR, Horton DK, Corbin, Jr. BR, Talbert RE (1991) Crop and herbicide rotations for johnsongrass (*Sorghum halepense*) control. Weed Sci 39:660-666.

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

Haragan PD (1991) Weeds of Kentucky and adjacent states. The Univ. Press of Kentucky. Pp 194-195.

Hatzios KK (1982) Effects of sethoxydim on the metabolism of isolated leaf cells of soybean [*Glycine max* (L.) Merr.].Plant Cell Rep 1:87-90.

Heap I. The International Survey of Herbicide Resistant Weeds. Online. Internet. September 8, 2014. Available www.weedscience.com.

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The world's worst weeds distribution and biology. Honolulu, HI: The University Press of Hawaii. Pp 54-61.

Ingle M, Rogers BJ (1961) The growth of mid-western strain of *Sorghum halepense* under controlled conditions. Amer J Bot 48:392-396.

Ishikawa H, Yamada S, Hosaka H, Kawana T, Okunuki S, Kohara K (1985) Herbicidal properties of sethoxydim for the control of gramineous weeds. J Pestic Sci 10:187-193.

Iwataki I, Hirono Y, (1979) The chemical and herbicidal activity of alloxydim-sodium and related compounds. *In* H Geissbuhler, ed, Advances in Pesticide Science, Fourth International Congress on Pesticide Chemicals. Permagon Press, Oxford, p 235-243.

Johnson DB, Norsworthy JK (2014). Johnsongrass (*Sorghum halepense*) management as influenced by herbicide selection and application timing Weed Technol. 28:142-150.

Johnson DB, Norsworthy JK, Scott RC (2014). Distribution of herbicide-resistant johnsongrass (*Sorghum halepense*) in Arkansas. Weed Technol 28:111-121.

Johnson WG, Frans RE, Parsch LD (1991) Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence herbicides. Weed Technol 5:87-91.

Keeley PE, Thullen RJ (1981) Control and competitiveness of johnsongrass (*Sorghum halepense*) in cotton (*Gossypium hirsutum*). Weed Sci 29:356-359.

Keeley PE, Thullen RJ (1989) Growth and interaction of johnsongrass (*Sorghum halepense*) with cotton (*Gossypium hirsutum*). Weed Sci 37:339-344.

Keeley PE, Thullen RJ, Carter CH, Miller JH (1984) Control of johnsongrass (*Sorghum halepense*) in cotton (*Gossypium hirsutum*) with glyphosate Weed Sci 32:306-309.

Lee TT (1980) Characteristics of glyphosate inhibition of growth in soybean and tobacco callus cultures. Weed Res. 20:365-369.

McWhorter CG (1961) Morphology and development of johnsongrass plants from seeds and rhizomes. Weeds 9:558-562.

McWhorter CG (1971a) Anatomy of johnsongrass. Weed Sci 19:385-393.

McWhorter CG (1971b) Growth and development of johnsongrass ecotypes. Weed Sci 19:141-147.

McWhorter CG (1993) A 16 year survey on levels of johnsongrass (*Sorghum halepense*) in Arkansas, Louisiana, and Mississippi. Weed Sci 41:669-677.

Nalewaja JD (1999) Cultural practices for weed resistance management. Weed Technol 13:643-646.

Nelson KA, Renner KA (2013) Weed management in wide- and narrow- row glyphosate resistant soybean. Journal of Prod Ag 12:460-465.

Owen MDK, Green JM (2011) Herbicide resistant crops: utilities and limitations for herbicide resistant weed management. Agri Food Chem 59:5819-5829.

Oyer EB, Gries GA, Rogers BJ (1959) The seasonal development of johnsongrass plants. Weeds 7:13-19.

Ray TB (1982a) The mode of action of chlorisulfuron: a new herbicide for cereals. Pestic Biochem Physiol 17:10-17.

Ray TB (1982b) The mode of action of chlorisulfuron: the lack of direct inhibition of plant DNA synthesis. Pestic Biochem Physiol 18:262-266.

Riar DS, Norsworthy JK, Johnson DB, Scott RC, Bagavathiannan M (2011) Glyphosate resistance in a johnsongrass (*Sorghum halepense*) biotype from Arkansas. Weed Sci 59:299-304.

Rost TL (1984) The comparative cell cycle and metabolic effects of chemical treatments on root tip meristems. III. Chlorisulfuron. J Plant Growth Reg 3:51-63.

Sauer H, Wild A, Rühle W (1987) The effect of phosphinothricin (glufosinate) on photosynthesis—II. The causes of inhibition of photosynthesis. Z Naturforsch 42c (Biosciences 42): 270–278.

Spencer ER (1974) All About Weeds. New York, NY: Dover Publications. Pp 24-27.

Tachibana K, Watanabe T, Sekizuwa Y, Takematsu T (1986) Accumulation of ammonia in plants treated with bialaphos Journal of Pest Sci 11:33-37.

Tharp BE, Schabenberger O, Kells JJ (1999) Response of annual weed species to glufosiante and glyphosate Weed Technol. 13:542-547.

Talbot MW (1928) Johnsongrass as a weed. U.S. Dept Agr Farmer's Bul 1537.

Tranel PJ, Wright TR (2002) Resistance of weeds to ALS-inhibiting herbicides: What have we learned? Weed Sci 50:700-712.

Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CB, Powles SB (2007) Evolution of glyphosate-resistant johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. Weed Sci 55:566-571.

Warwick SI, Black LD (1983) The biology of Canadian weeds. 61.*Sorghum halepense* (L.)Pers. Can J Plant Sci 63:997-1014.

Webster EP, Bryant KJ, Earnest LD (1999) Weed control and economics in nontransgenic and glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:586-593.

Wood ML, Murray DS, Banks JC, Verhalen LM, Westerman RB, Anderson KB (2002) Johnsongrass (*Sorghum halepense*) density effects on cotton (*Gossypium hirsutum*) harvest and economic value. Weed Technol 16:495-501.

Xiu Y (2012) National Agricultural Statistics Service (NASS): *Agricultural Chemical Use Database*. http://www.pestmanagement.info/nass/ Accessed August 16, 2012.

CHAPTER 5
SUMMARY

Experiments were conducted over three years near Alexandria, LA on a Coushatta silt loam soil to determine glufosinate rates and timings to control rhizomatous johnsongrass [*Sorghum halepense* (L.) Pers.] in soybean [*Glycine max* (L.) Merr.]. Treatments include glufosinate applied at 0.5, 0.6, and 0.7 kg ai ha^{-1} to 46 cm johnsongrass, followed by (fb) sequential applications of 0.5 or 0.6 kg ha^{-1} timed either 3 or 4 wk after initial. Data indicate the applying glufosinate at 0.7 kg ha^{-1} followed by (fb) a sequential application of 0.6 kg ha^{-1} 4 wk after the initial application provided the greatest johnsongrass control and reduction in johnsongrass height throughout the season. Johnsongrass heights at harvest were reduced more when a sequential rate of glufosinate is applied at 0.6 kg ha^{-1} compared to 0.5 kg ha^{-1}. Soybean yields were maximized following the sequential application of 0.6 kg ha^{-1} followed by the 0.5 kg ha^{-1} of glufosinate, but the sequential application timing of 3 or 4 wk after the initial application did not influence soybean yield. Data confirms that glufosinate rates and timings are a good control option for rhizomatous johnsongrass.

Further experiments were conducted for two years near Alexandria, LA on a Coushatta silt loam soil to determine the control of rhizome johnsongrass using a sequence of chlorimuron, clethodim, and fomesafen in soybean. All treatments include chlorimuron at 9 g ai ha^{-1}, clethodim at 140 g ai ha^{-1}, and fomesafen at 260 g ai ha^{-1}. Applications include early-postemergence (EPOST), mid-postemergence (MPOST), and late-postemergence (LPOST), which corresponded to two-, five-, and eight- trifoliate soybean, respectively. Glufosinate was added as a comparison treatment at 450 g ai ha^{-1} applied at all three application timings. Data indicated that glufosinate applied sequentially is comparable in control where clethodim treatments were applied EPOST regardless of sequence of chlorimuron and fomesafen 35 DA LPOST. Furthermore, johnsongrass control at harvest was highest with glufosinate applied sequentially and clethodim fb chlorimuron fb fomesafen. No difference in johnsongrass heights was detected between treatments at harvest. Soybean yields are similar to sequential applications of glufosinate when clethodim is applied LPOST. Data suggests treatments where clethodim is applied EPOST is a good control option for control of johnsongrass and is comparable to sequentially applied glufosinate.

Trials were conducted for three years on Coushatta silt loam soil near Alexandria, LA to assess johnsongrass control with glufosinate rate and timing in cotton (*Gossypium hirsutum* (L.)). Treatments include 2 applications of glufosinate at 0.9 fb 0.6 kg ai ha^{-1} or 3 applications of glufosinate at 0.6 kg ha^{-1} fb 0.6 kg ha^{-1} fb 0.6 kg ha^{-1}, treatments were initiated 2, 3, or 4 wk after planting (WAP), sequentials were applied 2 or 3 wk after initial glufosinate application. Data indicates that timing of initial and sequential glufosinate applications is effective for control of rhizomatous johnsongrass. Environmental factors affected glufosinate applications made 10 WAP, research was unable to precisely determine the proper timing of the initial glufosinate application, however, data indicates that initial applications 2 to 4 WAP provided the greatest control of johnsongrass. Similarly, in conjunction with greatest johnsongrass control, the greatest reduction in johnsongrass heights as a percent of the nontreated was observed following three glufosinate applications that were initiated 4 WAP. Initiating treatments 4 WAP resulted in greatest johnsongrass control and greatest reduction in johnsongrass heights, additionally, cotton lint yield was maximized following two glufosinate applications when the first application was applied 4 WAP or following three glufosinate applications regardless of application timing. Furthermore, yields were greater when timing the sequential application 3 wk after initial and initial is 3 or 4 WAP or when sequential applications are timed 2 wk after the initial and initial is 4 WAP. Data confirms that sequential applications of glufosinate is an effective tool for managing rhizomatous johnsongrass in cotton.

In conclusion, applying glufosinate sequentially is a good option to control rhizome johnsongrass in soybean, but timing and rate are important factors to consider. However, when non-selective herbicides are not used, clethodim applied EPOST was comparable in control at harvest with sequentially applied glufosinate. Additionally, when growers are considering herbicides for control of johnsongrass, chlorimuron and fomesafen will not provide an increase in control in sequences with clethodim. Applying glufosinate in cotton is a good option to control rhizome johnsongrass, but total applications and timing are important factors for control. Three glufosinate applications applied 3 wk apart with the initial application 4 WAP resulted in greatest control and reduction in johnsongrass heights while maximizing cotton yield.

Data indicates applying glufosinate sequentially can provide good control of rhizome johnsongrass in cotton and soybean. Furthermore, producers have options to control rhizome johnsongrass when managing for glyphosate-resistance. However, more research is needed combining more modes of action with glufosinate to effectively manage rhizome johnsongrass and mitigate weed resistance issues.

APPENDIX

Appendix A. Johnsongrass control 14 DAT as influenced by height and glufosinate rate.[a,b]

Johnsongrass height	0.5 kg ha^{-1}	0.6 kg ha^{-1}	0.7 kg ha^{-1}
		---------------------------%--------------------------	
15 cm	53 c	58 bc	69 abc
31 cm	45 c	48 c	57 bc
46 cm	88 ab	92 a	96 a

[a] Abbreviations: DAT, d after treatment
[b] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05.

Appendix B: Soybean injury as influenced by initial glufosinate application rate, sequential glufosinate application rate, and sequential glufosinate application timing.[a,b]

Data Collection	Injury
	---------------------------%--------------------------
20 DAT	0 a
28 DAT	0 a
Harvest	0 a

[a] Abbreviations: DAT, d after treatment
[b] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05

Appendix C: Johnsongrass control and soybean yield as influenced by sequential timing.[a,b]

	Johnsongrass control 20 DAT	Soybean yield
Sequential timing	------------------%---------------	kg ha^{-1}
3 WAT	83 a	2555 a
4 WAT	82 a	2421 a

[a] Abbreviations: DAT, d after treatment; WAT, weeks after treatment
[b] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05

Appendix D. Johnsongrass heights (% of nontreated) 28 DAT as influenced by initial glufosinate rate.[a,b]

Data collection	0.5 kg ha^{-1}	0.6 kg ha^{-1}	0.7 kg ha^{-1}
		---------------------------%--------------------------	
28 DAT	47 a	41 a	38 a

[a] Abbreviations: DAT, d after treatment
[b] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05.

Appendix E: Soybean injury as influenced by sequences of clethodim, fomesafen, and chlorimuron 10 DAT in 2011 and 2012.[a,b]

	Soybean injury	
Year	------------------------------------%------------------------------------	
2011	0 a	0 a
2012	0 a	0 a

[a] Abbreviations: DAT, d after treatment;

[b] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05

Appendix F: Cotton injury as influenced by total number of glufosinate applications, timing of initial glufosinate application, and timing of sequential glufosinate application 10 DAT in 2011, 2012, and 2013.[a,b]

	Soybean injury	
Year	------------------------------------%------------------------------------	
2011	0 a	0 a
2012	0 a	0 a
2013	0 a	0 a

[a] Abbreviations: DAT, d after treatment;

[b] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05

Appendix G: Johnsongrass control and cotton lint yield as influenced by total number of glufosinate applications.[a]

	Johnsongrass control At harvest	Johnsongrass height % of nontreated	Cotton lint yield
Total number of applications	------------------%---------------		kg ha^{-1}
2	89 a	87 b	997 a
3	67 b	33 a	719 b

[a] Means followed by the same letter are not significantly different based on Tukey's HSD at P ≤ 0.05

VITA

Randall Lee Landry was born and raised in west Vernon Parish in a small town. Farming was not a way of life for him or his family, yet still had an interest in agriculture. He attended elementary and high school at Pitkin High School in Pitkin. After high school graduation in 2003, he had plans to pursue a degree in biology. As his college career progressed at Louisiana State University in Alexandria (LSUA), the degree he sought had changed to focus more on biological research. He had studied under Dr. Carol Corbat, Professor and Department Chair of Biological Sciences, in a senior research project mapping and trying to pinpoint competitiveness of an invasive dove on an indigenous dove in central Louisiana; this persuaded him to pursue a career in research. He enrolled in the School of Plant, Environmental, and Soil Sciences under the direction of Drs. Daniel O. Stephenson, IV. and James L. Griffin in 2011 and is currently a candidate for the Master of Science degree with a focus in Weed Science. Randall is currently a Research Associate in Weed Science for Dr. Daniel O. Stephenson, IV with the Louisiana State University Agricultural Center.