Mississippi State University

Scholars Junction

Theses and Dissertations Theses and Dissertations

8-7-2010

Assessing long-term viability of glyphosate-resistant technology as a foundation for cropping systems

Jason Wade Weirich

Follow this and additional works at: https://scholarsjunction.msstate.edu/td

Recommended Citation

Weirich, Jason Wade, "Assessing long-term viability of glyphosate-resistant technology as a foundation for cropping systems" (2010). *Theses and Dissertations*. 747.
https://scholarsjunction.msstate.edu/td/747

This Graduate Thesis - Open Access is brought to you for free and open access by the Theses and Dissertations at Scholars Junction. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Scholars Junction. For more information, please contact scholcomm@msstate.libanswers.com.

ASSESSING LONG-TERM VIABILITY OF GLYPHOSATE-RESISTANT TECHNOLOGY AS A FOUNDATION FOR CROPPING SYSTEMS

By

Jason Wade Weirich

A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Weed Science
in the Department of Pant and Soil Sciences

Mississippi State, Mississippi

August 2010

ASSESSING LONG-TERM VIABILITY OF GLYPHOSATE-RESISTANT

TECHNOLOGY AS A FOUNDATION FOR CROPPING SYSTEMS

By

Jason Wade Weirich

Approved:

David R. Shaw
Giles Distinguished Professor of
Weed Science
(Major Professor and Director of
Dissertation)

Gregory Ibendahl
Associate Extension Professor of
Agriculture Economics
(Minor Professor)

Daniel B. Reynolds
Endowed Chair of Agronomy
Professor of Weed Science
(Committee Member)

John D. Byrd Jr.
Extension/Research
Professor of Weed Science
(Committee Member)

Gary N. Ervin
Associate Professor of
Biological Sciences
(Committee Member)

William L. Kingery
Professor of Agronomy
Graduate Coordinator

Melissa J. Mixon
Interim Dean of the College of
Agriculture and Life Sciences

Name: Jason Wade Weirich

Date of Degree: August 7, 2010

Institution: Mississippi State University

Major Field: Weed Science

Major Professor: Dr. David R. Shaw

Title of Study: ASSESSING LONG-TERM VIABILITY OF GLYPHOSATE-RESISTANT TECHNOLOGY AS A FOUNDATION FOR CROPPING SYSTEMS

Pages in Study: 50

Candidate for Degree of Doctor of Philosophy

The introduction of glyphosate-resistant (GR) crops in the late 1990s changed the way producers used herbicides to control weeds. Since the introduction of GR crops producers have relied on glyphosate alone for weed control instead of utilizing multiple modes of action for weed control. This over-reliance resulted in several weed species developing resistance to glyphosate. This has resulted in organizations from the public and private sector questioning the sustainability of GR cropping systems.

Researchers from Illinois, Indiana, Iowa, Mississippi, Nebraska, and North Carolina established 156 on-farm trials to determine the sustainability of GR cropping systems. The objectives of this study were: to determine the economics of a university weed resistance best management practice (BMP) versus a producers' normal production practice; to evaluate when a producer that is risk neutral (profit maximizing) or risk averse should adopt a weed resistance BMP; and to compare the influences of using a university weed resistance BMP to a producer's normal production practice on the 27 most common weed species in Mississippi. In all instances, the university weed resistance BMP utilized multiple modes of action in conjunction with glyphosate.

A university weed resistance BMP can provide the same level of control on 27 of the most common weeds in Mississippi that a producer has become accustomed to with a glyphosate alone system, while delaying or controlling GR weeds. A university weed resistance BMP resulted in an increase in weed control cost, but similar yields and economic returns when compared to a producer's normal production practice. Rotating a GR crop with a different GR crop resulted in higher economic returns when compared to a continuous GR cropping system or a GR crop followed by a non-GR crop rotation. Producers are often reluctant to adopt a weed resistance BMP because of the perceived increased cost for weed control. A risk neutral or risk averse producer should adopt a weed resistance BMP and feel confident that their decision will provide weed control equivalent to a glyphosate alone weed control program before resistance developed, delay or control GR weeds and be economically sound.

DEDICATION

I would like to dedicate this work to my wife, Megan, our son John Wayne, Wayne and Barbara Weirich, Gilbert and Kay Brown, and Jerry and Pam Weirich. Megan's willingness to move to Mississippi while I continued my education was a big commitment and I am thankful that she did. It has been a journey that we will never forget. The countless hours spent hand weeding sandburs, hoeing devil claw and pigweeds, and peaceful time spent in the cab of a tractor while growing up inspired me to become a weed scientist. Without all of your guidance I would not be where I am today.

ACKNOWLEDGEMENTS

The author expresses his appreciation to the many people who assisted in conducting this research. Special thanks go to my major advisor, Dr. David R. Shaw, for his constructive criticism and instruction throughout the course of my research. Appreciation also extends to Dr. Daniel B. Reynolds, Dr. John D. Byrd, Dr. Gregory Ibendahl, and Dr. Gary Ervin for expending time and effort as members of my graduate committee. In addition to my graduate committee, I want to thank Dr. Keith H. Coble, Dr. Jeffery L. Willers, Dr. Darrin M. Dodds, Dr. Jonathan Huff and Wade Givens for their help and advice during my studies at Mississippi State University. I would like to thank the Monsanto Company for funding this research. Many thanks go to the numerous student workers who helped with collection of data and the many hours we spent soil sampling.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Glyphosate is a broad spectrum herbicide that controls many annual and perennial weeds. Glyphosate was introduced in the early 1970s.[1] Glyphosate inhibits the growth of plants by affecting aromatic amino acid biosynthesis through the inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS; 2.5.1.19) of the shikimate pathway.[2,3] The introduction of glyphosate resistant (GR) corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* L. (Merr.)] in the 1990s provided farmers with a simple, broad-spectrum weed control option.[4,5] Glyphosate is foliar-applied and is used for both burndown and postemergence applications in GR crops.[6] In 2009, GR corn, cotton, and soybean were planted in the United States on 68, 71, and 91% of planted hectares, respectively.[7] The introduction of GR crops transformed the way many producers managed their weeds. Producers chose GR crops because glyphosate made weed control easier and more effective, provided little to no crop injury, increased profit, required less tillage, and did not restrict crop rotations. Since the introduction of GR crops, the use of tank mixtures and sequential applications of more than one family of herbicides has decreased, as many producers now rely only on glyphosate for weed control.[8] Since glyphosate has no residual activity, several applications are typically made each year to provide season-long weed control. This overreliance on glyphosate as the sole weed control herbicide for more than a decade has resulted in the selection of weeds resistant to glyphosate. The first GR weed was discovered in 1996 and by 2010, eighteen species worldwide have been confirmed resistant to glyphosate.[9] When the first weed resistance was documented, the sustainability of GR technology was questioned by public and private organizations. Despite the growing concern of the exclusive use of glyphosate and the resulting evolution of GR weeds, adoption and use of this technology continues to increase globally. This widespread exclusive use of a single herbicide, albeit incredibly successful initially, highlights the need for scientists to educate growers on how to prevent or delay the development of GR weeds and preserve this technology.

Producers will use any given technology or suite of management practices if there is a clear advantage or benefit, such as reduced cost for weed management, improved efficacy on hard-to-control weeds, simplicity, or increased net returns.[10] In a survey of growers conducted in 2005, costs or economics was always a prominent concern when growers were asked about factors involved in considering the implementation of herbicide resistance management practices.[11] Prior to the introduction of GR crops, producers intensively scouted fields for weeds and planned weed management programs in their fields that often mandated the use of multiple applications of herbicides with different modes-of-action or tillage to control weeds season-long. The use of a GR production system in conjunction with other herbicides with different modes-of-action or tillage are options that researchers are now investigating to develop weed control programs that are economically feasible and preserve GR technology for future use.

GR cropping systems have been readily adopted on a wide scale for over a decade. Researchers from six states developed a study, collectively entitled the "Benchmark Study", to evaluate the sustainability of GR cropping system from economic and weed management standpoints. Prior to the start of the study, producers from Iowa, Illinois, Indiana, Mississippi, Nebraska, and North Carolina were surveyed in 2005 to compile data on herbicide use patterns, troublesome weeds, and grower perceptions of weed problems. [12] After completion of the survey, a study was initiated to evaluate how the development of GR weeds could be minimized and test whether a weed resistance best management practice (BMP) was more economic and agronomically sustainable than the producers' normal production practice. Across the six states, 156 producers were selected to participate in the farm-scale study from 2006-2010.[13] Seven production systems were utilized: continuous GR corn, cotton, or soybean, GR soybean followed by GR corn or GR cotton, and GR soybean followed by non-GR corn or rice (*Oryza sativa* L.). The overall objective of the study was to assess long-term viability of GR technology as a foundation for cropping systems, evaluate weed population shifts, and determine economic viability of a university weed resistance BMP versus the producers' normal production practice. At the initiation of the study data were recorded from producer participants on past weed control practices used. Each year, university weed science researchers would collect a multitude of data. Each spring, soil cores were collected to estimate weed populations in the soil seed bank. During the growing season, four weed density samples were collected across the field at geo-referenced points: 1) prior to burndown 2) before the first postemergence herbicide application 3) two weeks after the last postemergence herbicide application and 4) prior to defoliation or harvest. Each count was conducted on each half of the field where there were 21-25 geo-referenced points. Producers were given a field record book prior to the beginning of the season to collect all input variables (i.e. seed, tillage, pesticide applications) and crop yield. These data will be used to build the economic comparisons of the two weed control practices.

Data in the following chapters are a subset of the data collected across six states, four years, and 156 locations. The objectives of the research in the following chapters were to evaluate GR management by comparing the economics and to determine when it is economically feasible to implement a weed resistance BMP using data from all six states, and evaluate weed density changes over time using a GR weed resistance BMP and a growers' normal weed control practice in Mississippi. This study focused on collection of data on weed population changes over time under two different production practices and crop yields in paired comparisons across a number of crops and crop systems.

Literature Cited

1. Burnside OC, Rationale for developing herbicide-resistant crops. Weed Technol. 6:621–625 (1992).

2. Radosevich SR, Ghersa CM, and Comstock G, Concerns a weed scientist might have about herbicide tolerant crops. Weed Technol. 6:635–639 (1992).

3. Martinez-Ghersa MA, Worster CA, and Radosevich SR, Concerns a weed scientist might have about herbicide-tolerant crops: a revisitation. Weed Technol. 17:202–210 (2003).

4. Askew SD, Shaw DR, and Street JE, Red rice (*Oryza sativa*) control and seedhead reduction with glyphosate. Weed Technol. 12:504–506 (1998).

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

6. Gonzini LC, Hart SE, and Wax LM Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:354–360 (1999).

7. McKinley TL, Roberts RK, Hayes RM, and English BC, Economic comparison of herbicides for johnsongrass (*Sorghum halepense*) control in glyphosate-tolerant soybean (*Glycine max*). Weed Technol. 13:30–36 (1999).

8. Scott R, Shaw DR, and Barrentine WL, Glyphosate tank mixtures with SAN 582 for burndown or postemergence applications in glyphosate-tolerant soybean (*Glycine max*). Weed Technol. 12:23–26 (1998).

9. [CTIC] Conservation Technology Information Center, National Crop Residue Management Survey Data 2004. http://www.ctic.purdue.edu/Core4/CT/CT.html [accessed 20 February 2010]

10. Johnson WG, Bradley PR, Hart SE, Buesinger ME, and Massey RE, Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays*). Weed Technol. 14:57–65 (2000).

11. Beckie HJ, and Gill G , Strategies for managing herbicide-resistant weeds. In H. P. Singh, D. R. Batish, and R. K. Kohli, eds. Handbook of Sustainable Weed Management. Binghamton, NY: The Haworth Press, Inc. (2006).

12. Shaw DR, Givens WA, Farno LA, Gerard PD, Jordan D, Johnson WG, Weller SC, Young BG, Wilson RG, and Owen MDK, Using a grower survey to assess the benefits and challenges of glyphosate-resistant cropping systems for weed management in U.S. corn, cotton, and soybean. Weed Technol. 23:134-149 (2009).

13. Shaw DR, Owen MDK, Weller SC, Young BG, Wilson RG, and Jordan D, Benchmark study: an introduction to field-scale research on glyphosate-resistant cropping systems. Pest Manag. Sci. in-press (2010)

CHAPTER II

BENCHMARK STUDY: ASSESSING THE EFFECTS OF GLYPHOSATE-BASED WEED MANAGEMENT PROGRAMS ON FARM-LEVEL PROFITABILITY

Abstract

Glyphosate-resistant (GR) crops have changed the way producers manage weeds and implement control strategies. Since the introduction of GR crops, producers in many instances have relied on glyphosate almost exclusively to control a broad spectrum of weeds. This over-reliance on glyphosate has resulted in the evolution of glyphosate resistance in some weed species. Producers and scientists are concerned about the sustainability of GR crops and glyphosate as a management tactic. When a producer must make a decision about weed control strategies, economic costs, simplicity, and benefits of the program are the primary criteria used for selection and implementation. Studies across six states were initiated in 2006 to compare the economics of a weed resistance best management practice (BMP) system with a producer's normal production system. Resistance BMP systems recommended by university scientists were always more costly, but provided similar yields and economic returns. Rotation of GR crops resulted in a higher net return (corn and soybean) compared to continuous GR crop (cotton and soybean) or rotation of a GR crop with a non-GR crop (corn). Growers can implement weed resistance BMP strategies with the confidence that their net returns will be equivalent in the short and long term; resistance BMPs will prevent or delay the evolution of GR weeds in their fields, which should result in substantial savings.

Introduction

Since the introduction of GR corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* L. (Merr.)] in 1998, 1997 and 1996, respectively, reliance on glyphosate as the primary or exclusive weed control tool has increased dramatically. Herbicide-resistant crops have the ability to increase weed control efficacy, simplify weed management and increase different herbicide sites-of-action used on a given crop to deal with resistant weed management strategies.[1-3] Glyphosate-resistant crops provide producers the flexibility to control a wide range of weeds with little to no crop injury.[4-8] Glyphosate-resistant crops have increased confidence in weed control, which has increased the popularity of conservation tillage.[9] Other benefits that a producer may perceive at the implementation of GR crops may include improved weed control, reduced management and labor inputs, less reliance on tillage, and reduced herbicide cost.[9-12]

Glyphosate has been an effective herbicide to control weeds that have developed resistance to other herbicide modes-of-action.[13,14] Glyphosate inhibits the growth of plants by affecting aromatic amino acid biosynthesis through the inhibition of 5-enolpyruvyl shikimate-3-phosphate synthase (EPSPS; 2.5.1.19) of the shikimate pathway[15,16]. With the introduction of GR crops, glyphosate can be applied directly to the crop with little concern for injury. However, since the introduction of GR crops, the use of tank mixtures and sequential applications of more than one family of herbicides has decreased, as many producers solely rely on glyphosate for weed control. Use of herbicide-resistant crops could increase dependency on a single specific herbicide to control weeds, which could result in the development of herbicide-resistant weeds.[2]

The first GR weed was discovered in 1996, and by 2010 eighteen species worldwide have been confirmed resistant to glyphosate.[17] Palmer amaranth (*Amaranthus palmeri* S. Wats.), common waterhemp (*Amaranthus rudis* Sauer), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), hairy fleabane [*Conyza bonariensis* (L.) Cronq.], horseweed [*Conyza canadensis* (L.) Cronq.], Sumatran fleabane [*Conyza sumatrensis* (Retz.) E. H. Walker], sourgrass [*Digitaria insularis* (L.) Mez ex Ekman], junglerice [*Echinochloa colona* (L.) Link], goosegrass [*Eleusine indica* (L.) Gaertn.], wild poinsettia (*Euphorbia heterophylla* L.), kochia [*Kochia scoparia* (L.) Schrad.], Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], rigid ryegrass (*Lolium rigidum* Gaudin), ragweed parthenium (*Parthenium hysterophorus* L.), buckhorn plantain (*Plantago lanceolata* L.), johnsongrass [*Sorghum halepense* (L.) Pers.], and liverseedgrass (*Urochloa panicoides* Beauv.) have developed resistance to glyphosate.[17] Glyphosate-resistant Palmer amaranth has been confirmed in nine states in the US and GR horseweed has been confirmed in 18 states in the US. [17] Between 1974 and 1995, the severity of *Amaranthus* spp. infestations increased in frequency as reported in surveys of troublesome weeds.[18] Horseweed has shown the highest levels of resistance at 8 to 13 fold over the susceptible biotype or 4 times the normal use rate of glyphosate.[19,20]

Prevention of herbicide resistance is much less expensive in the long-run than management of herbicide resistant weeds.[21] Peterson[22] reported costs to the producer increase substantially after development of herbicide resistance because of the lack of in-season weed control options. Once herbicide resistance has evolved, ineffective glyphosate applications result in weeds too large to be effectively controlled by other postemergence herbicides. Unfortunately, producers usually adopt herbicide-resistant weed management strategies only after a weed has evolved herbicide resistance,[15] and this approach to resistance management limits effectiveness. A herbicide resistance management program must be a priority for researchers, advisors, and producers now and in the future to preserve the viability of GR crop systems as well as other systems that could be developed in centuries ahead.

When a producer chooses production practices, one of the most important considerations is economic feasibility, and ultimately the impact on net returns. Economic evaluations have been built into field studies to examine the economic feasibility of a variety of weed management systems.[14-16,23] Herbicide cost is often the largest direct cost item in crop production.[24] Bradley et al. [25] reported that net income was more closely correlated to corn yield than specific weed management tactics. When a producer selects a weed management program, herbicide costs are considered more carefully than mode-of-action. In a survey of growers conducted in 2005, costs or economics were always a prominent concern when asked about factors involved in the implementation of herbicide resistance management practices.[26] If studies can show that implementation of resistance management practices does not reduce net returns, the likelihood of adoption of GR weed BMPs will increase. The purpose of this study was to use data from a long-term, six-state field scale project on GR management to compare the economics of a GR weed resistance BMP to the growers' normal weed control methods. This study focused on collection of data on weed population changes over time and crop yields in paired comparisons across a number of crops and crop systems.

Materials and Methods

Nearly 1200 producers from Iowa, Illinois, Indiana, Mississippi, Nebraska, and North Carolina were surveyed in 2005. [27] From this group, 156 producers across the six states were selected to participate in the farm-scale study from 2006-2008.[28] As is commonplace in a study such as this, a few fields were lost due to complexities such as ownership or renter changes, decisions to use other rotational crops, and crop failure due to natural disasters; by 2008, 150 fields remained in the study. Seven production systems were utilized: continuous GR corn, cotton, or soybean, GR soybean followed by GR corn or GR cotton, and GR soybean followed by non-GR corn or rice (*Oryza sativa* L.). Producers in Mississippi that were utilizing a GR soybean followed by non-GR rice and GR cotton followed by GR soybean production system didn't follow rotation guidelines, so these systems were not included in these data.

For the university-based weed resistance BMP strategy, scientists at each university used proven regional expertise to prescribe a herbicide program for each field based on current crop and future rotational crop along with in-season weed scouting. The prescription was given to the producer to implement on the university half of the field. If the herbicide that was prescribed wasn't available, alterations to the prescription were made to control problematic weeds. Producers collected data on all input variables (i.e. seed, tillage, pesticide applications) and crop yield in a field notebook that was collected at the end of the season. A partial budget was constructed from these records to determine variable input costs on each field for each year. Weed management costs consisted of herbicide costs, technology fees for GR seed, application costs, and any differences in tillage costs related to weed control. Each state obtained herbicide costs, tillage costs, and application costs from local retailers or their respective university crop budget generators. The herbicide costs from each state give a better representation of the actual costs the producer incurred

Net returns were calculated for each treatment based on the formula:

Net return = (Yield*December Cash Value each year) – Weed Control Cost

Data for yield and net return were subjected to ANOVA and means separated with Fisher's Protected LSD at $P \leq 0.05$ through SAS Proc Mixed, version 9.2.[29]

Results and Discussion

The university GR weed BMP system required more intensive inputs and management when compared to the producers' normal production practice (Table 2.1). There was a significant treatment by production system interaction; thus, data will be separated by production system. Interaction between production system and crop was not significant because the university weed management required more inputs across all crops, so these were combined by production system: continuous GR crop, GR crop followed by GR crop, and GR crop followed by non-GR crop. The university weed resistance BMP recommendation costs were higher than those from producers' normal production practice in all production systems except for GR crop followed by non-GR crop (Table 2.1). In a continuous GR crop production system, the university weed resistance management cost the producer $24.21/ha more than the producers' normal production practice. In a continuous GR cropping system, the universities BMP cost was higher than weed management cost for all other treatments except the university weed BMP control cost in a GR crop followed by GR crop rotation. Weed control cost for a

GR crop followed by GR crop followed the same trend, with the university weed resistance BMP costing $24.92/ha more than what the producer spent. In a GR crop followed by a non-GR crop, there was no difference in production cost between the university weed resistance BMP program and the producers' normal production practice. The university weed management cost for GR crop followed by non-GR crop was significantly lower than the BMP weed management cost for a continuous GR crop. The university weed management system generally used multiple modes-of-action herbicides for residual weed control followed by postemergence tank mixtures to provide adequate control of the weed species present. The input of these additional herbicides resulted in an increased weed management cost compared to the producers' normal production practice.

Across all five production systems, there were no statistical differences in yields between the university GR weed resistance BMP system and the producers' weed management program (Tables 2.2 and 2.3). Although yields were observed to vary among crop production systems, there was no statistical difference when compared across production systems. This is only noted here because of the discussion below on net return. Weed control was generally effective with both systems; thus, yields were optimized because of a lack of weed interferences. Similarly, other research has shown no differences in corn, cotton, and soybean yield when a glyphosate-based herbicide program is used with and without residual herbicides.[30-32]

The university GR weed BMP system resulted in no difference in net returns compared to the producers' system (Table 2.4). To calculate net returns, yields from each field were multiplied by the December commodity price for each year. Yields in the university GR weed BMP trended higher across the board, which resulted in an increase in total revenue. Although weed management costs were different between the two systems, overall they represented a small portion of the net returns, and therefore were offset by the yield increased for the university weed BMP.

With cotton excluded because of the lack of rotation, a GR crop followed by GR crop production system had higher net returns than continuous GR crop or GR crop followed by non-GR crop production systems, most likely because of the added benefit of crop rotation (i.e. yield increases) and increased weed management benefit of different herbicides in the rotational crop.[33] A continuous GR crop will see added benefit from the increased weed management, but not the rotation benefits. In years a non-GR crop is planted, producers will use conventional herbicides for weed management, which sometimes results in less effective weed control and net return compared to a rotation of GR crops. A GR crop followed by a non-GR crop has the added benefit from rotation to a different crop. The results from this study suggest that a rotation of GR crops is the best system based on net returns.

Producers are often reluctant to use other herbicides in combination with glyphosate because of concerns about high weed management costs. This study did in fact show this to be the case, in that herbicide costs increased with more intensive herbicide inputs. However, reduced weed pressure resulted in a trend toward higher crop yields, which offset the higher weed management costs. This study was conducted in six states, at 150 locations, over three years, four crops, and seven cropping systems. Thus, growers can implement these glyphosate resistance management strategies with the confidence that net returns will be equivalent in the short-term and over time long-term resistance management should delay or prevent the evolution of GR weeds in their fields, which, in turn creates substantial additional savings.

Literature Cited

1. Burnside OC, Rationale for developing herbicide-resistant crops. Weed Technol. 6:621–625 (1992).

2. Radosevich SR, Ghersa CM, and Comstock G, Concerns a weed scientist might have about herbicide tolerant crops. Weed Technol. 6:635–639 (1992).

3. Martinez-Ghersa MA, Worster CA, and Radosevich SR, Concerns a weed scientist might have about herbicide-tolerant crops: a revisitation. Weed Technol. 17:202–210 (2003).

4. Askew SD, Shaw DR, and Street JE, Red rice (*Oryza sativa*) control and seedhead reduction with glyphosate. Weed Technol. 12:504–506 (1998).

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

6. Gonzini LC, Hart SE, and Wax LM Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:354–360 (1999).

7. McKinley TL, Roberts RK, Hayes RM, and English BC, Economic comparison of herbicides for johnsongrass (*Sorghum halepense*) control in glyphosate-tolerant soybean (*Glycine max*). Weed Technol. 13:30–36 (1999).

8. Scott R, Shaw DR, and Barrentine WL, Glyphosate tank mixtures with SAN 582 for burndown or postemergence applications in glyphosate-tolerant soybean (*Glycine max*). Weed Technol. 12:23–26 (1998).

9. [CTIC] Conservation Technology Information Center, National Crop Residue Management Survey Data 2004. http://www.ctic.purdue.edu/Core4/CT/CT.html [accessed 20 February 2010]

10. Johnson WG, Bradley PR, Hart SE, Buesinger ME, and Massey RE, Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays*). Weed Technol. 14:57–65 (2000).

11. Beckie HJ, and Gill G , Strategies for managing herbicide-resistant weeds. In H. P. Singh, D. R. Batish, and R. K. Kohli, eds. Handbook of Sustainable Weed Management. Binghamton, NY: The Haworth Press, Inc. (2006).

12. Reddy KN and Whiting K, Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. Weed Technol. 14:204–211 (2000).

13. Shoup DE, and Al-Khatib K, Control of protoporphyrinogen oxidase inhibitor-resistant common waterhemp (*Amaranthus rudis*) in corn and soybean. Weed Technol. 14:204-211 (2004).

14. Smeda RJ, Snipes CE, and Barrentine WL, Identification of graminicide-resistant johnsongrass (*Sorghum halepense*). Weed Technol. 45:132-137 (1997).

15. Amrhein N, Deus B, Gehrke P, and Steinrucken HC, The site of the inhibition of the shikimate pathway by glyphosate. Plant Physiol. 66:830–834 (1980).

16. Rubin JL, Gaines CG, and Jensen RA, Enzymological basis for the herbicidal action of glyphosate. Plant Physiol. 70:833–839 (1982).

17. Heap I, The International Survey of Herbicide Resistant Weeds. www.weedscience.com [accessed 20 February 2010]

18. Webster TM and Coble HD, Changes in the weed species composition of the southern United States from 1974 to 1995. Weed Technol. 11:308-317 (1997).

19. VanGessel MJ, Glyphosate-resistant horseweed from Delaware. Weed Sci. 49:703–705 (2001).

20. Mueller TC, Massey JH, Hayes RM, Main CL, and Stewart CN Jr, Shikimate accumulates in both glyphosate-sensitive and glyphosate-resistant horseweed (*Conyza canadensis* L. Cronq.). J. Agric. Food Chem. 51:680–684 (2003).

21. Orson JH, The cost to the farmer of herbicide resistance. Weed Technol. 13:607–611 (1999).

22. Peterson DE, The impact of herbicide-resistant weeds on Kansas agriculture. Weed Technol. 13:632–635 (1999).

23. Krausz RF, and Kapusta G, Total postemergence weed control in imidazolinone-resistant corn. Weed Technol. 12:151–156 (1998).

24. Williams B, Economics of soybean production in Mississippi. In L. G. Heatherly and H. Hodges, eds. Soybean Production in the Midsouth. Boca Raton, FL: CRC Press. pp. 1–17 (1999).

25. Bradley PR, Johnson WG, Hart SE, Buesinger ML, and Massey RE, Economics of weed management in glufosinate-resistant corn (*Zea mays* L). Weed Technol. 14:495–501 (2000).

26. Givens WA, Shifts in herbicide use, tillage practices, and perceptions of glyphosate-resistant weeds following adoption of glyphosate-resistant crops. Ph. D. dissertation, Mississippi State University (2010).

27. Shaw DR, Givens WA, Farno LA, Gerard PD, Jordan D, Johnson WG, Weller SC, Young BG, Wilson RG, and Owen MDK, Using a grower survey to assess the benefits and challenges of glyphosate-resistant cropping systems for weed management in U.S. corn, cotton, and soybean. Weed Technol. 23:134-149 (2009).

28. Shaw DR, Owen MDK, Weller SC, Young BG, Wilson RG, and Jordan D, Benchmark study: an introduction to field-scale research on glyphosate-resistant cropping systems. Pest Manag. Sci. in-press (2010)

29. SAS/STAT(R) 9.2 User's Guide, Second Edition, PROC MIXED. Available online: http://support.sas.com/documentation/cdl/en/statug/63033/HTML/default/mixed_toc.htm, accessed 22 Feb 2010

30. Ferrell JA, and Witt WW, Comparison of glyphosate with other herbicides for weed control in corn (*Zea mays*): Efficacy and economics. Weed Technol. 16:701-706 (2002).

31. Burke IC, Troxler SC, Askew SD, Wilcut JW, and Smith WD, Weed management systems in glyphosate-resistant cotton. Weed Technol. 19:422-429 (2005).

32. Vangessel MJ, Ayeni AO, and Majek BA, Glyphosate in full-season no-till glyphosate-resistant soybean: role of preplant applications and residual herbicides. Weed Technol. 15:714-724 (2001).

33. Derksen, DA, Thomas AG, Lafond GP, Loeppky HA, and Swanton CJ, Impact of postemergence herbicides on weed community diversity within conservation-tillage systems. Weed Res. 35:311–320 (1995).

Table 2.1 Weed management costs for university implemented weed resistance programs compared to producer practices.[a]

Cropping system	Weed management program	
	University	Producer
	Weed Control Cost ($/ha)	
Continuous GR[b] crop	118.11	93.90
GR crop/GR crop	104.82	79.90
GR crop/Non-GR crop	88.50	74.19
LSD ($P < 0.05$)	14.54	

[a] LSD: Least significant difference separated by Fishers protected LSD at $p < 0.05$. Data are pooled over 150 locations from 2006-2008.
[b] glyphosate resistant

Table 2.2 Yield of continuous glyphosate resistant (GR) corn, cotton, and soybean from University implemented weed resistance best management practice (BMP) and producer weed management programs.[a]

Cropping system	Weed management program		P > F
	University	Producer	
	Yield (kg/ha)		
Continuous GR corn	10300	10150	NS
Continuous GR cotton[b]	910	880	NS
Continuous GR soybean	2740	2680	NS

a Data are pooled over 150 locations from 2006-2008.
b kg lint/ha

Table 2.3 Yield of glyphosate resistant (GR) soybean/GR corn and GR soybean/ Non-GR corn from university best management practice (BMP) and producer weed management programs.[a]

	Weed management program					
	University	Producer	University	Producer	University	Producer
Cropping system	GR Soybean		GR Corn		Non-GR Corn	
			Yield (kg/ha)			
GR soybean / GR corn	3980	3970	10730	10690	-	-
GR soybean / Non-GR corn	3530	3470	-	-	9520	9400
LSD ($P < 0.05$)	102.46		NS		NS	

[a] LSD: Least significant difference separated by Fishers protected LSD at $p \leq 0.05$. Data are pooled over 150 locations from 2006-2008

Table 2.4 Net returns of university best management practice (BMP) and producer weed management programs.[a]

Cropping system	Weed management program	
	University	Producer
	Net Return ($/ha)	
Continuous GR[b] crop	915.03	917.45
GR crop/GR crop	1154.10	1168.97
GR crop/Non-GR crop	999.11	994.99
LSD ($P < 0.05$)	126.29	

a LSD: Least significant difference separated by Fishers protected LSD at $p < 0.05$. Data are pooled over 150 locations from 2006-2008

b glyphosate resistant

CHAPTER III

BENCHMARK STUDY: TIMELINESS OF ECONOMIC DECISION-MAKING IN IMPLEMENTING WEED RESISTANCE MANAGEMENT STRATEGIES

Abstract

The development of glyphosate-resistant (GR) crops in the late 1990s made weed control in corn, cotton, and soybean simple. Glyphosate could be applied directly over the crop with little to no injury and this single herbicide controlled a broad spectrum of problematic weeds and grasses. With the rapid adoption of GR crops, many producers began to solely rely on glyphosate for weed control. This eventually led to the development of GR weeds. Producers are often reluctant to adopt a weed resistance best management practice (BMP) because of the added cost of additional herbicides to weed control programs that would reduce short-term revenue. This study was designed to evaluate when a producer that is risk neutral (profit maximizing) or risk averse should adopt a weed resistance BMP. A risk neutral producer will choose the system which gives them the greatest return, while a risk averse producer will sacrifice short-term revenue to avoid the risk of revenue loss from the development of herbicide resistance.

Whether a producer is risk neutral or risk averse, they should adopt a weed resistance BMP when the expected loss in revenue is greater than 30% and the probability of resistance development is 0.1 or greater. However, if the probability of developing resistance increases to 0.3, then the producer should adopt a weed resistance BMP when the expected loss is 10% or greater.

Given the scenarios analyzed, risk neutral or risk averse producers should implement a weed resistance BMP with confidence that they made the right decision economically, and avoided the risk of lost revenue from resistance. If a producer has any suspicion that they have or will develop resistance, proactive adoption of a weed resistance BMP is essential.

Introduction

Glyphosate, introduced in the early 1970's, is a broad spectrum herbicide that controls many annual and perennial weeds.[1] The introduction of glyphosate-resistant (GR) corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* L. (Merr.)] in the late 1990s provided farmers with a simple, broad-spectrum weed control option.[2,3] Glyphosate is foliar-applied and nonselective and is used for both burndown and postemergence applications in GR crops.[4] In 2009, GR corn, cotton and soybean were planted in the United States on 68, 71, and 91% of planted hectares, respectively.[5] The introduction of GR crops transformed the way many producers managed their weeds. Producers chose GR crops because glyphosate made weed control easy and effective, provided little to no crop injury, increased profit, required less tillage, and did not restrict crop rotations.

Prior to the incorporation of GR crops, producers used a suite of chemicals to achieve season-long weed control. Since the introduction of GR crops the over-reliance on glyphosate as the primary or sole weed control option has resulted in the development of GR weeds. The first GR weed was found in 1996, and by 2010, eighteen weed species have developed resistance to glyphosate.[6] Once a weed develops resistance to glyphosate, it is usually too large to be controlled by other herbicide applications.

Development of GR weeds has resulted in the need to adopt different weed control practices to control or prevent the development of GR weeds.

In a survey of growers conducted in 2005, cost or economics was always a prominent concern when growers were asked about factors involved in the implementation of herbicide resistance management practices.[7] When a producer selects a production practice, the decisive factor is usually the impact on net returns instead of which best management practices (BMP) may be optimal from a weed management perspective. BMPs utilize weed control methods used prior to the incorporation of GR crops in conjunction with the current glyphosate-based weed control methods. A downfall of the GR system is that producers will usually increase the adoption of weed resistance BMPs only after the development of GR weeds.[8] Use of soil residual herbicides and different postemergence herbicides with multiple modes-of-action to achieve adequate control or delay the development of GR weeds are areas that researchers are investigating to demonstrate sustainable GR cropping technologies. Producers are often reluctant to add additional modes-of-action to weed management programs due to the increased cost and perception of decreased short-term revenue. If producers want glyphosate to remain at its current level of effectiveness, weed resistance BMPs must be implemented to delay or prevent GR weeds from spreading to areas where resistance has not been confirmed.

The purpose of this study was to use data from a long-term, six-state field scale project on GR management to determine the best time to implement a weed resistance BMP. This study focused on economic data from paired comparisons across a number of crops and crop systems to develop the optimal decision to implement a weed resistance BMP.

Materials and Methods

Producers from Iowa, Illinois, Indiana, Mississippi, Nebraska, and North Carolina were surveyed in 2005,[9] and from this group 156 producers across the six states were selected to participate in the farm-scale study from 2006-2010.[10] For more details on the study, see Shaw et al.[10] Across these six states, farm-scale studies were established in 2006-2010 to evaluate the producers' weed management program versus a university weed resistance BMP strategy. The university weed resistance BMP utilized scientists at each university to prescribe herbicide programs for each field based on field history and in-season weed scout reports for the producer to implement on the university side. The recommendations consisted of multiple modes-of-action and soil residuals to delay or control GR weeds.

The economic feasibility of a weed resistance management program was evaluated with PROC DTREE in SAS version 9.2.[11] The PROC DTREE method was used to evaluate three input datasets to determine whether to implement a resistance management program or continue with current practices. The three input data sets consisted of: 1. a decision model; 2. probability of resistance; and 3. A payoff table. The decision model consisted of 4 decision variables (adopt or not adopt in each year) and 8 chance variables (resistance or not and uncertain revenue) in each year. Figure 3.1 shows a partial diagram of decisions for four years and the outcomes for three years. The assumption was made that once a field has a population of GR weeds, that population will be present henceforth. Therefore, the model was set so all subsequent years' resistant weed populations would be present. Probabilities were assigned to the resistance variables and increased or decreased in increments of 0.1 to evaluate all possible outcomes. For each given set of probabilities there were a total of 50,000 possible outcomes.

Weed management costs per hectare and net returns per hectare for a continuous GR crop, GR crop followed by a different GR crop, and GR crop followed by non GR crop from Weirich et al.[12] were utilized in the payoff data set. Based on previous research, the revenue distribution for a mixed Midwestern farm was found to have a coefficient of variation (C. V.) of 0.175.[13] Both commodity price and yield risk were included. This base case is4 used as the base revenue C.V. in year one. Given the mean revenue reported by Weirich et al. this C.V. implies a standard deviation of $160.[12] The five scenarios were designed to be symmetric and have a standard deviation of 160 in year one. It is assumed that price uncertainty increases as one looks further into the future. Based on a random walk of price from year to year, price risk is assumed to increase 10% in year two, 52% in year three and 84% in year four. Yield risk is assumed to remain the same across years. The five revenue outcomes of bad, low, expected, good, and great were assigned probabilities of 0.1, 0.2, 0.4, 0.2, and 0.1 respectively to address revenue risk.

Net returns after the development of resistance in a producers' field were reduced by multiplying net return by a percent in 10% increments, unless the producer adopted the BMP, then net returns remained the same. The evaluation value for each of the 50,000 outcomes were calculated as the sum of net returns each year minus the cost of weed management and revenue loss from the development of resistance. Two criterions were used to address risk neutral and risk averse producers. A risk neutral producer only cares about which option gives the highest return, while a risk averse producer will sacrifice some return to minimize the risk of lost revenue caused by the development of herbicide resistance. If a producer is risk neutral, PROC DTREE maximizes expected profit (i.e. is ambivalent to risk). However, if a producer is risk averse the model maximizes the expected utility which captures the disutility or risk. The risk tolerance used in this analysis is set to 6% of the total revenue; a typical level of moderate risk aversion.[11] Evaluation values were then subjected to a sensitivity analysis to determine at which given probabilities a producer should adopt a weed resistance BMP.

Results and Discussion

Since the introduction of GR crops and over-reliance on glyphosate, the probability of GR weeds has increased. Given the unlikely probability of 1 for no resistance, a producer should choose not to adopt the weed resistance BMP (Tables 3.1, 3.2, 3.3, and 3.4). Since there is no loss in revenue, producers' should continue to use glyphosate alone because of the increased cost of the weed resistance BMP. Since there was no risk of resistance, a risk averse producer should also elect not to adopt this strategy. The optimal decisions for a profit maximizing producer, with a 30% reduction in revenue if resistance develops and they choose not to adopt, would be to adopt all four years for all given probabilities of resistance, unless the probability of resistance is 0.0 (Table 3.1). The added cost to adopt a weed resistance BMP is offset by the chance the producer lost 30% revenue if resistance did develop. If the producer was risk averse, they would also elect to adopt the weed resistance BMP. Once the percent of revenue lost due to resistance exceeded 30%, a weed resistance BMP should be adopted at all probabilities of resistance development unless that probability was 0.

Once the percent reduction in revenue drops to 20%, a risk neutral producer should not adopt the weed resistance BMP in year one, but wait until year two and all subsequent years when the probability of resistance is 0.1 (Table 3.2). With a 0.1 probability of resistance development in year one, a risk neutral producer could possibly take a chance in the first year that resistance would not develop and keep the weed management cost lower than if the weed resistance BMP were implemented. However, a risk averse producer should adopt a weed resistance BMP in all years when the probability of resistance is equal to or greater than 0.1. A risk averse producer avoids any chance of resistant weed selection and subsequent reduction in revenue by implementing the weed resistance BMP at the earliest time.

When the percent reduction in revenue decreases to 10%, a risk neutral producer should not adopt a weed resistance BMP all four years when the probability of resistance is 0.0 or 0.1 (Table 3.3). However, once the probability of resistance increases to 0.2 the producer should not adopt a weed resistance BMP in year one, but should the three following years. The producer should adopt a weed resistance BMP if the probability for resistance is 0.3 or greater. A risk averse producer should adopt the weed resistance BMP all four years when the probability of resistance is greater than 0.1.

If there was no chance to lose revenue due to the development of weed resistance to herbicides, neither a risk neutral nor risk averse producer should adopt a weed resistance BMP in all years at all given probabilities of resistance (Table 3.4). The added costs that a producer would spend on a weed resistance BMP would see no added benefit in revenue when compared to the producers' glyphosate alone weed management practice.

A risk neutral or risk averse producer should adopt a weed resistance BMP in all years when the expected loss in revenue is 30% or greater and the probability of developing herbicide resistance weeds is 0.1 or greater. While a producer who is risk neutral will choose the most profitable GR system regardless of risk, a risk averse producer will give up some revenue to minimize some of the risk of lost revenue from the development of resistance. The results from this study suggest that if a producer has any suspicion of resistance, they should adopt a weed resistance BMP and feel confident the right decision was made regardless of the risk behavior.

Literature Cited

1. Franz JE, Mao MK, and Sikorski JA, Glyphosate: A Unique GlobalPesticide. Washington, DC: American Chemical Society. 653 p (1996).

2. Reddy KN and Koger CH, Herbicide resistant crops and weed management. Pages 549–580 in H. P. Singh, ed. Handbook of Sustainable Weed Management. Binghamton, NY: The Haworth Press Inc. (2004).

3. Shaner, D, The impact of glyphosate-tolerant crops on the use of other herbicides and on resistance management. Pestic. Sci. 56:320–326 (2000).

4. James C and Krattiger AF, Global review of the field testing and commercialization of transgenic plants (1986 to 1995: The First Decade of Crop Biotechnology). Ithaca, NY: ISAA Briefs 1. 31 p (1996).

5. USDA-NASS, Acreage. http://usda.mannlib.cornell.edu/usda/nass/Acre//2000s/2009/Acre-06-30-2009.pdf, Accessed 4 May 4, 2010 (2009).

6. Heap I, The international survey of herbicide resistant weeds. www.weedscience.com [accessed 17 May 2010] .

7. Givens WA, Shifts in herbicide use, tillage practices, and perceptions of glyphosate-resistant weeds following adoption of glyphosate-resistant crops. Ph. D. dissertation, Mississippi State University (2010).

8. Amrhein N, Deus B, Gehrke P, and Steinrucken HC, The site of the inhibition of the shikimate pathway by glyphosate. Plant Physiol. 66:830–834 (1980).

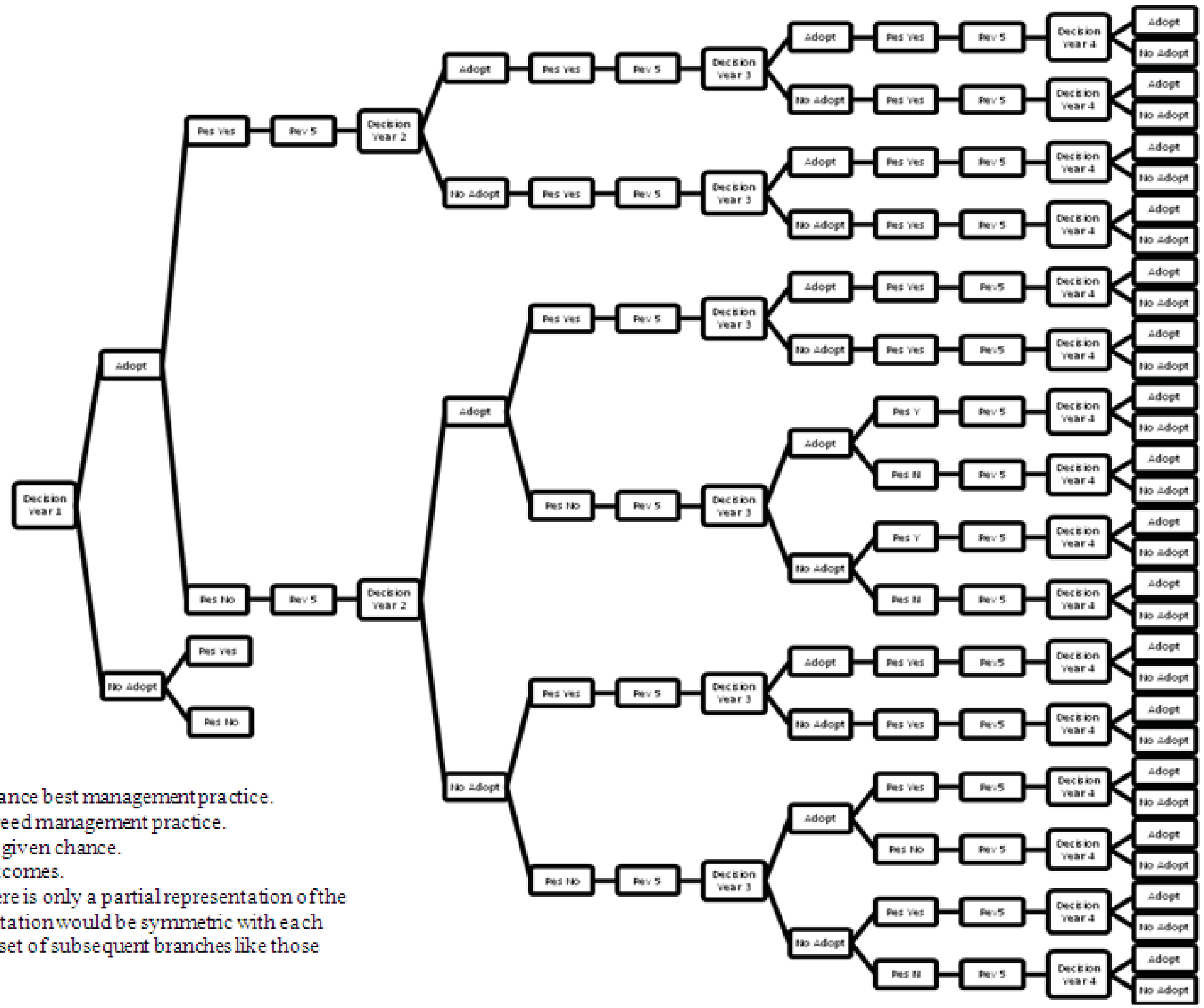
9. Shaw DR, Givens WA, Farno LA, Gerard PD, Jordan D, Johnson WG, Weller SC, Young BG, Wilson RG, and Owen MDK, Using a grower survey to assess the benefits and challenges of glyphosate-resistant cropping systems for weed management in U.S. corn, cotton, and soybean. Weed Technol. 23:134-149 (2009).

10. Shaw DR, Owen MDK, Weller SC, Young BG, Wilson RG, and Jordan D, Benchmark study: an introduction to field-scale research on glyphosate-resistant cropping systems. Pest Manag. Sci. in-press (2010).

11. SAS/STAT(R) 9.2 User's Guide, Second Edition, PROC DTREE. Available online: http://support.sas.com/documentation/cdl/en/orpmug/59678/HTML/default/dtree_sect1.htm, accessed 21 May 2010.

12. Weirich JW, Shaw DR, Owen MDK, Dixon PM, Weller SC, Young BG, Wilson RG, and Jordan D, Benchmark Study: Assessing the effects of glyphosate-based weed management programs on farm-level profitability. Pest Manag. Sci. in-press (2010).

13. Anderson JD, Barnett BJ, and Coble KH, Impacts of the SURE standing disaster assistance program on producer risk management and crop insurance programs. Paper for the AAEA Summer Meetings, Milwaukee, WI, July 2009.



Adopt = Implement weed resistance best management practice.
No Adopt = Continue current weed management practice.
Res = Resistance present at any given chance.
Rev = Five possible revenue outcomes.
Note: the decision tree shown here is only a partial representation of the model structure. A full representation would be symmetric with each branch from the nodes having a set of subsequent branches like those shown for the path depicted.

Figure 3.1 Representation of Decision Model Structure

Table 3.1 Optimal decisions for risk neutral (profit maximizing) producers to adopt a weed resistance best management practice or continue with normal weed control practices with a 30% reduction in revenue if resistance develops.

Probability of resistance		Revenue	Optimal decision[a]			
Yes	No	% Reduction if resistance is yes and No Adopt	Year one	Year two	Year Three	Year four
0.0	1	30	No Adopt	No Adopt	No Adopt	No Adopt
0.1	0.9	30	Adopt	Adopt	Adopt	Adopt
0.2	0.8	30	Adopt	Adopt	Adopt	Adopt
0.3	0.7	30	Adopt	Adopt	Adopt	Adopt
0.4	0.6	30	Adopt	Adopt	Adopt	Adopt
0.5	0.5	30	Adopt	Adopt	Adopt	Adopt
0.6	0.4	30	Adopt	Adopt	Adopt	Adopt
0.7	0.3	30	Adopt	Adopt	Adopt	Adopt
0.8	0.2	30	Adopt	Adopt	Adopt	Adopt
0.9	0.1	30	Adopt	Adopt	Adopt	Adopt
1	0.0	30	Adopt	Adopt	Adopt	Adopt

a Optimal decisions were determined by PROC DTREE in SAS

Table 3.2 Optimal decisions for risk neutral (profit maximizing) producers to adopt a weed resistance best management practice or continue with normal weed control practices with a 20% reduction in revenue if resistance develops.

Probability of resistance		Revenue	Optimal decision[a]			
Yes	No	% Reduction if resistance is yes and No Adopt	Year one	Year two	Year Three	Year four
0.0	1	20	No Adopt	No Adopt	No Adopt	No Adopt
0.1	0.9	20	No Adopt	Adopt	Adopt	Adopt
0.2	0.8	20	Adopt	Adopt	Adopt	Adopt
0.3	0.7	20	Adopt	Adopt	Adopt	Adopt
0.4	0.6	20	Adopt	Adopt	Adopt	Adopt
0.5	0.5	20	Adopt	Adopt	Adopt	Adopt
0.6	0.4	20	Adopt	Adopt	Adopt	Adopt
0.7	0.3	20	Adopt	Adopt	Adopt	Adopt
0.8	0.2	20	Adopt	Adopt	Adopt	Adopt
0.9	0.1	20	Adopt	Adopt	Adopt	Adopt
1	0.0	20	Adopt	Adopt	Adopt	Adopt

[a] Optimal decisions were determined by PROC DTREE in SAS

Table 3.3 Optimal decisions for risk neutral (profit maximizing) producers to adopt a weed resistance best management practice or continue with normal weed control practices with a 10% reduction in revenue if resistance develops.

Probability of resistance		Revenue	Optimal decision[a]			
Yes	No	% Reduction if resistance is yes and No Adopt	Year one	Year two	Year Three	Year four
0.0	1	10	No Adopt	No Adopt	No Adopt	No Adopt
0.1	0.9	10	No Adopt	No Adopt	No Adopt	No Adopt
0.2	0.8	10	No Adopt	Adopt	Adopt	Adopt
0.3	0.7	10	Adopt	Adopt	Adopt	Adopt
0.4	0.6	10	Adopt	Adopt	Adopt	Adopt
0.5	0.5	10	Adopt	Adopt	Adopt	Adopt
0.6	0.4	10	Adopt	Adopt	Adopt	Adopt
0.7	0.3	10	Adopt	Adopt	Adopt	Adopt
0.8	0.2	10	Adopt	Adopt	Adopt	Adopt
0.9	0.1	10	Adopt	Adopt	Adopt	Adopt
1	0.0	10	Adopt	Adopt	Adopt	Adopt

[a] Optimal decisions were determined by PROC DTREE in SAS

Table 3.4 Optimal decisions for risk neutral (profit maximizing) producers to adopt a weed resistance best management practice or continue with normal weed control practices with a 0% reduction in revenue if resistance develops.

Probability of resistance		Revenue	Optimal decision[a]			
Yes	No	% Reduction if resistance is yes and No Adopt	Year one	Year two	Year Three	Year four
0.0	1	0	No Adopt	No Adopt	No Adopt	No Adopt
0.1	0.9	0	No Adopt	No Adopt	No Adopt	No Adopt
0.2	0.8	0	No Adopt	No Adopt	No Adopt	No Adopt
0.3	0.7	0	No Adopt	No Adopt	No Adopt	No Adopt
0.4	0.6	0	No Adopt	No Adopt	No Adopt	No Adopt
0.5	0.5	0	No Adopt	No Adopt	No Adopt	No Adopt
0.6	0.4	0	No Adopt	No Adopt	No Adopt	No Adopt
0.7	0.3	0	No Adopt	No Adopt	No Adopt	No Adopt
0.8	0.2	0	No Adopt	No Adopt	No Adopt	No Adopt
0.9	0.1	0	No Adopt	No Adopt	No Adopt	No Adopt
1	0.0	0	No Adopt	No Adopt	No Adopt	No Adopt

[a] Optimal decisions were determined by PROC DTREE in SAS

CHAPTER IV

BENCHMARK STUDY: EFFECTIVENESS OF A UNIVERSITY RECOMMENDED WEED RESISTANCE BEST MANAGEMENT PRACTICE AND A PRODUCERS NORMAL PRODUCTION PRACTICE IN MISSISSIPPI

Abstract

Glyphosate resistant (GR) crops have changed the way we view agronomic weed control. Glyphosate is a broad spectrum herbicide that can be applied directly overtop of GR crops with little to no injury. Since the introduction of GR crops, the use of different modes of action and tillage has decreased. This has caused several weed species to evolve resistance to glyphosate, and thus has placed a challenge on researchers to develop sound weed control options that will provide the excellent weed control to which producers have become accustomed, and at the same time assure sustainability of GR crop systems. On-farm studies across Mississippi were initiated in 2006 to compare the influences of a university recommended weed resistance best management practice (BMP) to a producer's normal production practice on the 27 most common weed species in Mississippi. A university weed resistance BMP and producers' normal glyphosate production practice were comparable for control of the 27 weed species evaluated. The adoption of a university weed resistance BMP reduced redvine populations in a continuous GR cotton production system. Pitted morningglory, henbit, and annual bluegrass populations increased in a continuous GR cotton production system when compared to a continuous GR soybean or GR soybean/rice production system.

Populations of henbit, carpetweed, annual bluegrass, prickly sida, and common chickweed increased when a continuous GR soybean or GR soybean/rice production systems are utilized when compared to a continuous GR cotton production system. A producer can implement a university-recommended weed resistance BMP strategy and achieve the same level of weed control achieved with glyphosate alone. The weed resistance BMP uses multiple modes of action tailored to each specific field to help prevent, delay, or control weeds that are resistant to glyphosate which will provide greater control of GR weeds and sustain GR technology for future use.

Introduction

A broad-spectrum and highly translocated herbicide was discovered in 1970, glyphosate.[1] Glyphosate stops aromatic amino acid biosynthesis in plants through the inhibition of 5-enolpyruvyl shikimate-3-phosphate synthase (EPSPS; 2.5.1.19) of the shikimate pathway.[2,3] The use of glyphosate as the foundation for weed control dramatically increased when glyphosate-resistant (GR) corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* L. (Merr.)] were introduced in 1998, 1997 and 1996, respectively. Producers select GR crops because it increases weed control efficacy, decreases management time, increases crop flexibility, controls a broad-spectrum of weed species with little or no crop injury, reduces reliance on tillage for weed control, increases simplicity, and decreases weed control cost.[4-15]

Since the introduction of GR crops, the use of tank mixtures and sequential applications of more than one family of herbicides has decreased as many producers rely only on glyphosate for weed control, which results in a potential increase of GR weeds.[16] In years past, producers used a soil-applied herbicide to reduce weed emergence and growth in the early part of the production season.[13] Producers now typically rely on glyphosate for season-long weed control. Some producers apply glyphosate several times through the season: burn-down, pre-plant, early- and late-postemergence, and after harvest. This over reliance on one herbicide and mode of action has resulted in the development of GR weeds. The first GR weed was discovered in 1996 and by 2010 eighteen species worldwide have been confirmed resistant to glyphosate.[17] Palmer amaranth (*Amaranthus palmeri* S. Wats.), common waterhemp (*Amaranthus rudis* Sauer), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), hairy fleabane [*Conyza bonariensis* (L.) Cronq.], horseweed [*Conyza canadensis* (L.) Cronq.], Sumatran fleabane [*Conyza sumatrensis* (Retz.) E. H. Walker], sourgrass [*Digitaria insularis* (L.) Mez ex Ekman], junglerice [*Echinochloa colona* (L.) Link], goosegrass [*Eleusine indica* (L.) Gaertn.], wild poinsettia (*Euphorbia heterophylla* L.), kochia [*Kochia scoparia* (L.) Schrad.], Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], rigid ryegrass (*Lolium rigidum* Gaudin), ragweed parthenium (*Parthenium hysterophorus* L.), buckhorn plantain (*Plantago lanceolata* L.), johnsongrass [*Sorghum halepense* (L.) Pers.], and liverseedgrass (*Urochloa panicoides* Beauv.) have developed resistance to glyphosate.[17] To manage resistant weeds or delay other species from development of resistance requires the use of different modes-of-action or tillage for acceptable control. Glyphosate is still an effective tool to control several weed species. Tank mixtures of soil residual herbicides or other foliar-applied herbicides with glyphosate may help control or delay resistance and sustain GR technology as a viable option.

The weed seedbank in the soil is the primary force of weed diversity in the field. Seedbanks reflect the past and present agricultural management strategies and also are an indication of problem weed species that might arise in the future.[18,19] Alterations to the weeds emerged represent relatively immediate impacts of changed farm practices, whereas alteration of the seedbank represents long term trends associated with changes in production practices.[20,21] Alterations to the seedbank can be caused by over-reliance of glyphosate as the sole herbicide for a weed control program. Weed populations have been greatly influenced by the use of glyphosate over the past decade.

The purpose of this study was to use data from a four-year, field-scale, project on GR management to compare the efficacy on weed control and weed population shifts between two weed control programs: university weed resistance best management practice and a producers normal glyphosate based production system in Mississippi. This study focused on collection of data on weed population changes over time in paired comparisons across a number of crops and crop systems.

Materials and Methods

Farm-scale studies in Mississippi were established in 2006-2010 to evaluate a continuous glyphosate weed management versus a university weed resistance best management practice (BMP) strategy. Mississippi producers were surveyed in 2005 [22] and 20 producers across the state were selected to participate in the farm-scale study. Due to natural losses over the study duration, 18 producers remained in the study by 2009. [23] Four production systems were utilized: continuous GR cotton or soybean, GR soybean followed by GR cotton, and GR soybean followed by non-GR rice (*Oryza sativa* L.). Producers in the GR soybean followed by GR cotton didn’t follow rotation guidelines, and thus were not utilized in the analysis. Fields in the study ranged from 13 to 25 ha. Each field was then split into two equal halves. After the field was split a point sample pattern was established in the shape of a W using GPS.[23] For the university weed resistance BMP strategy, state expertise was used to prescribe herbicide programs tailored to each specific field based on field history and in-season weed scout reports. The university weed resistance BMP utilized the weed population densities from the prior year and in-season weed scout data to develop a weed control program that used soil residual herbicides combined with multiple modes-of-action incorporated with timely applications, with the goal to optimize weed management and prevent the development of GR weeds. The producer would implement this prescription on the university half of the field, while continuing his normal production practice on the other half. To evaluate the efficacy of the treatments, weed densities were collected (0.5-m^2 quadrat) at 21-25 geo referenced points on a W pattern at 4 different sample times in the season: 1) Prior to planting 2) before the first postemergence herbicide application 3) two weeks after the last postemergence herbicide application and 4) prior to harvest or defoliation.[23]

Through the four-year study, 96 weed species were present at some point during the growing season. Of the 96 weed species observed, only 27 weed species were present in the season all four years (see Table 4.1 for a list of these 27 species).

Data across the points on one half of the field were summarized to give a value for each weed species. Due to the large number of sample sites that contained no weeds (had counts of zero), the summation of weed density was increased by one. The data were log transformed. Data for year, production system, weed management, and sample times were subjected to ANOVA through SAS Proc Mixed, version 9.2.[24]

Results and Discussion

There was no evidence on any species that weed management system had an effect on densities of any of the 27 weed species present in the field counts (Table 4.1). Weeds at the locations involved in the study were not GR. The lack of resistance still allows producers to achieve excellent control with glyphosate alone and the university recommendation was developed to control or prevent GR weeds; thus, no differences existed between the two weed control practices were manifest. However, redvine was the only weed species significantly impacted by weed management system (Pr>F .0154, Table 4.1). Crop*weed management (production system) interactions differentiate weed densities as affected by the crop planted, weed management, and production system utilized during the four years of the project. Thus, a university based weed resistance BMP reduced redvine densities in a continuous GR cotton production system. In this study, cotton was only present in one production system that was no-tillage Redvine is a woody perennial vine found in cultivated fields, fence rows, riverbanks and forest. With the increased popularity of no-till production systems redvine has continued to be one of the most troublesome weeds in the Mid-South.[25] Redvine is a significant pest in Mississippi cotton production and must be considered when weed control programs are developed. Since the university weed resistance BMP used herbicides with multiple modes of action, redvine populations were reduced.

Sample time significantly affected the probability of detection of a given weed species for 22 of the 27 weed species present: large crabgrass, horseweed, ivyleaf morningglory, johnsongrass, and common cocklebur were not significant (Table 4.2). The lack of control by both weed management practices resulted in persistence or germination of new seedlings throughout the four different sample times. The weed management practices utilized on both halves of the field, resulted in adequate control of the other 22 species and resulted in sample times where the species were present and sample times when species were absent. When a weed control program is planned, one must consider all weed species in the field to develop a sound weed control program.

Production system was significant on densities for pitted morningglory, henbit, carpetweed, annual bluegrass, prickly sida, and common chickweed (Table 4.2). Thus, across the four year study, a continuous GR cotton production system resulted in increased densities of pitted morningglory, henbit, and annual bluegrass when compared to a continuous GR soybean or GR soybean/rice production system. A continuous GR soybean or GR soybean/rice production system caused an increase in densities of henbit, carpetweed, annual bluegrass, prickly sida, and common chickweed when compared to a continuous GR cotton production system. Production system was not significant for the other 21 species because there was no trend for an increased or decreased presence in either of the production systems. Henbit and annual bluegrass are both winter annuals that are currently controlled with a burndown or preplant application of glyphosate or tillage prior to planting. Pitted morningglory and prickly sida are summer annuals and some of the most common, and troublesome weeds in cotton and soybean production in Mississippi.[26] Carpetweed and common chickweed are prostrate growing weeds that are currently controlled with a postemergence application of glyphosate.

Crop*production system significantly affected populations of sticky chickweed, barnyardgrass, prickly sida, and common chickweed (Table 4.2). This suggests that population densities of sticky chickweed, barnyardgrass, prickly sida, and common chickweed increased when soybean was planted in a production system of continuous GR soybean or GR soybean/rice, while these populations remained the same in a continuous GR cotton production system because of the intensive weed control programs utilized in cotton. Barnyardgrass is one of the most common weed species in soybean production in Mississppi.[26] Barnyardgrass has become a difficult weed to control with glyphosate alone. Use of specific soil residual herbicides tank mixed with glyphosate can improve control of barnyardgrass. These data also confirm that prickly sida and barnyardgrass are two of the most common weeds in Mississippi soybean production. Weed control programs must prioritize control of these weeds to sustain GR technology for the future.

With the adoption of a university weed resistance BMP, producers will see a reduction in populations of redvine in continuous GR cotton. Sample time affected the probability of large crabgrass, horseweed, ivyleaf morningglory, johnsongrass, and common cocklebur and resulted in the detection of these weeds through the growing season at the majority of sample times. This research indicates these weed species are or may become more prevalent in fields in which a glyphosate-based weed control or a similar university weed resistance BMP is practiced. Populations of pitted morningglory, henbit, and annual bluegrass increased in a continuous GR cotton production system compared to a continuous GR soybean or GR soybean/rice production system and populations of henbit, carpetweed, annual bluegrass, prickly sida, and common chickweed increased in a continuous GR soybean or GR soybean/rice production system when compared to a continuous GR cotton production system. Regardless of the production system, producers, advisors, and researchers must develop weed control options to control these species. Utilization of alternate techniques to control these species is vital for the future of GR technology in Mississippi. A producer can feel confident that the adoption of the university weed resistance BMP will help prevent, control, or delay the development of GR weeds in Mississippi and preserve GR technology.

Literature Cited

1. Franz JE, Mao MK, and Sikorski JA, Glyphosate: A Unique GlobalPesticide. Washington, DC: American Chemical Society. 653 p (1996).

2. Amrhein N, Deus B, Gehrke P, and Steinrucken HC, The site of the inhibition of the shikimate pathway by glyphosate. Plant Physiol. 66:830–834 (1980).

3. Rubin JL, Gaines CG, and Jensen RA, Enzymological basis for the herbicidal action of glyphosate. Plant Physiol. 70:833–839 (1982).

4. Burnside OC, Rationale for developing herbicide-resistant crops. Weed Technol. 6:621–625 (1992).

5. Radosevich SR, Ghersa CM, and Comstock G, Concerns a weed scientist might have about herbicide tolerant crops. Weed Technol. 6:635–639 (1992).

6. Martinez-Ghersa MA, Worster CA, and Radosevich SR, Concerns a weed scientist might have about herbicide-tolerant crops: A revisitation. Weed Technol. 17:202–210 (2003).

7. Askew SD, Shaw DR, and Street JE, Red rice (*Oryza sativa*) control and seedhead reduction with glyphosate. Weed Technol. 12:504–506 (1998).

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

9. Gonzini LC, Hart SE, and Wax LM, Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 13:354–360 (1999).

10. McKinley TL, Roberts RK, Hayes RM, and English BC, Economic comparison of herbicides for johnsongrass (*Sorghum halepense*) control in glyphosate-tolerant soybean (*Glycine max*). Weed Technol. 13:30–36 (1999).

11. Scott R, Shaw DR, and Barrentine WL, Glyphosate tank mixtures with SAN 582 for burndown or postemergence applications in glyphosate-tolerant soybean (*Glycine max*). Weed Technol. 12:23–26 (1998).

12. [CTIC] Conservation Technology Information Center, National Crop Residue Management Survey Data 2004. http://www.ctic.purdue.edu/Core4/CT/CT.html [accessed 20 February 2010]

13. Johnson WG, Bradley PR, Hart SE, Buesinger ME, and Massey RE, Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays*). Weed Technol. 14:57–65 (2000).

14. Beckie HJ, and Gill G , Strategies for managing herbicide-resistant weeds. *In* H. P. Singh, D. R. Batish, and R. K. Kohli, eds. Handbook of Sustainable Weed Management. Binghamton, NY: The Haworth Press, Inc. (2006).

15. Reddy KN and Whiting K, Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. Weed Technol. 14:204–211 (2000).

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

17. Heap I, The International Survey of Herbicide Resistant Weeds. www.weedscience.com [accessed 5 May 2010]

18. Cavers PB, Seed banks: Memory in soil. Can. J. Soil Sci. 75:11–13 (1995).

19. Dorado J, Del Monte JP, and López-Fando C, Weed seedbank response to crop rotation and tillage in semiarid agroecosystems. Weed Sci. 47:67–73 (1999).

20. Buhler DD, Hartzler RG, and Forcella F, Implications of weed seedbank dynamics to weed management. Weed Sci. 45:329–336 (1997).

21. Dekker J, Soil weed seed banks and weed management. J. Crop Prod. 2:139–166 (1999).

22. Shaw DR, Givens WA, Farno LA, Gerard PD, Jordan D, Johnson WG, Weller SC, Young BG, Wilson RG, and Owen MDK, Using a grower survey to assess the benefits and challenges of glyphosate-resistant cropping systems for weed management in U.S. corn, cotton, and soybean. Weed Technol. 23:134-149 (2009).

23. Shaw DR, Owen MDK, Weller SC, Young BG, Wilson RG, and Jordan D, Benchmark study: an introduction to field-scale research on glyphosate-resistant cropping systems. Pest Manag. Sci. in-press (2010)

24. SAS/STAT(R) 9.2 User's Guide, Second Edition, PROC MIXED. Available online: http://support.sas.com/documentation/cdl/en/statug/63033/HTML/default/mixed_toc.htm, accessed 5 May 2010

25. Webster TM, Weed survey—southern states, broadleaf crops subsection. Proc. South. Weed Sci. Soc. 54:244–259 (2001).

26. Webster TM Weed survey—southern states: Broadleaf crops subsection. Proc. South. Weed Sci. Soc. 58:291-306 (2005).

Table 4.1 Analysis of variance for weed densities across four years and 18 locations in Mississippi as affected by weed management[a], production system[b], and crop[c].

Weed Species		Sources of variation[d]		
Common Name	Latin Name	weed management	production system *weed management	crop*weed management (production system)
			Pr > F	
Annual bluegrass	*Poa annua* L.	0.7128	0.6799	0.9018
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.	0.8567	0.8390	0.9452
Broadleaf signalgrass	*Urochloa platyphylla* (Nash) R.D. Webster	0.9544	0.5811	0.7717
Buttercup sp.	buttercup sp.	0.9322	0.9767	0.9940
Carolina geranium	*Geranium carolinianum* L.	0.4947	0.7986	0.9245
Carpetweed	*Mollugo verticillata* L.	0.6748	0.8298	0.9623
Common chickweed	*Stellaria media* (L.) Vill.	0.7777	0.9674	0.8954
Common cocklebur	*Xanthium strumarium* L.	0.6147	0.747	1
Entireleaf morningglory	*Ipomoea hederacea* var. *integriuscula* Gray	0.4577	0.9139	0.9639
Goosegrass	*Eleusine indica* (L.) Gaertn.	0.2813	0.6481	1
Henbit	*Lamium amplexicaule* L.	0.9637	0.9642	0.9805
Horseweed	*Conyza canadensis* (L.) Cronq.	0.6723	0.9897	0.9492
Hyssop spurge	*Chamaesyce hyssopifolia* (L.) Small	0.7568	0.4797	0.4319
Ivyleaf morningglory	*Ipomoea hederacea* Jacq.	0.9675	0.8212	0.8942

Table 4.1 (continued)

Weed Species		Sources of variation[d]		
Common Name	Latin Name	weed management	production system *weed management	crop*weed management (production system)
			Pr > F	
Johnsongrass	*Sorghum halepense* (L.) Pers.	0.8407	0.9061	0.8277
Large crabgrass	*Digitaria sanguinalis* (L.) Scop.	0.8118	0.9136	0.9639
Pitted morningglory	*Ipomoea lacunosa* L.	0.3467	0.5098	0.7831
Prickly sida	*Sida spinosa* L.	0.3680	0.6122	0.8355
Purslane speedwell	*Veronica peregrina* L.	0.7324	0.9552	0.9646
Redvine	*Brunnichia ovata* (Walt.) Shinners	0.2738	0.2731	0.0154
Shepherd's purse	*Capsella bursa-pastoris* (L.) Medik.	0.5626	0.7483	0.7964
Sibara	*Sibara virginica* (L.) Rollins	0.5297	0.7757	0.6909
Spotted spurge	*Chamaesyce maculata* (L.) Small	0.2846	0.6433	1
Sticky chickweed	*Cerastium glomeratum* Thuill.	0.5743	0.7190	0.8258
Tall waterhemp	*Amaranthus tuberculatus* (Moq.) Sauer	0.8128	0.9476	0.9517
Wild garlic	*Allium vineale* L.	0.9536	0.9574	1
Yellow nutsedge	*Cyperus esculentus* L.	0.8711	0.6441	0.9866

[a] University weed resistance best management practice and producers normal production practice
[b] Continuous glyphosate-resistant cotton or soybean, and glyphosate-resistant soybean followed by rice
[c] Cotton, corn, and soybean
[d] Weed densities were log transformed prior to analysis to account for nonhomogeneity of variance.

Table 4.2 Analysis of variance results for weed densities across four years and 18 locations in Mississippi as affected by sample time[a], production system[b], and crop[c].

	Source of variation[d]		
weed species	sample timing	production system	crop*production system
		Pr > F	
Annual bluegrass	<.0001	0.0126	0.2014
Barnyardgrass	<.0001	0.6284	<.0001
Broadleaf signalgrass	0.0229	0.2707	0.8278
Buttercup sp.	0.0088	0.7526	0.5924
Carolina geranium	0.0227	0.6457	0.1848
Carpetweed	<.0001	0.0155	0.4898
Common chickweed	<.0001	0.0019	<.0001
Common cocklebur	0.131	0.427	1
Entireleaf morningglory	<.0001	0.1976	0.755
Goosegrass	0.0434	0.5918	0.9862
Henbit	<.0001	<.0001	0.2965
Horseweed	0.3429	0.3929	0.4482
Hyssop spurge	<.0001	0.6666	0.3146
Ivyleaf morningglory	0.0609	0.0689	0.964
Johnsongrass	0.1005	0.2739	0.5202
Large crabgrass	0.0548	0.2487	0.9419
Pitted morningglory	<.0001	0.0192	0.2384
Prickly sida	<.0001	0.0069	0.0001
Purslane speedwell	<.0001	0.0573	0.1082
Redvine	0.0042	0.9217	0.0842
Shepherd’s purse	<.0001	0.0986	0.7011
Sibara	0.0001	0.632	0.8662
Spotted spurge	0.0183	0.3796	1
Sticky chickweed	<.0001	0.0693	0.0089
Tall waterhemp	0.0048	0.7637	0.0396
Wild garlic	<.0001	0.5849	0.9508
Yellow nutsedge	<.0001	0.5393	0.2779

a 1) Prior to planting 2) before the first post 3) two weeks after the first post and 4) prior to harvest or defoliation

bContinuous glyphosate-resistant cotton or soybean, and glyphosate-resistant soybean followed by rice

cCotton, corn, and soybean

d Weed densities were log transformed prior to analysis to account for nonhomogeneity of variance.