5-2017

Decision Support Software for Palmer Amaranth Weed Control

Karen Renee Lindsay
University of Arkansas, Fayetteville

Decision Support Software for Palmer Amaranth Weed Control

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Agricultural Economics

by

Karen R. Lindsay
University of Arkansas
Bachelor of Science in Agricultural Business, 2014

May 2017
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

Dr. Michael P. Popp
Thesis Director

Dr. Michael R. Thomsen
Committee Member

Dr. Jason K. Norsworthy
Committee Member

Abstract

Herbicide-resistant Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] has been identified as one of the most troublesome weeds, specifically for corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] producers in the southern United States. The use of herbicide technology remains the most widely used method of weed control, despite the evolution of herbicide-resistant Palmer amaranth. Therefore, a need currently exists for research and extension education to encourage the adoption of Integrated Pest Management (IPM) to address the problem of herbicide-resistant Palmer amaranth in the southern United States. By equipping crop producers, educators, and weed management consultants with tools to evaluate the long-run biological and economic implications of different Palmer amaranth weed control practices, producers are expected to realize the benefits of adopting IPM strategies. As such, the Palmer Amaranth Management (PAM) software was developed to help producers, educators and researchers, and weed management consultants analyze long-run implications of chemical and non-chemical weed control options in crop production in the mid-southern United States. In addition to promoting the regional adoption of IPM techniques, PAM is expected to improve coordination among researchers, educators, and extension agents, and help producers to realize the economic and environmental benefits of IPM adoption, such as improved crop yields and increased profitability, preservation of the long-term efficacy of available herbicides, and minimized environmental risks. Therefore, the research objective of this project was to develop a decision support software program to highlight the long-term effects of management practices on soil seedbank and economics to encourage the adoption of IPM methods for Palmer amaranth.

Acknowledgments

I would like to express my sincere gratitude to my thesis advisor, Dr. Michael Popp, for his unceasing support and mentorship throughout my time at the University of Arkansas. I would also like to thank my committee members, Drs. Michael Thomsen and Jason Norsworthy, for their insight, thoughtful and detailed feedback, and support throughout my studies and research. In addition, I would like to acknowledge Dr. Muthukumar Bagavathiannan for his significant contribution to this research. Lastly, I would like to thank the faculty and staff of the Department of Agricultural Economics and Business at the University of Arkansas for their exceptional support and dedication to their students. I will continuously strive to express my gratitude, not through words but, through hard work and dedication to the betterment of agriculture throughout the remainder of my career.

Dedication

To my educators who taught me to believe in myself.

Table of Contents

I. Introduction

A. Problem Statement

Palmer amaranth's Effects on Agricultural Production

Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] is an invasive species, commonly known as "pigweed", that is considered one of the most prevalent and problematic weed species in the southern United States (US) with negative economic effects on crop production (Ward et al. 2013). Palmer amaranth has shown increasing resistance to several herbicide technologies, including but not limited to glyphosate, acetolactate synthase (ALS)-inhibiting herbicides, and triazines (Ward et al. 2013). As such, Palmer amaranth is one of the most challenging herbicide-resistant weeds causing great losses to cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] production in the southern United States (Webster and Nichols 2012; Riar et al. 2013a; Riar et al. 2013b). In addition, Palmer amaranth has recently caused increased concern in other agriculturally significant regions in the United States, mainly in the Southern (Webster and Nichols 2012; Riar et al. 2013a-b) and Midwestern (Jhala et al. 2014) regions.

This rapid proliferation has caused Palmer amaranth to be regarded as the "most troublesome" weed in crop production in the United States (Van Wychen 2016) threatening the profitability and sustainability of U.S. agriculture. Moreover, its i) ability grow rapidly; ii) have extensive genetic diversity; iii) adaptation to poor growing environments; and iv) tendency for progressive herbicide resistance have further allowed for the invasion of Palmer amaranth in agricultural systems (Ward et al. 2013). The inability to effectively control Palmer amaranth can have severe negative effects on crop production and the attendant economic viability thereof. With seed production occurring within two to three weeks of seedling emergence (Keeley et al.

1987), Palmer amaranth is highly competitive with many row-crops. Even a few uncontrolled escapes may cause severe crop yield reductions, as one female Palmer amaranth plant may produce nearly 600,000 seeds (Keeley et al. 1987) which can lead to an invasion of Palmar amaranth within the first three years of crop production (Norsworthy et al. 2014). If left uncontrolled, it has been shown that one Palmer amaranth plant may lower yield by up to 68 percent (Klingaman and Oliver 1994) in soybean production, more than 50 percent in cotton yields (Morgan et al. 2001), and up to 91 percent in corn production (Massinga et al. 2001).

The Threat of Herbicide-resistant Palmer Amaranth

Herbicides remain the primary tools for effective weed management, but over-reliance on few herbicide options has resulted in the evolution of herbicide-resistant weeds. Prevalent to the southern US, glyphosate-resistant Palmer amaranth is one such weed (Webster and Nichols 2012; Ward et al. 2013). Moreover, Palmer amaranth has evolved resistance to an increasing number of herbicides, often showing multiple resistances (Ward et al. 2013). The first documented incidence of glyphosate-resistant Palmer amaranth in the US occurred in Georgia in 2005 (Culpepper et al. 2006), and 2006 marked the first Palmer amaranth population with resistance to both glyphosate and the ALS-inhibitor, pyrithiobac-sodium (Sosnoskie et al. 2011). A survey conducted in the Mississippi Delta region of Arkansas in 2012 confirmed approximately 89 and 73 percent had Palmer amaranth populations that demonstrated survival rates of more than 90 percent to the herbicides, pyrithiobac and glyphosate, respectively (Bagavathiannan and Norsworthy 2016). Initially used in combination with other herbicides for burndown and management of perennial species in soybean production, glyphosate grew in popularity after the introduction of Roundup Ready crop technologies in 1996 due to its low price and the ability to apply the herbicide in-season (Owen 2016). Palmer amaranth resistance to other important herbicide groups, such as triazines and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitors, has also been documented in the mid-western US (Ward et al. 2013; Jhala et al. 2014). If appropriate measures are not implemented, producers will continue to lose herbicide options for controlling Palmer amaranth. The rapid evolution and spread of herbicide resistance in Palmer amaranth poses significant threats to successful crop production.

Economic and Environmental Significance of Herbicide Resistance

Severe yield losses and growing weed management costs in row-crop production systems have resulted from the proliferation of Palmer amaranth particularly in the southern and mid-western regions of the US. Cotton, corn, and soybean are major agricultural commodities in the mid-southern states of Arkansas, Louisiana, Mississippi, and Tennessee with respective $500 million, $1.4 billion, and $3.8 billion in total annual producer revenues of (USDA-NASS 2016a-t). Given the above production values and previously reported yield reductions resulting from an infestation of Palmer amaranth (Morgan et al. 2001; Massinga et al. 2001; Klingaman and Oliver 1994), the resultant estimated economic loss could equal as much as $250 million, $1.3 billion, and $2.5 billion for cotton, corn, and soybean producers in the mid-southern US in 2015, respectively, for a total estimated loss of over $4 billion. That estimate however excludes cost and effect of weed control efforts farmers have employed. As such, the estimate is likely on the high end.

Furthermore, Palmer amaranth has contributed to increased weed management costs such as use of herbicides, tillage, and hand weeding (Sosnoskie and Culpepper 2014). A 2011 survey conducted by Riar et al. (2013b) showed that producers in the midsouthern region spent from \$114 ha^{-1} to \$137 ha^{-1} in weed control costs in ‘Roundup Ready’ and ‘LibertyLink’ cotton, respectively. In addition to the increasing costs of weed management of Palmer amaranth that comes with increased herbicide use, environmental effects are also of concern, consequently, contributing to the use of mechanical methods such as tillage (DeVore et al. 2013). Although tillage remains an economically viable method of mechanical weed control (Popp et al. 2001, DeVore 2013), glyphosate-resistant Palmer amaranth further poses a severe threat to the sustainability of conservation tillage systems (Price et al. 2011). Many producers have therefore returned to hand weeding to control Palmer amaranth in the southern US (Price et al. 2011; Riar et al. 2013b).

Significance of an IPM Approach to Palmer Amaranth Control

Many agricultural producers tend to seek to reduce Palmer amaranth resistance using “reactive” weed control methods to combat herbicide resistance after it has already occurred (Mueller et al. 2005, Owen 2016). Conversely, a “proactive” approach focuses on preventing the onset of herbicide resistance in the first place (Mueller et al. 2005) and promotes more diversified management options. “Proactive”, integrated weed management strategies might seem more expensive than a single-herbicide based weed management strategy; however, such integrated weed management practices are more economical and sustainable in the long-run (Mueller et al. 2005). Therefore, integrated pest management (IPM) techniques that integrate chemical and non-chemical weed control options are vital for abating the selection pressure imposed by any single management technology for successful and sustainable Palmer amaranth management (Owen 2016).

Management of the Palmer amaranth soil seedbank management is one such “proactive” resistance management method (Dekker 1999). The soil seedbank can be defined as the number of “reserves of viable seeds” in the soil (Dekker 1999). Simulation models have shown that the risk of herbicide “resistance evolution” is associated with soil seedbank size (Neve et al. 2011;

Bagavathiannan and Norsworthy 2013). However, traditional weed management methods are based on the economic threshold (ET) method that only promotes the employment of management technologies when weed densities exceed a yield loss threshold resulting in economic implications (Norris 1999; Bagavathiannan and Norsworthy 2012). However, the ET method fails to adequately address the likelihood of weed seed production and subsequent higher seedbanks that increase weed management expenses and thereby further elevate the risk of resistance evolution (Klingaman and Oliver 1994; Norris 1999; Bagavathiannan and Norsworthy 2012). This is particularly true for Palmer amaranth which can produce hundreds of thousands of seeds (Keeley et al. 1987). Therefore, the allowance of a sub-threshold level of Palmer amaranth escapes may have negative effects on the ability to control this species in the future and importance must be placed on minimizing soil seedbank levels by eradicating Palmer amaranth escapes through IPM techniques (Bagavathiannan and Norsworthy 2012). Norris (1999) suggested abandoning the ET method for a “no seed threshold” (NST) in which no weed escapes are allowed. Norsworthy et al. (2014) found evidence of the need for a “zero-tolerance threshold” method of control for Palmer amaranth due to its high proliferation and resistance evolution after introducing 200,000 glyphosate-resistant Palmer amaranth seeds into a square meter in four different cotton fields with no infestation of Palmer amaranth. Within the first two years, 20 percent of each field was infested; within three years, 95 to 100 percent of the fields were infested with Palmer amaranth (Norsworthy et al. 2014).

Obstacles to IPM Adoption

Best management practices (BMPs) and innovative management techniques that promote the IPM approach to herbicide resistance have been developed as a collective effort between the USDA-APHIS and the Weed Science Society of America (Norsworthy et al. 2012). Many BMP techniques focus on herbicide rotation, timeliness of herbicide use at the recommended label rates, as well as non-chemical approaches such as crop rotation and burning (Norsworthy et al. 2012). Norsworthy et al. (2012) stress the importance of the diversification of BMPs and producer knowledge of herbicide modes of action.

While producers are willing to adopt some BMPs, producers show a higher willingness to adopt BMPs that promise short-term gain but may be less effective in the long-term over those that are more effective in the long-term but require more effort and short-term costs. Hence, the overall level of adoption of the most effective weed control BMPs still remains low (Owen 2016). A 2011 survey by Riar et al. (2013b) showed that one constraint to producer BMP adoption is lack of education on the long-term benefits of BMP adoption. Producer management options are often based on short-term economic benefits rather than methods that promote long-term weed control and thereby long-term economic benefits (Norris 1999). However, as previously discussed, weed control programs that do not include IPM approaches may be economical in the short-term, but will lead to the evolution of resistance and therefore create greater weed control costs in the long-term. Furthermore, convincing producers of the economic viability of a proactive, IPM approach to Palmer amaranth management remains a substantial challenge to extension personnel (Owen 2016).

The use of seedbank modeling that estimates appropriate timing of weed management options based on the timing of a weed's life cycle combined with information on the economic implications of such options can provide a solution by better equipping producers with the knowledge necessary to make better management decisions (Dekker 1999). Although several BMPs for management of Palmer amaranth were established with direction from simulation modeling work by Neve et al. (2011), this modeling was designed as a research tool for educational and extension purposes, not as a decision-support software (DSS) tool. Hence the need among extension personnel and other educators for an effective, user-friendly, DSS tool to demonstrate the long-term biological and economic viability of IPM strategies for Palmer amaranth.

B. Research Objective

The research objective of this project was to develop a DSS program to promote IPM approaches to Palmer amaranth management with emphasis on long-term effects on soil seedbank and economics. This objective supports the goal of the National IPM Roadmap, in particular the employment of IPM methods to protect “human health and the environment” while increasing economic benefits (USDA 2013).

C. Rationale

The rationale that underlies the development of the DSS, Palmer Amaranth Management (PAM) software, is that by providing crop producers and weed management educators and consultants the means to evaluate the long-term biological and economic implications of different Palmer amaranth management practices, producers will realize the value of employing a “proactive” management strategy (Mueller et al. 2005). This will lead to wider adoption of IPM strategies.

Stakeholder-identified Needs

The PAM model was developed based on several stakeholder-identified needs. Norsworthy et al. (2007) conducted a survey to learn crop consultant perceptions on the needs among cotton producers in Arkansas. The survey showed that Palmer amaranth was one of the most problematic weeds for cotton producers in Arkansas and resistance management was therefore identified as the top research and education need (Norsworthy et al. 2007). Two 2011 regional surveys stressed the need for research and extension efforts to address the problem of herbicide-resistant Palmer amaranth among cotton and soybean in southern states (Riar et al. 2013a; Riar et al. 2013b). Webster and Nichols (2012) further emphasize the importance of focusing on ways to preserve the efficacy of herbicides.

D. Project Goals

It is anticipated that the PAM software program will encourage the adoption of comprehensive IPM techniques for effective Palmer amaranth management among corn, cotton, and soybean producers. The DSS will serve as an instrumental tool for the guidance of integrated management of Palmer amaranth through the use of existing research information to demonstrate the long-term biological (seedbank size and resistance) and economic consequences of several management options. Further, the software will promote the regional adoption of IPM techniques, improve coordination among researchers, educators, and extension agents, and help stakeholders realize the economic and environmental benefits of IPM adoption. Finally, PAM will help producers improve crop yields and profitability through the adoption of IPM techniques, preserve the long-term efficacy of available herbicides, and minimize the environmental risks associated with increased herbicide use. The expected benefits of PAM directly support the goals of the National IPM Roadmap, in promoting the employment of IPM methods to lower “human health risks” and negative “environmental” consequences associated with weed control methods and improving crop production and profitability (USDA 2013).

E. Thesis Overview

Chapter II provides a general introduction to the PAM software that may be downloaded at http://agribusiness.uark.edu/decision-support-software.php along with a detailed user manual. Chapter II serves as a management guide that will help users to better understand how they might use PAM to implement IPM methods of weed management. This chapter provides a discussion on the comparison of alternative strategies to highlight the economic and biological implications of those alternative strategic decisions. Note that these management decisions are designed to represent a typical production situation and the approaches a producer may wish to consider; they are not, however, intended as management recommendations. Finally, Chapter III provides a brief summary of the PAM project with a discussion of its intended purpose as well as software use caveats and limitations. Chapter III will also discuss future research and ways to improve future modeling efforts.

F. References

Bagavathiannan, M.V. and J.K. Norsworthy. 2012. "Late-Season Seed Production in Arable Weed Communities: Management Implications." Weed Science 60(3):325-334. DOI: http://dx.doi.org/10.1514/WS-D-11-00222.1.

Bagavathiannan, M.V. and J.K. Norsworthy. 2013. "Postdispersal Loss of Important Arable Weed Seeds in the Midsouthern United States." Weed Science 61(4):570-579. DOI: http://dx.doi.org/10.1614/WS-D-13-00065.1.

Bagavathiannan, M.V. and J.K. Norsworthy. 2016. "Multiple-Herbicide Resistance Is Widespread in Roadside Palmer Amaranth Populations." PLOS ONE, April 12, 2016. DOI: http://dx.doi.org/10.1371/journal.pone.0148748.

Culpepper, S.A., T.L. Grey, W.K. Vencill, J.M. Kichler, T.M. Webster, S.M. Brown, A.C. York, J.W. Davis, and W.W. Hanna. 2006. "Glyphosate-Resistant Palmer amaranth (Amaranthuss palmeri) Confirmed in Georgia." Weed Science 54(5):620-626. DOI: http://dx.doi.org/10.1614/WS-06-001R.1.

Dekker, J. 1999. "Soil Weed Seed Banks and Weed Management" in "Expanding the Context of Weed Management." D.D. Bulher, ed. New York: NY. The Hawthorne Press, pp. 139-159.

DeVore, J.D., J.K. Norsworthy, and K. Brye. 2013. "Influence of Deep Tillage, a Rye Cover Crop, and Various Soybean Production Systems on Palmer Amaranth Emergence in Soybean." Weed Technology 27(2):263-270. DOI: http://dx.doi.org/10.1614/WT-D-12-00125.1.

Duke S.O., J. Lydon, W.C. Koskinen, T.B Moorman, R.L. Chaney, and R. Hammerschmidt. 2012. "Glyphosate Effects on Plant Mineral Nutrition, Crop Rhizophere Microbiota, and Plant Disease in Glyphosate-Resistant Crops." Journal of Agricultural and Food Chemistry 60(42):10 375-10 397. DOI: http://dx.doi.org/10.1021/jf302436u.

Jhala, A.J., L.D. Sandell, N. Rana, G.R. Kruger, and S.Z. Knezevic. 2014. "Confirmation and Control of Triazine and 4-Hydroxyphenylpyruvate Dioxygenase-Inhibiting Herbicide Resistant Palmer Amaranth (Amaranthus palmeri) in Nebraska." Weed Technology 28(1):28-38. DOI: http://dx.doi.org/10.1614/WT-D-13-00090.1.

Klingaman, T.E. and L.R. Oliver. 1994. "Palmer amaranth (Amaranthus palmeri) Interference in Soybeans (Glycine max)." Weed Science 42(4):523-527. URL: http://www.jstor.org/stable/4045448.

Massinga, R.A., R.S. Currie, M.J. Horak, and J Boyer Jr. 2001. "Interference of Palmer amaranth in Corn." Weed Science 49(2):202-208. DOI: http://dx.doi.org/10.1614/0043-1745(2001)049[0202:IOPAIC]2.0.CO;2.

Morgan, G.D., P.A. Bauman, and J.M. Chandler. 2001. "Competitive Impact of Palmer Amaranth (Amaranthus palmeri) on Cotton (Gossypium hirutum) Development and

Yield." Weed Technology 15(3):408-412. DOI: http://dx.doi.org/10.1614/0890-037X(2001)015[0408:CIOPAA]2.0.CO;2.

Mueller, T.C., P.D. Mitchell, B.G. Young, and A.S. Culpepper. 2005. "Proactive Versus Reactive Management of Glyphosate-Resistant or -Tolerant Weeds." Weed Technology 19(4):924–933. DOI: http://dx.doi.org/10.1614/WT-04-297R.1.

Neve, P., J.K. Norsworthy, K.L. Smith, and I.A. Zelaya. 2011. "Modeling Glyphosate Resistance Management Strategies for Palmer amaranth (Amaranthus palmeri) in Cotton." Weed Technology 25(3):335-343. DOI: http://dx.doi.org/10.1614/WT-D-10-00171.1.

Norris, R.F. 1999. "Ecological Implications of Using Thresholds for Weed Management" in "Expanding the Context of Weed Management." D.D. Bulher, ed. New York: NY. The Hawthorne Press, pp. 31-58.

Norsworthy, J.K., G. Griffith, T. Griffin, M. Bagavathiannan, and E.E. Gbur. 2014. "In-Field Movement of Glyphosate-Resistant Palmer Amaranth (Amaranthus palmeri) and Its Impact on Cotton Lint Yield: Evidence Supporting a Zero-Threshold Strategy." Weed Science 62(2):237-249. DOI: http://dx.doi.org/10.1614/WS-D-13-00145.1.

Norsworthy, J.K., K.L. Smith, R.C. Scott, and E.E. Gbur. 2007. "Consultant Perspectives on Weed Management Needs in Arkansas Cotton." Weed Technology 21(3):825–831. DOI: http://dx.doi.org/10.1614/WT-D-13-00070.1.

Norsworthy, J.K., S.M. Ward, D.R. Shaw, R.S. Llewellyn, R.L. Nichols, T.M. Webster, K.W. Bradley, G. Frisvold, S,B. Powles, N.R. Burgos, W.W. Witt, and M. Barrett. 2012. "Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations." Weed Science 60(sp1):31-62. DOI: http://dx.doi.org/10.1614/WS-D-11-00155.1.

Owen, M.D.K. 2016. "Diverse Approaches to Herbicide-Resistant Weed Management." Weed Science 64(sp1):570-584. DOI: http://dx.doi.org/10.1614/WS-D-15-00117.1.

Popp, M.P., T.C. Keisling, C.R. Dillon, and P.M. Manning. 2001. "Economic and Agronomic Assessment of Deep Tillage in Soybean Production on Mississippi River Valley Soils." Agronomy Journal 93(1):164-169. DOI: http://dx.doi.org/ 10.2134/agronj2001.931164x.

Price, A.J., K.S. Balkcom, S.A. Culpepper, J.A. Kelton, R.L. Nichols, and H. Schomberg. 2011. "Glyphosate-Resistant Palmer amaranth: A Threat to Conservation Tillage." Journal of Soil Water Conservation 66(4):265-275. DOI: http://dx.doi.org/10.2489/jwsc.66.4.265.

Riar, D.S., J.K. Norsworthy, L.E. Steckel, D.O. Stephenson, T.W. Eubanks, and R.C. Scott. 2013. "Assessment of Weed Management Practices and Problem Weeds in the Midsouth United States-Soybean: A Consultant's Perspective." Weed Technology 27(3):604-611. DOI: http://dx.doi.org/10.1614/WT-D-12-00167.1.

Riar, D. S., J.K. Norsworthy, L.E. Steckel, D.O. Stephenson, and J.A. Bond. 2013. "Consultant Perspectives on Weed Management Needs in Midsouthern United States Cotton: A

Follow-Up Survey." Weed Technology 27(4):778-787. DOI: http://dx.doi.org/10.1614/WT-D-13-00070.1.

Sosnoskie, L.M., J.M. Kichler, R.D. Wallace, and A.S. Culpepper. 2011. "Multiple Resistance in Palmer Amaranth to Glyphosate and Pyrithiobac Confirmed in Georgia." Weed Science 59(3):321-325. DOI: http://dx.doi.org/10.1614/WS-D-10-00132.1.

Sosnoskie, L.M. and A.S. Culpepper. 2014. "Glyphosate-Resistant Palmer Amaranth (Amaranthus palmeri) Increases Herbicide Use, Tillage, and Hand-Weeding in Georgia Cotton." Weed Science 62(2):393-402. DOI: http://dx.doi.org/10.1614/WS-D-13-00077.1.

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). 2016. "2015 Arkansas, Louisiana, Mississippi, and Tennessee Corn, Cotton and Soybean Production in US Dollars." Accessed January 2017. https://quickstats.nass.usda.gov.

United States Department of Agriculture (USDA), National Institute of Food and Agriculture (NIFA). 2013. "National Roadmap for Integrated Pest Management." Accessed January 2017. https://nifa.usda.gov/sites/default/files/resources/National%20Road%20Map%20for%20Integrated%20Pest%20Management.pdf.

Van Wychen, L. 2016. "2015 Survey of the Most Common and Troublesome Weeds in the United States and Canada." Weed Science Society of America National Weed Survey Dataset. Accessed December 2016. http://wssa.net/wp-content/uploads/2015-Weed-Survey_FINAL1.xlsx.

Ward, S.M., T.M. Webster, and L.E. Stekel. 2013. "Palmer amaranth (Amaranthus palmeri): A Review." Weed Technology 27(1):12-27.

Webster, T.M. and R.L. Nichols. 2012. "Changes in the Prevalence of Weed Species in the Major Agronomic Crops of the Southern United States: 1994/1995 to 2008/2009." Weed Science 60(2):145-157.

II. Decision Support Software for Palmar Amaranth Management

A. Introduction

The decision-support software (DSS), Palmer Amaranth Management (PAM) model (Bagavathiannan et al. 2017), was developed using the Microsoft Excel® software to help cotton, corn, and/or soybean producers, educators, and extension agents with implementing integrated pest management (IPM) techniques for Palmer amaranth control to promote long-term economic sustainability of crop production (Lindsay et al. 2017). The software and manual may be downloaded from http://agribusiness.uark.edu/decision-support-software.php as of January 11, 2017. The PAM software integrates agronomic, biological, and economic information to help the end user recognize the magnitude of long-term implications of adopting various management strategies to help make more informed management decisions. Specifically, this software provides decision-support for IPM of Palmer amaranth by using existing research (Neve et al. 2011) to facilitate a better understanding of the long-term biological and economic benefits of different management options (Mueller et al. 2005). This will help producers realize increased crop yields and profitability through implementation of IPM techniques that preserve the long-term efficacy of existing herbicide options and further reduce the attendant human health risks and environmental effects of resistance to herbicide use (USDA 2013). Since PAM was specifically developed as a planning and educational tool to assist producers and educators generate comparison of several Palmer amaranth management options for their effect on long-term Palmer amaranth seedbank levels and economic returns, it is important to note that while this software does account for pre-existing resistance and the probability of growing resistance under any chosen strategy, it is not intended for use as an herbicide resistance simulation model (Bagavathiannan et al. 2017).

The basic framework for PAM is based on the Ryegrass Integrated Management (RIM) software model which was developed at the University of Western Australia (AHRI 2013) to assist producers and researchers with management of the invasive species, annual rigid ryegrass (*Lolium rigdum*), within the Southern regions of Australia (Lacoste and Powles 2014; Lacoste and Powles 2015; Lacoste and Powles 2016).

Like the RIM model, PAM utilizes the Microsoft Excel® platform because it is available to most users who likely have some experience with the software, making PAM a more user-friendly and powerful educational tool by reaching a greater audience. Although Excel® is powerful enough to perform necessary calculations, its toolbars and menu options are thought to distract the end user, and therefore, improvements were made using Visual Basic for Applications (VBA) programming language to create more software-like features and appealing visuals within the software platform. To protect the integrity of PAM's calculations, the software is locked in the execution mode and only input cells and userforms are activated to allow for the selection of user-specific parameter values that reflects their situation.

The PAM model consists of three fundamental components: 1) Palmer amaranth population dynamics; 2) management; and 3) economics. The population dynamics and management components were designed using expert opinion of weed scientists, Drs. M. Bagavathiannan and J. Norsworthy, along with review of existing literature. These components work together to provide output for the comparison of alternate strategies, including annual seedbank size, annual crop yield potential, annual net returns, and net present value (NPV). The NPV represents the sum total of annual net returns over a ten-year planning horizon of crop production and is defined as follows:

(1) $$\text{NPV}= \sum_{\text{i}=1}^{10} \frac{ACNR_i}{(1+k)^{\text{i}}}$$

where NPV is the sum total of economic returns to crop production over a ten-year period expressed in today's dollars (Robison and Barry 1996), $ACNR_i$ are economic returns to crop production for cotton, corn, or soybean production that depend on yield, crop price, and production costs as specified by the user and substantiated by default values using University of Arkansas Cooperative Extension crop cost of production estimates (Flanders et al. 2015; Scott et al. 2016), and k is the annual risk-adjusted, real discount or amortization rate set at 5% to represent a mid-range estimate of discount rates to convert future costs and revenue flows to today's dollars. This discount rate ranges from 3 to 10% in agricultural production analyses as reported by Hardie (1984), although higher values may also be used for very uncertain cashflows. A ten-year planning horizon was chosen to allow the program to cycle through a full 3-year rotation.

The **population dynamics** component of PAM is designed to simulate the life cycle of Palmer amaranth from the spring seedbank through seedbank replenishment at the end of the growing season to estimate the size of the soil weed seedbank and aboveground Palmer amaranth density at varying stages in a growing season (Bagavathiannan et al. 2017). The software measures expected seed production as a factor of "seedling emergence", crop competition, and "density-dependence" (Jha 2008). Palmer amaranth "seedling emergence" occurs from April through September in the Southern region (Jha 2008). The aboveground seedbank population is consequently organized into "cohorts" (Neve et al. 2011) to characterize crop competitiveness, fecundity levels, and the effects of density-dependence on survival, growth, and fecundity of Palmer amaranth (Jha 2008; Massinga et al. 2001).

The **management** sub-model is designed to characterize different crop and weed control options that have potential direct or non-direct effects on weed population dynamics that may produce different outcomes on dispersal of the seedbank and successive seedling emergence. These weed management options affect long-term weed population dynamics and economic benefits. To estimate these direct and/or non-direct effects on weed populations, efficacies were allocated for each management option based on their effects on overall ability to control Palmer amaranth.

The **economics** component of PAM is designed to replicate southern US crop production practices using crop budgeting and discounting techniques to determine overall profitability among strategies surrounding Palmer amaranth management (Kay et al. 2015). One important feature of the PAM model is its ability to demonstrate the magnitude of long-term benefits (NPV) vs. potential short-term losses ($ACNR_i$). Specifically, the NPV represents the economic value of "proactive" resistance management strategies to highlight the savings that would otherwise be spent on additional weed control options if Palmer amaranth resistance was allowed to evolve (Mueller et al. 2005). This type of analysis helps producers to maximize the sum of all earnings over a 10-year period in today's dollars and select the strategy with the highest NPV. Further, the user has the ability to specify discount rates to reflect differences in risk and/or different crop yield improvement over time shows the level of sensitivity to interest rate and yield growth expectations (Lindsay et al. 2017).

The objective of this chapter is thus to describe how a user can develop and interpret a comparison among alternative management strategies to combat Palmer amaranth with hopes to maximize profitability while at the same time minimizing Palmer amaranth seedbank and managing risk. Note that further detailed operating instructions are available in the user manual and tutorials of the software (Lindsay et al. 2017) and not shown here to minimize redundancy.

B. Materials and Methods

General Comments about PAM

The model flow chart provided in Figure 2.1 is designed to assist with understanding the flow of information between the PAM user-interface worksheets, ‘Systems’, ‘Strategy’, and ‘Output’ (Lindsay et al. 2017). The user may define their current operation(s) in the ‘Systems’ worksheet which will be used to generate a default 10-year strategy in the ‘Strategy’ worksheet. From the ‘Strategy’ worksheet, the user may make a number of modifications to the strategy and save up to six strategies for comparison in the ‘Output’ worksheet.

The PAM model is an Excel® program with an ‘.xlsm’ file extension. Because PAM operates in full-screen mode, the user is prompted upon exit (by left-clicking the ‘X’ button in the upper, right corner of the screen) to either save the file, close the file without changes, or return back to the program to restore Excel® back to the default settings that were disabled to ensure proper function of the full-screen mode. The user is, therefore, instructed to run PAM without other Excel® spreadsheets open simultaneously. In the event that PAM is closed without following the above prompts, the user should reopen PAM and re-exit the program as previously described.

The PAM user interface operates through the use of several ‘controls’ including command buttons, userforms, drop-down lists (data validation), and conditional formatting (Lindsay et al. 2017). Command buttons operate via VBA event procedures to automate the processes that permit the user to navigate across worksheets, operate userforms, enter operation parameters or revert to default values, and compare strategies. Userforms allow the user to make parameter specifications based on their current operation. Data validation (via drop-down lists) limits user-specifications to a pre-selected group of options, where necessary, to safeguard the integrity of the software. Lastly, conditional formatting (error checking) notifies the user if a modification to a cell could potentially lead to errors by modifying the appearance of the cell temporarily until the user corrects the error.

Model Design and Implementation

The PAM model follows three steps to modify operation parameters and develop multiple IPM strategies for comparison: 1) "define" the current (default) system(s) to specify the user's current operation parameters or use default values; 2) "build" various management strategies through the modification of crop production and weed management options given attendant crop trait technologies; and 3) "compare" side-by-side output results of various saved strategies (Bagavathiannan et al. 2017).

Parameter Value Settings

While user input for values that vary considerably across location and various operations is allowed, other parameter values, such as herbicide prices and efficacy values related to the ecology and biology of Palmer amaranth were sourced from literature and/or based on expert opinion and, therefore, cannot be modified. A significant portion of these parameter values were attained from a previously developed Palmer amaranth resistance simulation model (Neve et al. 2011) as well as publications cited by Ward et al. (2013). Default parameters pertaining to some of the economic calculations such as expected prices received and yields as well as weed control and other input costs are based on recommendations provided by University of Arkansas Cooperative Extension Service publications and expert opinion (Flanders et al. 2015; Scott et al. 2016).

(1) <u>Step 1: Define the Current Production System using the 'Systems' Worksheet in PAM</u>

Upon left-clicking the 'START' command button on the 'Title' worksheet that appears when the software is first opened, the user will be taken to the 'Systems' worksheet where the user will define their current system by customizing a set of production variables, such as crop rotation, crop traits, yield, expected prices received, and total specified expenses that are further broken down into subcategories as well as current weed densities and herbicide resistance levels. The 'Calculate Total Specified Expenses' userforms, accessed by left-clicking the gray 'Calculate Total Specified Expenses' command button (Figure 2.2(1)), allow for the customization of acre-based input and yield-specific harvest expenses as well as operating interest for each crop. As previously noted, these default values are based on recommendations provided by University of Arkansas Cooperative Extension Service publications (Flanders et al. 2015). Note, the total specified expenses calculated do not include weed control and seed costs at expected yield. The 'Specify Fall Options' userform, accessed by left-clicking the gray 'Specify Fall Options' command button (Figure 2.2(2)), allows the user to specify fall options, such as cost and quantity for field practices, including moldboard ploughing, use of cereal rye and/or cover crop mix, and windrow burning. Broadcast or drill-seed planting methods for fall cover crops may also be specified. Default values for the 'Fall Options' are based on recommendations provided by expert opinion. The user may also modify herbicide application costs, such as labor, fuel, and the amortization (discount) rate and define the level of pre-existing resistance to different herbicides or modes of action as well as the initial weed density. The initial weed density represents the number of Palmer amaranth escapes (in plants per 250 square ft) that were observed during the previous production year (Year 0) for the existing system.

For the purpose of demonstration, two different systems (Figures 2.2 and 2.3) have been defined to show how existing conditions will affect future production cycles. The expected yield, price, total specified expenses, labor and fuel rates, and fall option prices and rates are set at default for both systems and are held constant for the ten-year analysis framework; therefore, the model does not account for changes in yield and prices over time except by way of the discount or amortization rate (Figure 2.2(3)). Setting a higher discount rate than 5%, for example, would represent a higher level of risk for yield and price estimates. Whereas, setting a very low discount rate would represent greater yield growth potential and/or lesser risk.

The differences among these two initial production systems demonstrate their effect on outcomes. The ‘Corn/Cotton/Soybean’ system (Figure 2.2) begins its rotation with corn, followed by cotton and full-season soybean. Note that the user is expected to (Figure 2.2(4)) define a typical crop rotation by selecting from one to three crops and also select up to four crop traits for each crop. These selections form the default settings for the ‘Strategy’ worksheet (Figure 2.4) and may be changed when building various strategies for comparison. In the ‘Corn/Cotton/Soybean’ system, which can be renamed when saving systems, corn production will use crop traits of: ‘Roundup Ready’ in Year 1, ‘Roundup/LibertyLink’ in Year 4, ‘Enlist’ in Year 7, and ‘Conventional’ in Year 10. Likewise, cotton production will use ‘Roundup Ready’ in Year 2, ‘LibertyLink’ in Year 5, and ‘Enlist’ in Year 8. The full-season soybean rotation will use ‘LibertyLink’ in Year 3, ‘Roundup Ready’ in Year 6, and ‘Enlist’ in Year 9. The weed density is set at 16-25 plants per 250 square ft (Very High). The expected (pre-existing) resistance levels for Roundup (glyphosate) and acetolactate synthase (ALS) inhibitors are set at ‘High’ and the expected resistance level for protoporphyrinogen oxidase (PPO) inhibitors is set at ‘Moderate’.

The ‘Diverse Traits’ system, as shown in Figure 2.3 begins its rotation with cotton, followed by corn and full-season soybean. Further, cotton production will use: ‘Glytol/LibertyLink’ in Year 1, ‘LibertyLink’ in Year 4, ‘Glytol/LibertyLink’ in Year 7, and ‘Enlist’ in Year 10. Corn production will use ‘Roundup Ready’ in Year 2, ‘Conventional’ in

Year 5, and ‘Roundup/LibertyLink’ in Year 8. The full-season soybean rotation will use ‘Xtend’ in Year 3, ‘Enlist’ in Year 6, and ‘Xtend’ in Year 9. Note that the weed density (Figure 2.3(1)) is set at 8-15 plants per 250 square ft (High). Like the ‘Corn/Cotton/Soybean’ system, the expected resistance levels for Roundup, ALS- and PPO-inhibiting technology are set at ‘High (Figure 2.3(2)) and are set at ‘Moderate’. The ‘Diverse Traits’ system will be used to generate the default strategy (Figure 2.4) to be used as a starting point for building strategies for comparison. Note that monocrop or two-crop rotations are also possible but not demonstrated here.

(2) Step 2: Build Appropriate Strategies using the ‘Strategy’ Worksheet in PAM using Observable Measures of Biological and Economic Efficacy

Upon left-clicking the blue next arrow in the ‘Systems’ worksheet (Figure 2.3(3)), the user will be taken to the ‘Strategy’ worksheet and the aforementioned ‘default’ strategy (Figure 2.4) will be loaded based on the user specifications provided in the ‘Diverse Traits’ system (Figure 2.3). The user may either use the default strategy or customize and save up to six 10-year strategies for later comparison in the ‘Output’ worksheet. Each strategy should be given a specific name and saved for later recall (Figure 2.4(1)). The user may return to the default strategy at any time by left-clicking the blue ‘Reset Strategy’ in the top, left corner of the worksheet (Figure 2.4(2)). Recall, the default strategy shown in Figure 2.4 uses the ‘Diverse Traits’ system to set the crop rotation and crop trait options.

During modifications, two important points to remember when working in the ‘Strategy’ page are that: 1) the ‘Reset Strategy’ button provides a starting point based on user-specifications in the ‘Systems’ page but does not necessarily generate a good default strategy recommendation that requires no attention from the user; and 2) conditional formatting is added to the bottom portion of the worksheet to guide the user in making appropriate management decisions (Figure

2.4(3)). The warning messages in the top row of the bottom section of the page are color-coded to help the user locate the inefficiencies within the strategy. The remaining two rows use gray with bolded yellow font. These rows provide direction about the current strategy and advise the user to look to the 'Crop rotation' and 'Specific crop trait' selection cells near the top of the strategy to make improvements. The error checking in the default strategy (Figure 2.4(3)) indicates the use of an inappropriate tank mix (yellow highlighting with bolded, italicized font) and a high frequency of 'Round up/LibertyLink' varieties planted (gray highlighting with bolded, yellow font).

As the user makes strategy modifications, they should make note of changes in NPV (Figure 2.4(4)) as defined in Equation 1. A higher NPV represents a more profitable strategy than a lower NPV associated with another strategy. As previously noted, sensitivity analyses may be performed by specifying various amortization rates to show differences in risk and/or crop yield improvements over time and/or expected changes in yield. These changes would be initiated in the 'Systems' page. Similar sensitivity analyses using different input cost and output price trend expectations may also be performed. Note that a strategy is thereby linked to a system and strategy changes always involve linkage to a particular system and attendant input assumptions.

When monitoring changes in the NPV, it is helpful to make note of changes in the blue output cells provided above the strategy selection cells. These values include weed control costs, spring seedbank, yield, and net returns (Figure 2.4(5)). Weed control costs (US dollars per acre) are the sum of estimated costs for selected herbicides technologies and applications, spring soil preparation, row spacing, and fall weed management options. Weed control costs are calculated using estimates provided by University of Arkansas Cooperative Extension Service publications

(Scott et al. 2016). The spring seedbank (000' seeds per 250 square ft) is the number of seeds in the soil in the spring and is estimated by adjusting the number of uncontrolled Palmer amaranth escapes late in the previous production year for possible overwintering seed losses (Bagavathiannan and Norsworthy 2012). Calculations for seedbank modifications are based on factors, such as user-specified weed density, fecundity, and post-dispersal seed loss (Massinga et al. 2001; Jha 2008; Neve et al. 2011; Bagavathiannan and Norsworthy 2012), seedling emergence (Jha 2008; Neve et al. 2011), and estimated "late-season" Palmer amaranth escapes (Neve et al. 2011; Bagavathiannan and Norsworthy 2012) as well as expert opinion. Note that seedling emergence does not equal the spring seedbank for a given year; rather, it is just a portion of the expected total seed in the soil. Yield (per acre) is calculated as the user-specified expected yield multiplied by the percent reduction in yield based on initial user-specified weed density and seedbank changes over time that are affected by management practices selected. Estimates of yield effects with varying Palmer amaranth pressure, is again based on literature (Klingaman and Oliver 1994; Morgan et al. 2001; Massinga et al. 2001; Ward et al. 2013) and expert opinion. Net returns (US dollars per acre) are calculated as the product of yield and the expected price received, less total specified expenses as modified from default values in the 'Systems' page and weed control costs.

In addition to the above measures, the user should pay attention to the risk of evolution resistance using the 'Risk Assessment' feature (Figure 2.4(6) and Figure 2.5) as well as monitor the timing of escapes using the 'Palmer Amaranth Escapes' feature (Figures 2.4(6) and 2.6). The estimated risk of resistance evolution evaluated on a 100 point scoring system using a weighted, 23-parameter model with higher scores indicating a greater risk of developing resistance evolution. Risk assessment parameters include but are not limited to seedbank size as well as user-specified parameters, such as crop rotations and crop traits in rotation, diversity of herbicide selections, and fall management options, and are based on expert opinion. Certain parameters receive a higher weighted value for the first four production years than the remaining years of production (Bagavathiannan et al. 2017). The 'Risk Assessment' shown in Figure 2.5 is based on the default strategy using the 'Diverse Traits' system. The default strategy appears to have a low risk of resistance evolution with a low score of 24 points (Figure 2.4(6)), however the user is reminded that diversified management is "key for preventing/managing resistance" (Norsworthy et al. 2012). Palmer amaranth escapes are the number of uncontrolled plants (per 250 square ft) at the indicated time during the production season (Bagavathiannan and Norsworthy 2012). The number and timing of Palmer amaranth escapes (Figures 2.4(6) and 2.6) provide additional information to help the user to determine when to make changes in management practices to eliminate or reduce the number of escapes occurring in any of the ten years in a strategy. For example, should escapes be high early in the production season, seedbed preparation, row spacing in soybean, burn down herbicide options, and fall options employed in the prior year may be most helpful in preventing future escapes.

For the purpose of demonstration, four different strategies have been defined to show how different types of changes can be made to the strategy options to affect the observable measures discussed above. These strategies are gradually built off the previous strategy, beginning with the default strategy to simulate how a user might use the software to pay attention to observable measures as changes are made to strategies. These changes are discussed in greater detail below and expressed in Table 2.1.

The 'Non-Diverse Options' strategy (Figure 2.7(1-4)) is built using the default strategy with the following modifications: 1) the 'Soil preparation' across all 10 years of production is changed from ‘Shallow Till’ to ‘No-till’ to reflect a strategy concerned with tillage conservation; 2) the ‘Specific crop traits’ for Years 2 through 6 and 9 through 10 have been changed to reflect a strategy that relies heavily on herbicide technologies rather than non-chemical control; and 3) all Fall options, including mouldboard ploughing, cover cropping, and windrow burning during years of soybean production have been removed from the strategy, again to reflect a strategy that relies heavily on herbicide technologies; and 4) inappropriate tank mixes have been adjusted to ensure the operation is using legal mixes. As a result of these changes, the NPV has fallen by more than $1,600 per acre from $1,585 with the default strategy to -$87 per acre (Figure 2.7(5)). The risk of resistance evolution increased from 24 points with the default strategy to 53 points (Figure 2.7(6)). Furthermore, the risk feedback provided via the ‘Risk Assessment’ feature (Figure 2.8) highlights high seedbank size and inadequate herbicide-resistant trait rotations and lack of fall practices as risk factors associated with the strategy and suggests reducing seedbank size by diversifying the strategy with fall options, increasing herbicide-tolerant crop trait rotations, and using cover crops in the fall to reduce the risk of evolution resistance. The number of Palmer amaranth escapes can easily be identified using the ‘Palmer Amaranth Escapes’ feature (Figure 2.9) which shows several escapes occurring within this strategy from mid-June in Year 1 and continuing to occur very frequently throughout the remaining periods of all remaining years of production.

The ‘No Till Poor Seedbank’ strategy (Figure 2.10(1-2)) is built using the ‘Non-Diverse Options’ strategy with the following modifications: 1) the herbicide, ‘Gramoxone’, is added to premergence periods for full-season soybean crops in Years 6 and 9; and 2) the herbicide, ‘Liberty’, is removed from the post emergence periods when corn is planted in Years 2, 5, and 8. Like the previous strategy, the ‘Soil preparation’ across all 10 years for the ‘No Till Poor

Seedbank' strategy also uses the 'No-till' option and the 'Specific crop traits' and 'Fall options' continue to reflect a strategy that relies heavily on herbicide technologies. As a result of these changes, the NPV has increased more than $1,000 per acre from -$87 per acre with the 'Non-Diverse' strategy to $981 per acre (Figure 2.10(3)). Similar to the previous strategy, the risk feedback suggests high seedbank size and inadequate herbicide trait rotations and lack of fall practices as risk factors associated with the strategy and suggests reducing seedbank size by diversifying the strategy with fall options to reduce the risk of evolution resistance. As expected, the risk of resistance evolution remains high with a score of 52 points (Figure 2.10(4)). Palmer amaranth escapes first occur from mid-June in Year 1 and continue to occur very frequently until the eighth year of production and occur a few more times in Year 9, during early-May and early- to mid-June.

The 'Diverse Options' strategy (Figure 2.11(1-2)) is built using the 'No Till Poor Seedbank' strategy with the following modifications: 1) 'Soil preparation' is changed from 'No-till' to 'Shallow Till' in Years 1 and 3; and 2) MB Plough is added to 'Fall' options in Year 1. The resulting NPV has increased from $981 to $2,008 per acre (Figure 2.11(3)). The risk feedback suggests inadequate herbicide trait rotations and lack of fall practices as risk factors associated with the strategy and suggests increasing herbicide-resistant trait rotation and including fall cover crops to reduce the risk of evolution resistance. This is reflected with a lower risk of resistance evolution score of 38 points, down from 52 points with the 'No Till Poor Seedbank' strategy (Figure 2.11(4)). This strategy also shows improvement with the first Palmer amaranth escapes occurring from mid-June in Year 1 until early-June in Year 3.

The 'Fall Option with Shallow Till' strategy (Figure 2.12(1-3)) is built using the 'Diverse Options' strategy with the following modifications: 1) 'Soil preparation' for Year 1 is changed back from ‘Shallow Till’ to ‘No-till’; and 2) a ‘Cover Crop Mix’ is added to ‘Fall’ option for Year 2 and, subsequently, ‘the herbicide, ‘Dicamba’, is automatically added to ‘Burn Down’ in the following year. The resulting NPV has decreased slightly from $2,008 per acre with the ‘Diverse Options’ strategy to $1,977 per acre (Figure 2.12(3)). Again, the risk feedback suggests inadequate herbicide trait rotations and lack of fall practices as risk factors associated with the strategy and suggests increasing herbicide-resistant trait rotation and including more fall cover crops to reduce the risk of evolution resistance. The risk of resistance evolution increased from 38 to 40 points (Figure 2.12(4)); however, Palmer amaranth escapes continue to decrease to minimal levels with the first Palmer amaranth escapes still occurring from mid-June in Year 1 but only continuing to until early-June in Year 2.

(3) Step 3: Compare Output Results using the ‘Output’ Worksheet in PAM

Upon left-clicking the blue next arrow in the ‘Systems’ worksheet, the user will be taken to the ‘Output’ worksheet. This worksheet provides a graphical visualization for easy comparison among strategies saved in the ‘Strategy’ worksheet. These visual comparisons allow for a 10-year comparison of spring ‘Seedbank’ (000’s of Palmer amaranth seeds per 250 square ft), annual yield potential, and annual ‘Net Returns’ (US dollars per acre) as well as the NPV (US dollars per acre) and risk of developing herbicide resistance as a percentage for each of the two strategies selected for comparison.

For the purpose of demonstration, Figure 2.13 and Table 2 provide a side-by-side comparison of the ‘Non-Diverse Options’ and ‘Diverse Options’ strategies (Figures 2.7 and 2.11) to demonstrate how changes made to the strategy options may affect seedbank size, crop yields, net returns, and risk of resistance. Notice that the spring ‘Seedbank’ (000’s per 250 square ft) is quite volatile for the ‘Non-Diverse Options’ strategy (Figure 2.13(1)). Conversely, the ‘Diverse

Options' strategy has low seedbank levels in the first few years of production with seedbank levels at zero in the remaining Years, 4 through 10 (Figure 2.13(1)). Moreover, the 'Yield Potential', as a percentage, for the 'Non-Diverse Traits' strategy shows some volatility, however, for the 'Diverse Options' strategy 'Yield Potential' remains relatively constant at 100 percent for most years with only a slight drop in Year 2 (Figure 2.13(2)). 'Net Returns' (US dollars per acre) show some fluctuation, but remain in the positive range of $168 to $356 per acre with the 'Diverse Options' strategy (Figure 2.13(3)). Conversely, the 'Non-Diverse Options' strategy achieves net returns of at least $168 per acre for the first two years of production only with the remaining years of production experiencing very low net returns or negative net returns as low as -$167 per acre occurring in Years 3, 6, and 9 (Figure 2.13(3)). The risk of evolution resistance scored 53 points for 'Non-Diverse Options' compared to 38 points with the 'Diverse Options' strategy (Figure 2.13(4)). The NPV for the 'Non-Diverse Options' strategy is very low at -$87/acre compared to $2,008/acre for the 'Diverse Options' strategy (Figure 2.13(5)).

C. Results and Discussion

Using the steps described above, PAM demonstrates how users may compare their current production environment to a strategic 10-year production approach to manage Palmer amaranth weed control. Various strategies were developed and described to reveal that even when holding crop rotation and crop trait packages constant, spring soil preparation and fall cultural practices can improve the efficacy of commonly employed herbicide-based weed control methods. Error checking and other automated producer advice along with information on the timing of Palmer amaranth escapes helps the user to quickly pinpoint areas to improve methods of weed prevention in a given strategy. Output comparisons further quantify changes in strategies to assist producers with making complex herbicide management decisions.

This software helps to illustrate how excessive reliance on a single mode of action in herbicides show negative seedbank and economic repercussions that were quite large when comparing initial strategies that relied more heavily on chemical methods to later strategies whose approach to weed control had greater diversity through the integration of chemical and non-chemical methods (Norsworthy et al. 2012). This comparison further helps to highlight the positive relationship between the diversity within a management strategy and the long-run economic implications. Conversely, this comparison also shows the negative consequences of using a strategy with fewer modes of action or one that relies heavily on chemical weed control methods with Palmer amaranth weeds escapes and poor soil seedbank values.

D. Tables

Table 2.1. Strategy Modifications

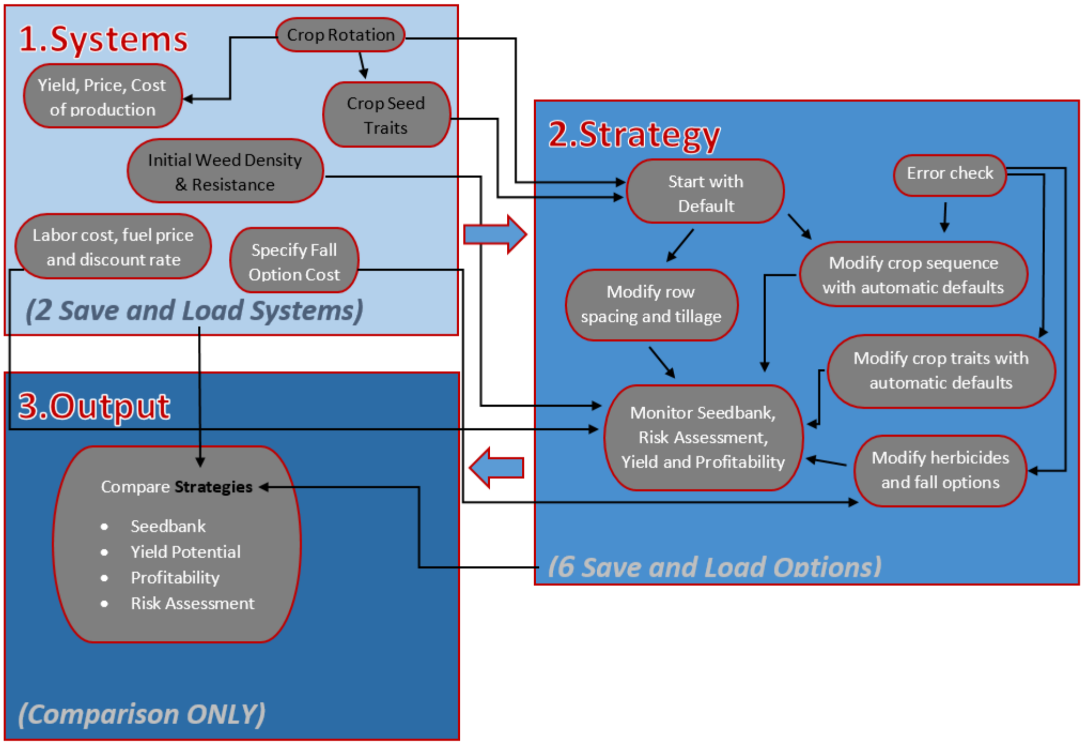
Strategy	Default	Non-Diverse Options	No Till Poor Seedbank	Diverse Options	Fall Option with Shallow Till
Soil Preparation [Year(s)]	Shallow Till [1-10]	No-till [1-10]	No Change	Shallow Till [1&3]	No -till [1]
Specific Crop Trait	Uses 'Diverse Traits' system	Heavy reliance on Roundup and LibertyLink	No Change	No Change	No Change
Herbicide Options [application period – Year(s)]	Uses 'Diverse Traits' system	No Change	+ Gramoxone [pre – 6&9] – Liberty [post – 2,5,&8]	No Change	+ Dicamba [burndown – 3] (following fall Cover Crop Mix in Year 2)
Fall Options [Year(s)]	MB Plough [1] Windrow Burn [3,6,&9] Cover Crop Mix [1] Cereal Rye [2-10]	No fall options to reflect reliance on herbicides only	No Change	+ MB Plough [1]	+ Cover Crop Mix [2]
Error Checking [Year(s)]	Tank Mix errors [3,6,&9] Roundup/LibertyLink planted too frequently	– Tank mix errors + Roundup planted too frequently + LibertyLink planted too frequently	No Change	No Change	No Change
NPV ($/acre)	$1,585	–$87	$981	$2,008	$1,977
Risk Assessment Score (1-100)	24 points	53 points	52 points	38 points	40 points
Risk Assessment Factors	Low resistance evolution risk; no recommendations	Seedbank size, poor crop rotation and fall practices	No Change	Poor crop trait rotations and fall practices only	No Change
Palmer amaranth Escapes (plants/250 sqft) [Year(s)]	Mid-June to early July [1] Mid-May to early July [2&3]	Mid-June [1] and continues frequently through [2-10]	Less frequent from early-May and early- to mid-June [9]	Less frequent [1-6]	Mid-June [1] to early-June [2] only

Table 2.2. Output Comparison of ‘Non-Diverse Options’ versus ‘Diverse Options’ Strategies

Strategy	**Non-Diverse Options**	**Diverse Options**
Annual spring Seedbank (000’s/205 sqft) [Year(s)]	High seedbank levels [4, 7, & 10]	Low seedbank levels [1-3]; Seedbank levels at zero (0) [4-10]
Yield Potential (percent) [Year(s)]	Volatility across [1-10]; Lowest yield potential [3, 6, & 9]	Steady near 100% [1-10];
Net Returns ($/acre)	Net returns ≥ $188/acre [1-2]; Very low [3-10]; with Negative returns ≤ –$167 [3, 6, & 9]	Net returns ≥$168/acre [1-10]
Risk of Resistance Evolution Score (100 point scale)	53 points	38 points
NPV ($/acre**)**	-$87	$2,008

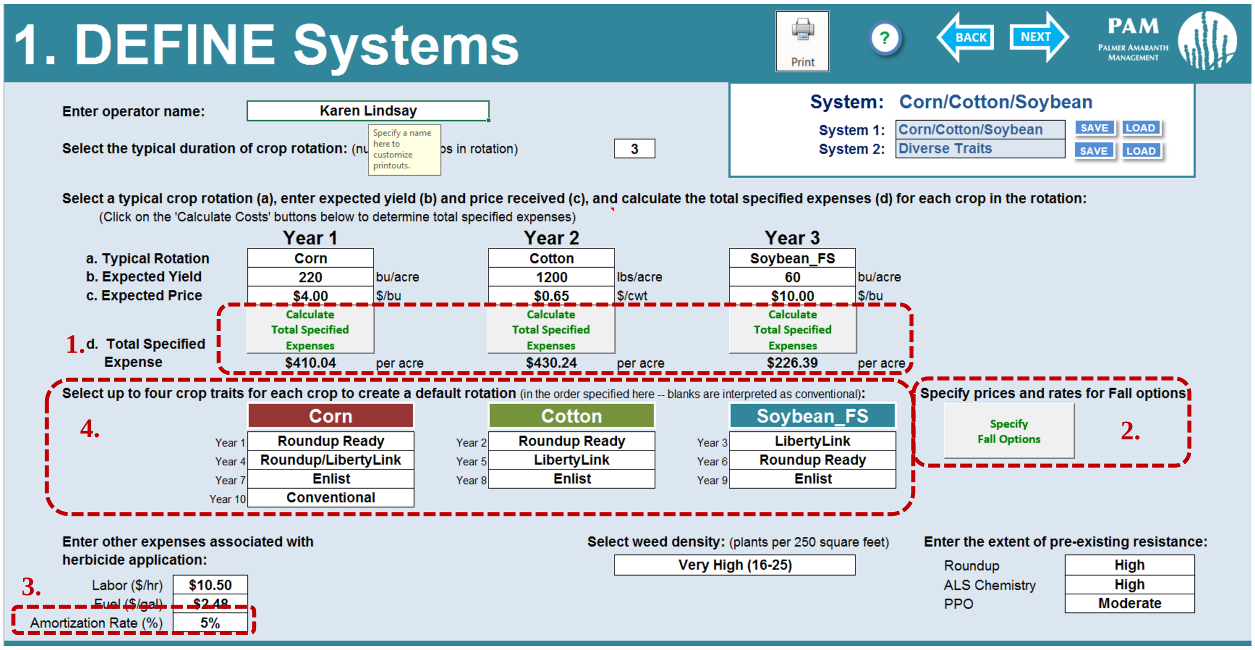
E. Figures

Figure 2.2. Model Flow Chart



Source: PAM User Manual (Lindsay et al. 2017)

Figure 2.2. ‘Corn/Cotton/Soybean’ System

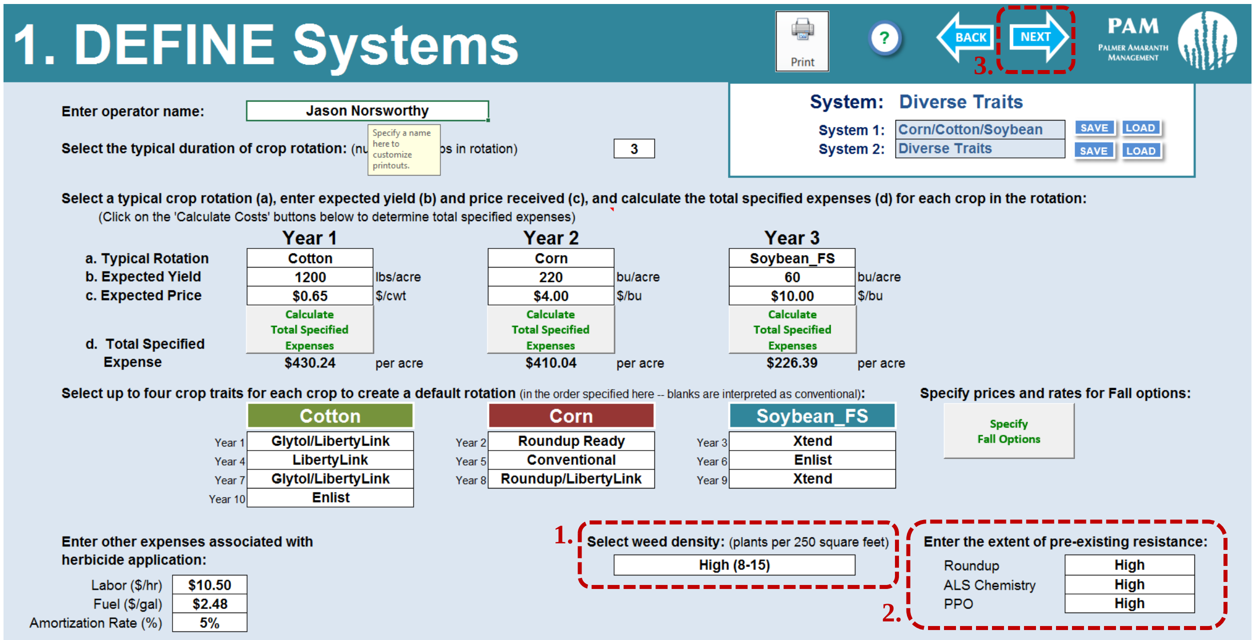


Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. The user may enter appropriate expenses for crop rotation using the ‘Calculate Total Specified Expenses’ command buttons.
2. The user may enter appropriate expenses for fall management options using the ‘Specify Fall Options’ command button.
3. The user may enter amortization rate based on anticipated level of risk associated with the operation.
4. The user may define a typical production rotation to generate default settings for the ‘Strategy’ worksheet.

Figure 2.3. ‘Diverse Traits’ System

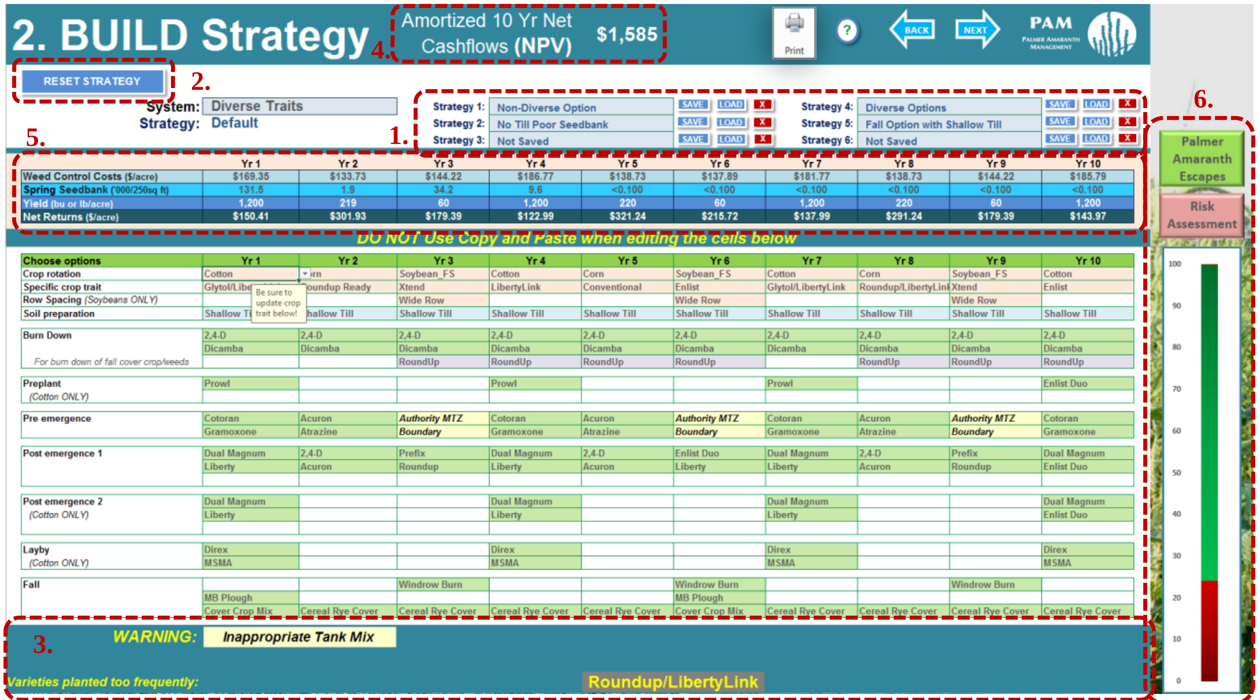


Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. Weed density is set at High (8-15 plants per 250 square ft).
2. Pre-existing resistance to Roundup, ALS- and PPO-inhibiting herbicides is set at high.
3. Left-click the ‘Next’ arrow (command button) to navigate to the ‘Strategy’ worksheet.

Figure 2.4. Default Strategy

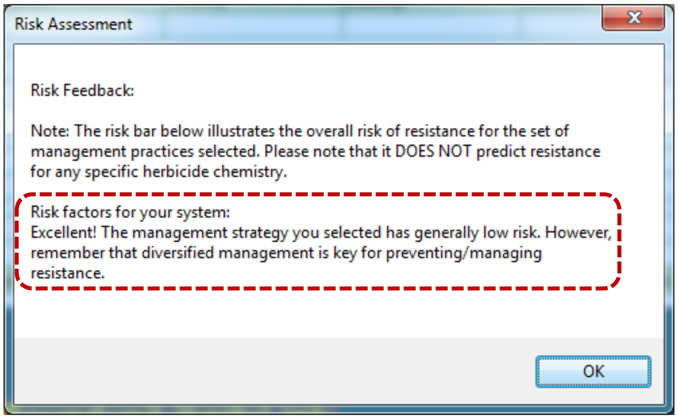


Source: PAM (Bagavathiannan et al. 2017)

Notes:

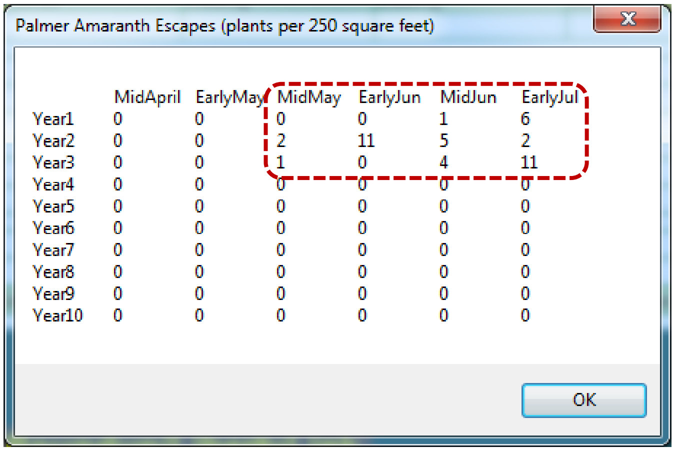
1. The user may save and assign names for up to six strategies for later comparison.
2. The user may recall default strategy by left-clicking the ‘Reset Strategy’ command button.
3. The user may use the conditional formatting (error checking) provided to identify potential errors or inefficiencies within the current strategy.
4. The user may use the net present value (NPV) as a guide to evaluate the long-run economic implication of strategic decisions.
5. The user may use biological and economic values in the blue output cells above the strategy selection cells as a guide to making appropriate modifications to the current strategy.
6. The user may monitor the risk of evolution resistance by left-clicking the ‘Risk Assessment’ button as well as monitor the timing of escapes by left-clicking the ‘Palmer Amaranth Escapes’ button.

Figure 2.5. Risk Assessment for the Default Strategy



Source: PAM (Bagavathiannan et al. 2017)
Note: The default strategy has a generally low risk of evolution resistance, however, diversified management is encouraged.

Figure 2.6. Palmer Amaranth Escapes by Year for the Default Strategy

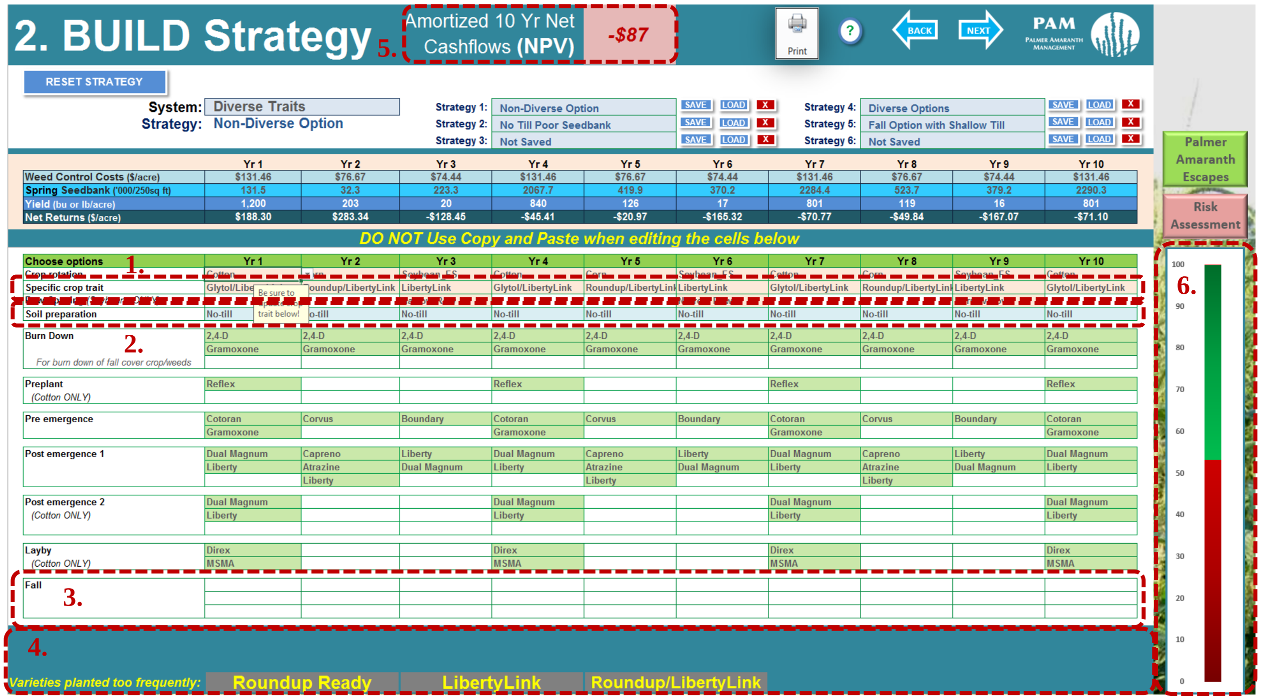

Palmer Amaranth Escapes (plants per 250 square feet)

	MidApril	EarlyMay	MidMay	EarlyJun	MidJun	EarlyJul
Year1	0	0	0	0	1	6
Year2	0	0	2	11	5	2
Year3	0	0	1	0	4	11
Year4	0	0	0	0	0	0
Year5	0	0	0	0	0	0
Year6	0	0	0	0	0	0
Year7	0	0	0	0	0	0
Year8	0	0	0	0	0	0
Year9	0	0	0	0	0	0
Year10	0	0	0	0	0	0

Source: PAM (Bagavathiannan et al. 2017)

Note: Initial Palmer amaranth escapes (plants per 250 square ft) occur during Year 1 from mid-June to early July. Escapes reoccur during Years 2 and 3 from mid-May through early July.

Figure 2.7. ‘Non-Diverse Options’ Strategy

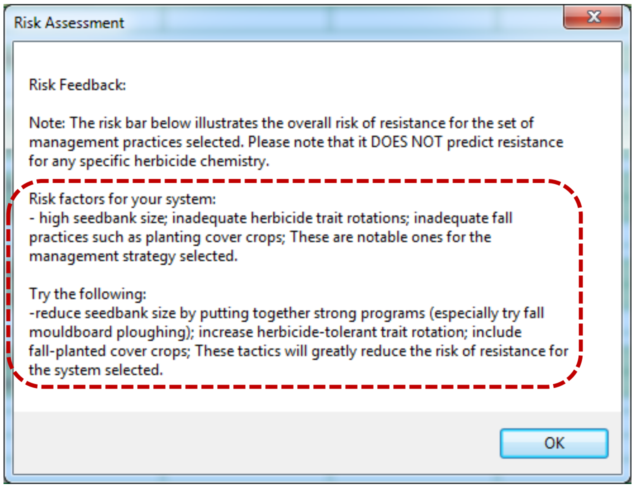


Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. The ‘Soil preparation’ is changed from ‘Shallow Till’ to ‘No-till’ to reflect a strategy using tillage conservation.
2. The ‘Specific crop traits’ have been changed to reflect a strategy that relies heavily on herbicide technologies.
3. All ‘Fall’ options have been removed from the strategy to reflect a strategy that relies heavily on herbicide technologies.
4. Inappropriate tank mixes have been adjusted to ensure the operation is using legal mixes.
5. Net present value (NPV) decreased from $1,585 per acre with the default strategy to -$87 per acre.
6. The risk of resistance evolution increased from 24 points with the default strategy to 53 points.

Figure 2.8. Risk Assessment for the 'Non-Diverse Options' Strategy



Source: PAM (Bagavathiannan et al. 2017)

Note: The risk feedback provided highlights high seedbank size and inadequate fall practice as risk factors associated with the strategy and suggests reducing seedbank size by diversifying the strategy with fall options, increasing herbicide-tolerant crop trait rotations, and using cover crops in the fall to reduce the risk of evolution resistance.

Figure 2.9. Palmer Amaranth Escapes for the 'Non-Diverse Options' Strategy

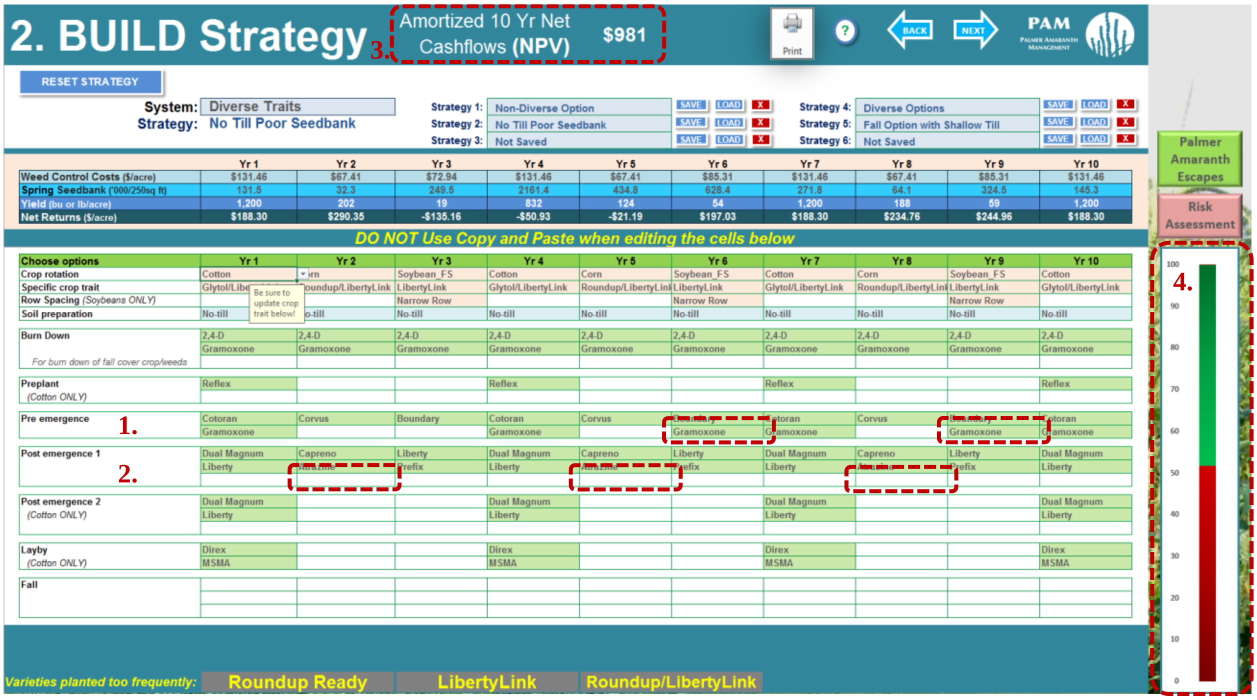
Palmer Amaranth Escapes (plants per 250 square feet)

	MidApril	EarlyMay	MidMay	EarlyJun	MidJun	EarlyJul
Year1	0	0	0	0	1	7
Year2	342	0	19	107	90	31
Year3	342	1	0	1	1	0
Year4	3	1	0	1	10	110
Year5	0	0	220	1272	1070	361
Year6	672	1	1	1	1	0
Year7	3	1	0	2	11	120
Year8	0	0	253	1463	1230	415
Year9	682	2	1	1	1	0
Year10	3	1	0	2	11	120

Source: PAM (Bagavathiannan et al. 2017)

Note: Palmer amaranth escapes (plants per 250 square ft) occur within this strategy from mid-June in Year 1 and continue to occur very frequently throughout the remaining periods of all remaining years of production.

Figure 2.10. ‘No Till Poor Seedbank’ Strategy

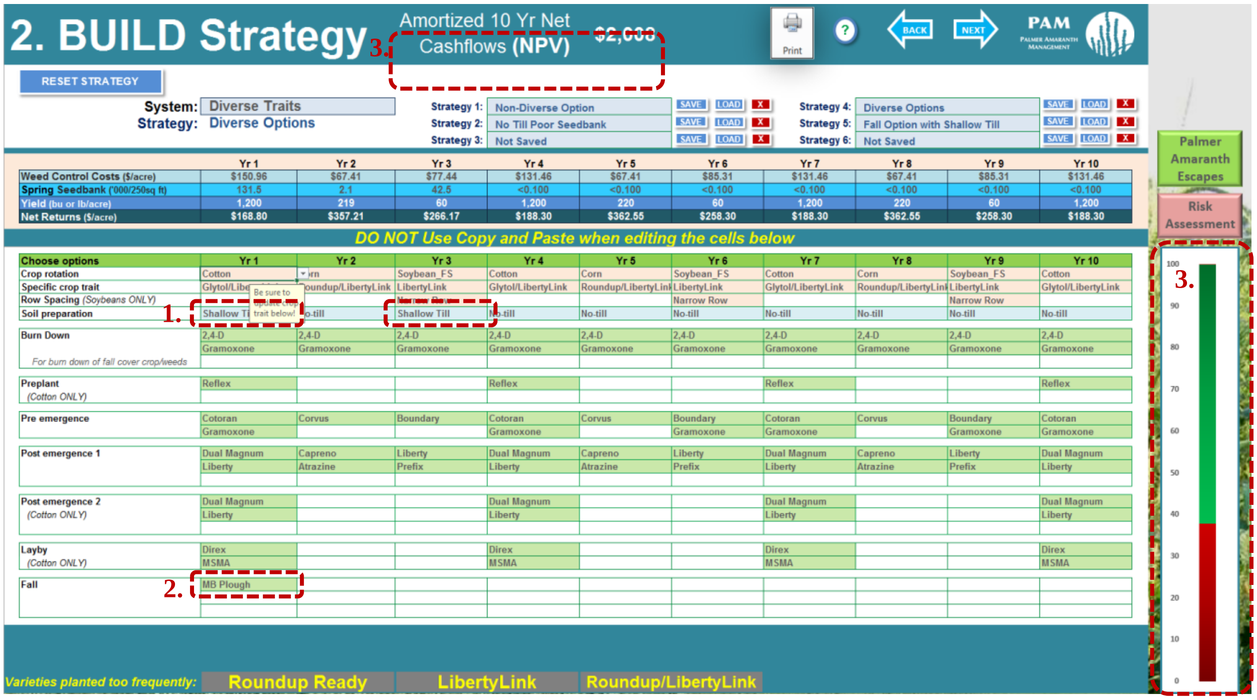


Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. ‘Gramoxone’ is added to preemergence periods for full-season soybean crops in Years 6 and 9.
2. ‘Liberty’ is removed from the postemergence periods when corn is planted in Years 2, 5, and 8.
3. Net present value (NPV) increased from -$87 with the ‘Non-Diverse Options strategy to $981 per acre.
4. The risk of resistance evolution decreased slightly from 53 points with the ‘Non-Diverse Options’ strategy to 52 points.

Figure 2.11. ‘Diverse Options’ Strategy

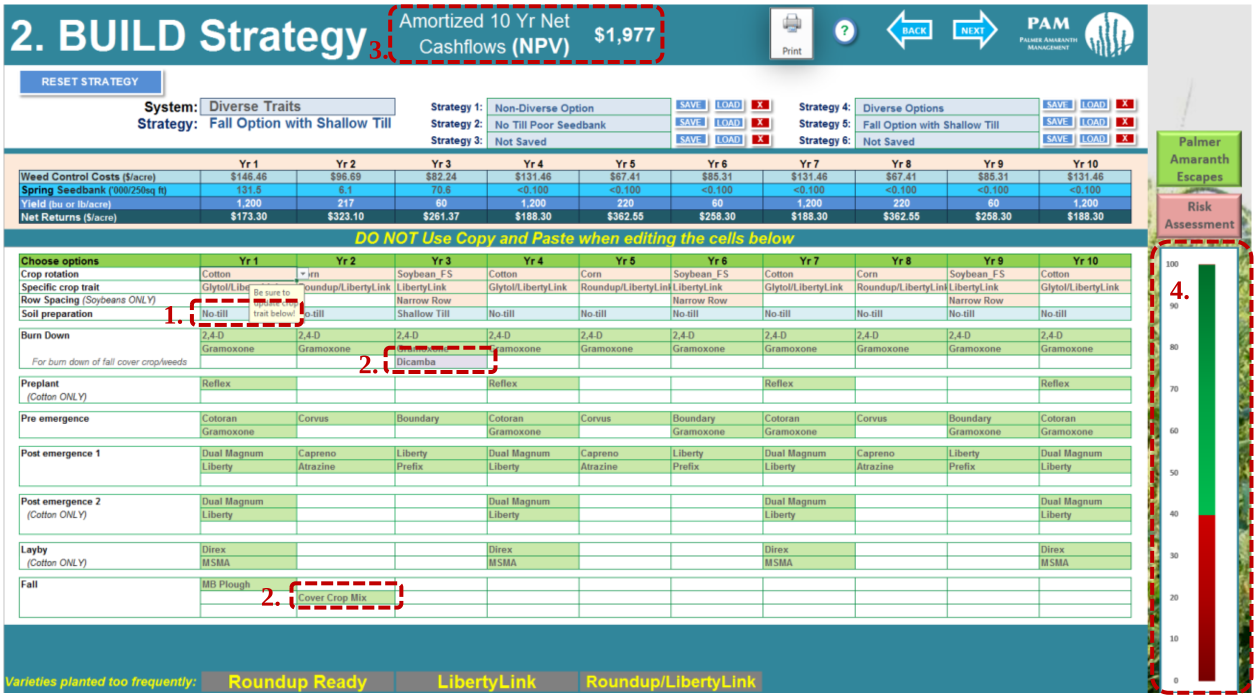


Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. ‘Soil preparation’ is changed from ‘No-till’ to ‘Shallow Till’ in Years 1 and 3.
2. Mouldboard plough is added as a ‘Fall’ options in Year 1.
3. Net present value (NPV) has increased from $981 per acre with the ‘No Till Poor Seedbank’ strategy to $2,008 per acre.
4. The risk of resistance evolution decreased from 52 points with the ‘No Till Poor Seedbank’ strategy to 38 points.

Figure 2.12. ‘Fall Option with Shallow Till’ Strategy

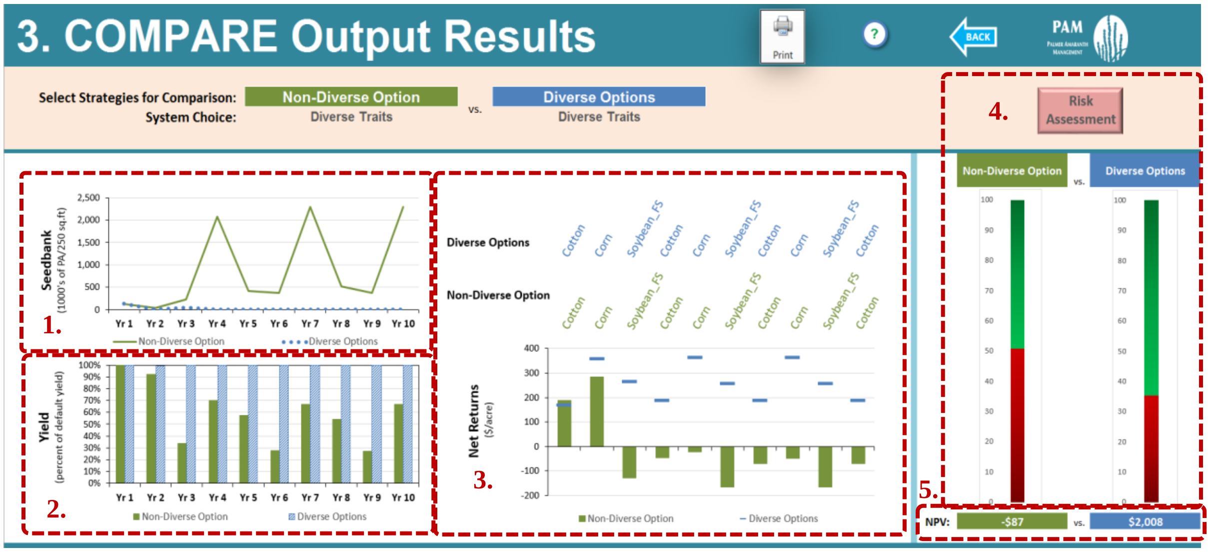


Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. ‘Soil preparation’ is changed back from ‘Shallow Till’ to ‘No-till’ for Year 1 only.
2. ‘Cover Crop Mix’ is added as a ‘Fall’ option in Year 2 and Dicamba is automatically added to ‘Burn Down’ in Year 3.
3. Net present value (NPV) has decreased from $2,008 per acre with the ‘Diverse Options’ strategy to $1,977 per acre.
4. The risk of resistance evolution increased slightly from 38 points with the ‘Diverse Options’ strategy to 40 points.

Figure 2.13. Output Comparison of 'Non-Diverse Options' and 'Diverse Options' Strategies



Source: PAM (Bagavathiannan et al. 2017)

Notes:

1. Spring 'Seedbank' (000's per 250 square ft) is volatile for the 'Non-Diverse Options' strategy. The 'Diverse Options' strategy has low seedbank levels in the first few years of production with seedbank levels at zero in the remaining Years, 4 through 10.
2. 'Yield' potential, as a percentage, for the 'Non-Diverse Options' strategy shows some volatility. The 'Diverse Options' strategy yield levels are at 100% for most years with only a slight drop in Year 2.
3. 'Net Returns' (US dollars per acre) show some fluctuation, but remains in the positive range of $168 to $356 per acre with the 'Diverse Options' Strategy. The 'Non-Diverse Options' strategy achieves net returns of at least $168 per acre for the first two years of production with the remaining years of production experiencing very low net returns or negative net returns as low as -$167 per acre.
4. The risk of evolution resistance the 'Non-Diverse Options' strategy scored 51 points out of 100 compared to the 'Diverse Options' strategy at 35 points.
5. The NPV for the 'Non-Diverse Options' strategy is experiencing a loss at -$87 per acre compared to $2,008 per acre for the 'Diverse Options' strategy.

F. References

Australian Herbicide Resistance Initiative (AHRI). 2013. "RIM: Ryegrass Integrated Management-Australian Herbicide Resistance Initiative." The University of Australia. Accessed August 2015. http://www.ahri.uwa.edu.au/RIM.

Bagavathiannan, M.V., K.R. Lindsay, M.P. Popp, and J.K. Norsworthy. 2017. "Palmer Amaranth Management." The University of Arkansas. http://agribusiness.uark.edu/decision-support-software.php#PAM.

Bagavathiannan, M.V. and J.K. Norsworthy. 2012. "Late-Season Seed Production in Arable Weed Communities: Management Implications." Weed Science 60(3):325-334. DOI: http://dx.doi.org/10.1514/WS-D-11-00222.1.

Flanders, A., R. Baker, T. Barber, T. Faske, H. Ginn, C. Grimes, J. Hardke, K. Lawson, G. Lorenz, R. Mazzanti, C. Norton, B. Robertson, and G. Studebaker. 2015. "2015 Crop Production Budgets for Farm Planning." University of Arkansas Cooperative Extension Service, Division of Agriculture. Accessed September 2016. http://uaex.edu/farm-ranch/economics-marketing/farm-planning/budgets/Budget_Text_2015.pdf.

Hardie, I.W. 1984. "Comparative Rents for Farmland and Timberland in a Subregion of the South." Southern Journal of Agricultural Economics 16(2):45-53.

Jha, P. 2008. "Biology and Ecology of Palmer amaranth (Amaranthus palmeri) and Tall Morningglory (Ipomoea purpurea)." PhD Thesis, Clemson University, USA.

Kay, R.D., W.M. Edwards, and P. Duffy. 2015. "Farm Management." Eighth Edition. New York, NY: McGraw-Hill Book Company.

Klingaman, T.E. and L.R. Oliver. 1994. "Palmer amaranth (Amaranthus palmeri) Interference in Soybeans (Glycine max)." Weed Science 42(4):523-527. URL: http://www.jstor.org/stable/4045448.

Lacoste, M. and S. Powles. 2014. "Upgrading the RIM Model for Improved Support of Integrated Management Expansion Efforts in Cropping Systems." Weed Technology 28(4):703-720. DOI: http://dx.doi.org/10.1614/WT-D-14-00020.1.

Lacoste, M. and S. Powles. 2015. "RIM: Anatomy of a Weed Management Decision Support System for Adaptation." Weed Science 63(3):676-689. DOI: http://dx.doi.org/10.1614/WS-D-14-00163.1.

Lacoste, M. and S. Powles. 2016. "Beyond Modelling: Considering User-Centered and Post-Development Aspects to Ensure the Success of a Decision Support System." Computers and Electronics in Agriculture 121(1):260-268. DOI: http://dx.doi.org/10.1016/j.compag.2016.01.003.

Lindsay, K.R., M.P. Popp, M.V. Bagavathiannan, and J.K. Norsworthy. 2017. "Palmer Amaranth Management User Manual." The University of Arkansas.

http://agribusiness.uark.edu/decision-support-software.php#PAM.

Massinga, R.A., R.S. Currie, M.J. Horak, and J Boyer Jr. 2001. “Interference of Palmer amaranth in Corn.” Weed Science 49(2):202-208. DOI: http://dx.doi.org/10.1614/0043-1745(2001)049[0202:IOPAIC]2.0.CO;2.

Morgan, G.D., P.A. Bauman, and J.M. Chandler. 2001. “Competitive Impact of Palmer Amaranth (Amaranthus palmeri) on Cotton (Gossypium hirutum) Development and Yield.” Weed Technology 15(3):408-412. DOI: http://dx.doi.org/10.1614/0890-037X(2001)015[0408:CIOPAA]2.0.CO;2.

Mueller, T.C., P.D. Mitchell, B.G. Young, and A.S. Culpepper. 2005. “Proactive Versus Reactive Management of Glyphosate-Resistant or -Tolerant Weeds.” Weed Technology 19(4):924–933. DOI: http://dx.doi.org/10.1614/WT-04-297R.1.

Neve, P., J.K. Norsworthy, K.L. Smith, and I.A. Zelaya. 2011. “Modeling Glyphosate Resistance Management Strategies for Palmer amaranth (Amaranthus palmeri) in Cotton.” Weed Technology 25(3):335-343. DOI: http://dx.doi.org/10.1614/WT-D-10-00171.1.

Norsworthy, J.K., S.M. Ward, D.R. Shaw, R.S. Llewellyn, R.L. Nichols, T.M. Webster, K.W. Bradley, G. Frisvold, S,B. Powles, N.R. Burgos, W.W. Witt, and M. Barrett. 2012. “Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations.” Weed Science 60(Sp1):31-62. DOI: http://dx.doi.org/10.1614/WS-D-11-00155.1.

Scott, R. C., L. T. Barber, J. W. Boyd, G. Selden, J. K. Norsworthy, and N. Burgos. 2016. “Recommended Chemicals for Weed and Brush Control.” Vers. MP-44. University of Arkansas Cooperative Extension Service, Division of Agriculture. Accessed January 2016. http://www.uaex.edu/publications/pdf/mp44/mp44.pdf.

Robison, L.J. and P.J. Barry. 1996. “Present Value Models and Investment Analysis.” Northport, Ala: The Academic Page, pp. 15-17.

United States Department of Agriculture (USDA), National Institute of Food and Agriculture (NIFA). 2013. “National Roadmap for Integrated Pest Management.” Accessed January 2017. https://nifa.usda.gov/sites/default/files/resources/National%20Road%20Map%20for%20Integrated%20Pest%20Management.pdf.

Ward, S.M., T.M. Webster, and L.E. Stekel. 2013. “Palmer amaranth (Amaranthus palmeri): A Review.” Weed Technology 27(1):12-27.

III. Conclusion

A. Project Summary

The objective of the PAM model was to develop a DSS program to encourage the use of IPM methods of Palmer amaranth weed control, specifically to improve long-term soil seedbank levels and economic benefits (Lindsay et al. 2017). The software was developed as an educational tool to provide producers, crop consultants, and educators affected by herbicide-resistant Palmer amaranth with a better understanding of IPM methods to realize long-term biological and economic sustainability by improving the long-term effectiveness of current herbicide technologies and reduce the human health risks and environmental effects associated with resistance to herbicide use (USDA 2013). Importantly, the model provides estimates that quantify the effect of various chemical and non-chemical weed control options that are easily tailored to a user-specific situation.

Model Use Caveats

This model uses default values that are based on existing literature and expert opinions in addition to user-specifications. The output results generated are strictly estimates and users are cautioned to “use their own judgment” when determining whether the output results are appropriate for their operation prior to making production changes (Lindsay et al. 2017).

Model Limitations

The PAM software is designed as an educational tool for use by corn, cotton, and soybean producers, extension agents, crop consultants, and other educators and researchers who wish to learn the advantages of various IPM methods. Several customizable input parameters are used to generate a default management strategy based on a user-specified situation as a starting point from which to build several IPM strategies for comparison. However, this default strategy does not represent a recommended management program. The main purpose of this software is to educate the user on the advantages/disadvantages of using different combinations of IPM techniques using what-if analyses. Note that PAM is not designed as a forecast model; rather, it is strictly meant to be a "demonstration-based" DSS to show potential changes in biology and economics in the long-term with changes in weed management options. Likewise, although PAM considers herbicide-resistance levels present and the possibility of evolution resistance, PAM should not be used to simulate herbicide resistance associated with a specified strategy. Moreover, PAM is a deterministic model and therefore does not provide information on variations across years and/or production parameters. The model is only expected to provide an average response for a given strategy. Fixed costs, such as equipment and other capital costs, are excluded from economic measures because the software is designed for existing operations that are with this capital already in use (Lindsay et al. 2017). Finally, PAM is intended to track the effect of selected management options on Palmer amaranth only; therefore, any observed changes in biological or economic output with respect to the deletion of or changes in herbicide options in strategy selections do not reflect the effect of those changes on other invasive species that may be present in the production area.

B. Future Modeling

The PAM model may be expanded to include other crops affected by Palmer amaranth, such as peanuts (*Arachis hypogaea* L.) (Culpepper et al. 2006; Ward et al. 2013), rice (*Oryza sativa* L.) (Norsworthy et al. 2013), and wheat (*Triticum aestivum* L.) (Webster and Nichols 2012). In Arkansas, Norsworthy et al. (2013) identified Palmer amaranth and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] as the "most troublesome" weeds among rice crop consultants. Future modeling may, therefore, be developed for the purpose of educating those involved in the production of crops that are affected by other invasive species in the southern US. Such invasive species include but are not limited to morning glory [*Ipomoea* (spp.)] among corn, cotton, and soybean production or nutsedges [*Cyperus* (spp.)] for cotton and soybean production (Webster and Nichols 2012). Along with Palmer amaranth, Riar et al. (2013) also identified morning glory [*Ipomoea* (spp.)] as the most troublesome weeds across Arkansas, Louisiana, Mississippi, and Tennessee in addition to barnyardgrass and horseweed [*Conyza canadensis* (L. Cronq.)] in Arkansas and Tennessee, and Italian ryegrass [*Lolium perenne* (L. ssp.) *multiflorum* (Lam.)] in Louisiana and Mississippi.

Furthermore, modifications to the user interface may be made more efficient if future modeling was designed with default settings in Microsoft Excel® rather than full-screen mode. Although PAM was initially designed in full-screen mode to enhance the user experience and provide added securities, this feature comes at the expense of slower run times and the need for additional display alerts on entry and exit to ensure Excel® is returned to default settings prior to exit. These issues may lead to user frustration and could limit the software's ability to achieve its objectives. In addition, the software may be locked and password protected without the application of full-screen mode. One possible solution to the above mentioned programming needs and pitfalls that come with the existing software platform could be to work with an internet-based platform in the future. This would eliminate the need for file sharing and the associated security implications while still providing the desired enhanced user experience and ease of access; however, a web-based platform may be too limited for a program that consists of a multitude of complex calculations and allows as much flexibility as PAM.

C. References

Culpepper, S.A., T.L. Grey, W.K. Vencill, J.M. Kichler, T.M. Webster, S.M. Brown, A.C. York, J.W. Davis, and W.W. Hanna. 2006. "Glyphosate-Resistant Palmer amaranth (Amaranthus palmeri) Confirmed in Georgia." Weed Science 54(4):620-626. DOI: http://dx.doi.org/10.1614/WS-06-001R.1.

Lindsay, K.R., M.P. Popp, M.V. Bagavathiannan, and J.K. Norsworthy. 2017. "Palmer Amaranth Management User Manual." The University of Arkansas. http://agribusiness.uark.edu/decision-support-software.php#PAM.

Norsworthy, J.K., J. Bond, and R.C. Scott. 2013. "Weed Management Practices and Needs in Arkansas and Mississippi." Weed Technology 27(3):623-630. DOI: http://dx.doi.org/10.1614/WT-12-00172.1.

Riar, D.S., J.K. Norsworthy, L.E. Steckel, D.O. Stephenson, T.W. Eubanks, and R.C. Scott. 2013. "Assessment of Weed Management Practices and Problem Weeds in the Midsouth United States-Soybean: A Consultant's Perspective." Weed Technology 27(3):604-611. DOI: http://dx.doi.org/10.1614/WT-D-12-00167.1.

United States Department of Agriculture (USDA), National Institute of Food and Agriculture (NIFA). 2013. "National Roadmap for Integrated Pest Management." Accessed January 2017. https://nifa.usda.gov/sites/default/files/resources/National%20Road%20Map%20for%20Integrated%20Pest%20Management.pdf.

Ward, S.M., T.M. Webster, and L.E. Stekel. 2013. "Palmer amaranth (Amaranthus palmeri): A Review." Weed Technology 27(1):12-27.

Webster, T.M. and R.L. Nichols. 2012. "Changes in the Prevalence of Weed Species in the Major Agronomic Crops of the Southern United States: 1994/1995 to 2008/2009." Weed Science 60(2):145-157.