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Use of Harvest Weed Seed Control Strategies in Arkansas Soybean

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

by

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Bachelor of Science in Agriculture, 2014

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Abstract

Today, most growers use chemical weed management programs; however, a sole reliance on herbicides will place more resistance selection pressure on the weeds to which the herbicide is being applied. As herbicide resistance continues to grow and rob growers of yield, alternative weed control options are being sought to create complex integrated weed management programs to prolong the use of effective herbicides. Harvest weed seed control (HWSC) is a non-chemical practice that has been widely adopted in Australia due to herbicide resistance problems. In most cases, herbicide-resistant weeds that survive applications of herbicides produce viable seed that pass through the combine during crop harvest. HWSC focuses on lowering the soil seedbank by targeting weed seeds that pass through a combine at harvest. Experiments were conducted at the University of Arkansas in 2014 and 2015 to test the efficacy of HWSC on weeds in a soybean production system. Palmer amaranth, which has been deemed the most troublesome weed in the U.S., retains better than 97% of its seed at crop maturity, making it a viable option for seed capture and destruction during harvest. The efficacy of narrow-windrow burning was tested on two small- and large-seeded grass and broadleaf weeds (Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory). All seed exposed to narrow-windrow burning treatments were killed. These data suggest that integration of HWSC into current weed management programs in soybean will be a valuable asset to lowering the soil seedbank and ultimately lowering the resistance selection pressure that is placed on herbicides due to lower weed densities.

Acknowledgments

The author would like to thank Bayer CropScience and the Arkansas Soybean Promotion Board for the funding of this project. I would also like to thank God, my wife, my family, and Dr. Jason Norsworthy for pushing me to do my best and providing guidance during the course of this work.

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List of Published Papers

A portion of the data from Chapter 2 appear in the following published manuscript:

Schwartz-Lazaro LM, Green JK, Norsworthy JK (2017) Seed retention of Palmer amaranth (*Amaranthus palmeri*) and barnyardgrass (*Echinochloa crus-galli*) in soybean. Weed Technol 31:617-622

Chapter One

General Introduction

The soybean industry in the United States (U.S.) produced 119,488,296.1 metric tons (4.39 billion bushels) in 2017 and Arkansas ranks eleventh nationally producing 4,858,464.9 metric tons (178.5 million bushels) (USDA-NASS 2017). Soybean is an annual legume belonging to the Fabaceae family and contributes approximately 18.7 billion USD to the U.S. economy (Wilson 2008). In 2017, Arkansas farmers planted 1,428,570 ha (3,530,000 A) of soybean, with an average yield of 3,433 kg ha^{-1} (51 bu A^{-1}) (USDA-NASS 2017).

The Arkansas soybean industry is primarily based on the highly fertile land in the eastern portion of the state throughout the Mississippi Delta. The crop is planted usually in late May to early June or once the soil temperature reaches approximately 13 C (55 F) by 9:00 A.M. for three consecutive days (UAEX 2018 Soybean Quick Facts). In Arkansas, soybean can be planted in either single or twin-rows with row spacing ranging from 18 to 97 cm (7 to 38 inches).

Soybean grain is comprised of approximately 38% protein and 18% oil (NCSPA 2011), making it a valuable oilseed crop and protein source. Soybean grain is processed into many different products such as bio-diesel blends, soy foods for human consumption, lubricants, and paint (Wilson 2008; NCSPA 2011). However, despite the importance of soybean to the global economy, proper weed management in a soybean cropping system remains a challenge, especially in lieu of herbicide resistance.

Agriculture has many troublesome weeds. In Arkansas, the most troublesome weeds in soybean are Palmer amaranth [*Amaranthus palmeri* (S.) Wats.], morningglory spp., barnyardgrass [*Echinochloa crus-galli* (P.) Beauv.], horseweed [*Conyza canadensis* (L.) Cronq.], hemp sesbania (*Sesbania herbacea* Scop.), sicklepod [*Senna obtusifolia* (L.) H.S. Irwin &

Barneby], and prickly sida (*Sida spinosa* L.) (Riar et al. 2013). A few of these problematic weeds are discussed in more detail below.

Palmer amaranth, a member of the Amaranthaceae family, is considered the most troublesome weed in Arkansas soybean (Riar et al. 2013). Palmer amaranth can reduce soybean yield up to 68%, depending on population size (Klingaman and Oliver 1994). Severe infestations in Arkansas production fields, has often resulted in soybean crops being abandoned (J.K. Norsworthy, personal communication). Palmer amaranth poses many problems due to its ability to evolve resistance to various herbicides including glyphosate. In Arkansas, glyphosate-resistant Palmer amaranth was first discovered in 2005 (Norsworthy et al. 2008). Additionally, Palmer amaranth has confirmed resistance to a wide array of acetolactate synthase-inhibiting herbicides (Heap 2018).

A single female Palmer amaranth plant can produce as many as 600,000 seeds (Keeley et al. 1987). As a result of its small seed size and high fecundity, glyphosate-resistant Palmer amaranth can rapidly colonize a crop production field if diverse management strategies are not integrated into the current production system in a swift manner (Norsworthy et al. 2014a). If herbicide application is not properly timed, some plants can escape control methods and produce seed that can lead to a buildup of the soil seedbank and increase risks of herbicide resistance in subsequent cropping years (Norsworthy et al. 2012).

Barnyardgrass is a summer annual and is considered the 8th most troublesome weed of soybean and the most troublesome weed of rice in Arkansas (SWSS 2012). Furthermore, barnyardgrass can reduce rice and soybean yields by up to 89 and 78%, respectively (Smith Jr. 1968; Vail and Oliver 1993). Currently Arkansas populations of barnyardgrass have evolved resistance to propanil, quinclorac, imazethapyr, and clomazone (Talbert and Burgos 2007;

Norsworthy et al. 2009; Riar et al. 2012). This potential for resistance evolution clearly highlights the need for other mechanisms for controlling barnyardgrass.

Johnsongrass [*Sorghum halepense* (L.) Pers.] and pitted morningglory (*Ipomoea lacunosa* L.) are also problematic weeds of Arkansas cropping fields. Johnsongrass is characterized as being an erect perennial grass with large underground rhizomes (Bryson and DeFelice 2009). Previous research has confirmed resistance to glyphosate, imazethapyr (Johnson et al. 2014) and fluazifop (J.K. Norsworthy, personal communication) in populations of johnsongrass from Arkansas.

Pitted morningglory is characterized as a climbing or vine-like annual that has deeply lobed cotyledons and glabrous leaves (Bryson and DeFelice 2009). Pitted morningglory has no known resistance to herbicides but does form a highly persistent seedbank (Norsworthy and Oliver 2002; Stephenson et al. 2006). Pitted morningglory interference with soybean can reduce yields by as much as 81% with the vines hindering crop harvest (Norsworthy and Oliver 2002).

Late season canopy closure in soybean provides ideal conditions for weeds to thrive (Nelson and Bullock 2003). In order to have a successful row-crop system, an effective weed management program is crucial. The only weed control option available prior to herbicides was the use of mechanical and cultural practices (Carpenter and Gianessi 1999). In the past two decades, weed control programs in soybean have changed dramatically. These changes can largely be attributed to the commercialization of glyphosate-resistant (Roundup Ready®) soybean in 1996. This introduction completely changed the way growers approached soybean weed control. In fact, postemergence (POST) weed control became easy and simple with growers relying solely on the use of glyphosate on most U.S. soybean acres (Livingston et al. 2015). The extensive and sole use of glyphosate consequently caused immense selection for resistance.

Resistance issues are not new, but herbicide resistance is growing in importance because no new modes of action (MOA) have been discovered and commercialized for more than two decades (Duke 2011).

Chemical control is the most widely used method of managing weeds today. Many different chemical weed control programs are available but the number of effective MOAs are limited. Dual Magnum (*S*-metolachlor), Sencor (metribuzin), Valor (flumioxazin), Zidua (pyroxasulfone), and Fierce (flumioxazin and pyroxasulfone) are just some of the preemergence (PRE) herbicides that are applied at planting or shortly thereafter in soybean. PRE herbicides are less likely to result in resistance evolution because most PRE applications are followed by an effective POST herbicide.

There are many POST herbicide options available for use in soybean and the weed control program will likely change dependent upon which technology, if any, the grower chooses to utilize. Roundup Ready, LibertyLink, and Xtend are widely used technologies in Arkansas soybean and thus glyphosate, glufosinate, and dicamba would be three of the most commonly POST-applied herbicides. Failure to use these or other POST-applied herbicides in an integrated weed management system will likely result in herbicide resistance evolving in weeds for which resistance has yet to be documented. In soybean, effective POST herbicides for Palmer amaranth are quite limited, further placing selection pressure on a few effective herbicides – a prescription for rapid evolution of resistance. For instance, protoporphyrinogen oxidase (PPO) herbicides were the only effective option for POST management of Palmer amaranth control in glyphosate-resistant soybean. The evolution of resistance to PPO herbicides is becoming more widespread leaving many growers with no effective POST options.

Herbicide-resistance, as previously discussed, is increasing in frequency and distribution each season. In Arkansas, there are multiple weed species, Palmer amaranth, barnyardgrass, horseweed, yellow nutsedge (*Cyperus esculentus* L.), common cocklebur (*Xanthium strumarium* L.), redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisifolia* L.), giant ragweed (*Ambrosia trifida* L.), johnsongrass, and goosegrass (*Eleusine indica* L.), just to name a few, that due to resistance, are causing problems in soybean (Heap 2018). Preserving the efficacy of the various herbicides that are currently in use is important for the future of weed control in cropping systems.

As a result of herbicide-resistant weeds threatening global agriculture, alternative methods of weed control need to be explored (Walsh et al. 2012). If alternative weed control measures such as harvest weed seed control (HWSC) practices can be proven successful in U.S. cropping systems, similar to that demonstrated in Australia, integration of these techniques in conjunction with herbicides will reduce the risk of herbicide resistance and result in a more sustainable weed management program.

In Australia, farmers are coincidently in a similar position as the U.S. in respect to herbicide-resistant weeds. As a result, different HWSC methods have been developed, evaluated and are now being adopted. These methods include narrow-windrow burning, the use of chaff carts, a bale-direct system, and use of the integrated Harrington Seed Destructor (iHSD, designed by Australian farmer Ray Harrington to destroy weed seed exiting the combine) (Walsh et 2013). Some of the HWSC methods like narrow-windrow burning require minimal additional costs, and a chute for funneling harvest residues can quickly be constructed and attached to present-day combines.

Weed seed retention is a crucial factor in the effectiveness of HWSC. If weed seeds shatter from the plant before harvest due to weather delays, or other problems, then the potential for weed seed collection and destruction is lost. HWSC systems can only target seeds that are collected by the combine during harvest. Weed seed retention research in Australia on annual ryegrass, wild radish (*Raphanus raphanistrum* L.), wild oat (*Avena fatua* L.), and brome grass (*Bromus* spp. Scop.) determined that, these species retained 85%, 99%, 77%, and 84%, respectively of total seed production above 15cm at wheat crop maturity (Walsh and Powles 2014). These results confirmed the potential for HWSC systems to target these species during harvest. In U.S. soybean production, Palmer amaranth and waterhemp (*Amaranthus tuberculatus* (Moq.) J.D. Sauer) were found to retain 95 to 99% of their seed production at soybean maturity; albeit, the impact of delayed harvest on seed retention of these two weeds is unknown (Norsworthy et al. 2014b; Schwartz et al. 2016).

Narrow-windrow burning is accomplished by funneling all harvest residues through a narrow chute attached to the rear of the combine, allowing the material to be concentrated in a tight (762mm), narrow-windrow that can be easily burned for weed seed destruction. Harvest residues are generally defined as the plant material that is blown from the rear of the combine. This plant material is made up of stems and seed coverings of the crop being harvested. In order for narrow-windrowing to be accomplished, a chute (Figure 1.1) is attached to the rear of a combine. The role of the chute is to concentrate the chaff and straw that is exiting the combine into a narrow row (~50 cm wide). Concentrating the harvest residues into a narrow row helps to increase the heat intensity during subsequent burning. Manufacturing the narrow-windrowing chute is extremely cheap ($200 to $400) compared to other input costs of a farming operation.

When using narrow-windrow burning it also does not require any extra equipment to be pulled or used on the field and no negative impact on the time in which the crop is harvested.

Research has been carried out on the effects and efficacy of narrow-windrow burning in Australia, and it was found that wild radish and annual ryegrass (*Lolium multiflorum* L.) seed could be destroyed through narrow-windrow burning (Walsh and Newman 2007; Walsh et al. 2013). Weed seed size and coat hardness may influence the seed's tolerance to heat, so the efficacy of narrow-windrow burning may differ depending on the type and amount of residue being burned.

Heat intensity is another factor influencing the mortality of weed seeds, and this intensity value will likely change dependent upon the type of crop and the amount of biomass associated with that crop. Heat intensity is calculated by subtracting the ambient temperature from each recorded temperature from a burn and summing the total number of degrees above ambient. For adoption of this method in the U.S., more research is needed to determine the exact heat intensity that must be achieved to kill the seed of various weed species.

In addition to narrow-windrow burning, chaff carts are another important HWSC system in Australian agriculture. A chaff cart operates by retrieving the chaff that is exiting the rear of the combine and transferring it on a conveyor belt to an enclosed "catch bin". Once the bin is full the chaff can be dumped by opening a rear door on the cart and leaving a pile of chaff on the ground that can be burned at a later time. This system, like narrow-windrow burning, also aims to destroy all of the weed seeds that would be present in the chaff fraction that exited the combine during harvest.

The bale-direct system is another technique that is used in Australian cropping systems but not widely adopted (Walsh et al. 2013). This system functions to bale weed seed-laced chaff that exits from the rear of the combine. Obtaining livestock feed is the overall goal of this system but weed seed can also be accumulated and removed (Walsh and Powles 2007; Walsh et al. 2013). This system does not serve to destroy weed seeds but to move seeds from the production field. Simply moving the seeds could be perceived as one that does not meet the goals of HWSC because essentially a grower would be removing weed seeds from a production field and spreading them to another area such as a livestock pasture. This, in turn, will replenish the soil seedbank inside the new area or even worse, introduce a new herbicide-resistant species into the new area.

The iHSD is yet another tool, which was created by Australian farmer Ray Harrington. The iHSD is essentially an impact mill that pulverizes or cracks the weed seed, therefore rendering weed seed nonviable. After pulverizing the chaff and weed seeds, the remains are returned to the field. This return to the soil helps to keep a cover on the ground and benefit the soil in respect to moisture and nutrients (Walsh et al. 2012; Walsh et al. 2013). Studies completed on the iHSD tested multiple revolutions per minute (rpms) and showed that more than 90% of annual ryegrass could be destroyed using this system at 1300 rpm (Walsh et al. 2012).

The research conducted for the presentation of this thesis will study the efficacy of harvest weed seed control strategies in Arkansas soybean production. Studies on the seed retention of Palmer amaranth and barnyardgrass, where Palmer amaranth and common cocklebur seed and burs exit the combine, the efficacy of narrow-windrow burning of soybean on the seeds of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory, and seed kill studies with heat will be conducted. Data from these experiments will be presented in subsequent chapters.

Literature Cited

Bryson C, DeFelice M, eds (2009) Weeds of the South. 1st edn. University of Georgia Press. Pp. 169, 416

Carpenter J, Gianessi L (1999) Herbicide tolerant soybeans: why growers are adopting roundup ready varieties. Journal of Agrobiotechnology Management and Economics 2:65-72

Duke SO (2011) Why have no new herbicide modes of action appeared in recent years? Pest Manag Sci 68:505-512

Heap I (2018) The international survey of herbicide resistant weeds. Online. http://www.weedscience.org. Accessed March 21, 2018.

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

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

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

Livingston M, Fernandez-Cornejo J, Unger J, Osteen C, Schimmelpfenning D, Park T, Lambert D (2015) The economics of glyphosate resistance management in corn and soybean production. United States Department of Agriculture, Economic Research Service (ERR-184)

[NCSPA] North Carolina Soybean Producers Association. Crop updates-how soybeans are used. 2011. http://ncsoy.org/media-resources/uses-of-soybeans/. Accessed March 21, 2018

Nelson GC, Bullock DS (2003) Simulating a relative environmental effect of glyphosate-resistant soybeans. Ecol Econ 45:189-202

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

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

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

Norsworthy JK, Scott R, Smith K, Still J, Estorninos Jr L, Bangarwa S (2009) Confirmation and management of clomazone-resistant barnyardgrass in rice. SWSS Proceedings 62:211

Norsworthy JK, Walsh MJ, Bagavathiannan MV, Bradley KW, Steckel L, Kruger G, Loux MM, Eubank T, Davis V, Johnson W, Young B, Powles S (2014b) Harvest weed seed control: testing Australian seedbank management tactics in USA soybean. WSSA Abstract 2014

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (SP I):31-62

Riar DS, Norsworthy JK, Srivastava V, Nandula V, Bond JA, Scott RC (2012) Physiological and molecular basis of acetolactate synthase-inhibiting herbicide resistance in barnyardgrass (*Echinochloa crus-galli*). J Agr Food Chem 61:278-289

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

Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284-290

Smith Jr RJ (1968) Weed competition in rice. Weed Sci 16:252-255

Stephenson D, Oliver L, Burgos N, Gbur, Jr. E (2006) Identification and characterization of pitted morningglory (*Ipomoea lacunosa*) ecotypes. Weed Sci 54:78-86

[SWSS] Southern Weed Science Society (2012) Weed Survey-Grass Crops Subsection. SWSS Proceedings 65:267-288

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21:324-331

[UAEX] University of Arkansas Extension-2018 Arkansas Soybean Quick Facts

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service. 2017 Quick Stats. Online. http://quickstats.nass.usda.gov/. Accessed March 21, 2018

Vail GD, Oliver LR (1993) Barnyardgrass (*Echinochloa crus-galli*) interference in soybeans (*Glycine max*). Weed Technol 7:220-225

Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crop Res 104:24-30

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27:431-436

Walsh MJ, Harrington RB, Powles SB (2012) Harrington seed destructor: a new nonchemical weed control tool for global grain crops. Crop Sci 52:1343-1347

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332-338

Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. Weed Technol 28:486-493

Wilson RF (2008) Soybean: Market Driven Research Needs. Pages 3-15 in G. Stacey ed. Genetics and Genomics of Soybean. New York, U.S.A.: Springer Science + Business Media, LLC.

Tables and Figures

Figure 1.1. Narrow-windrow chute that funnels all harvest residues into a row for burning. The chute is attached to the rear of a Case 2388 combine in Keiser, Arkansas. (Photo by Author)

Chapter Two

Palmer Amaranth and Barnyardgrass Seed Retention in Soybean

Abstract

Because of the growing problem of herbicide-resistant weeds, control programs must be diverse in order to be successful long term. Several alternative control strategies currently being investigated, focus on the destruction of weed seed during harvest are collectively referred to as harvest weed seed control (HWSC) techniques. HWSC has been effectively researched and implemented in Australia in wheat production systems. The effectiveness of HWSC is dependent on the percentage of weed seed that is retained by weeds at crop maturity. Experiments were conducted at the Arkansas Agricultural Research and Extension Center in Fayetteville, Arkansas, in 2015 to assess the seed retention of Palmer amaranth and barnyardgrass when grown in a soybean crop. Two different sampling methods were used in each experiment. One method consisted of randomly collecting eight Palmer amaranth and ten barnyardgrass plants per week; the second method was to place four trays beneath eight randomly selected plants. Seed collected in these trays was removed weekly and seed shed throughout the growing season estimated. Palmer amaranth seed production increased throughout the growing season and plants retained 97.6% of the total seed produced at soybean maturity. Barnyardgrass shed seed earlier in the growing season, with only 43% of total seed production retained at soybean maturity. Based on these findings, HWSC tactics will likely have a beneficial impact on the soil seedbank of Palmer amaranth; however, HWSC will have less impact on the barnyardgrass soil seedbank. Planting of an earlier maturing soybean may be one strategy to hasten crop harvest and in turn destroy a higher percentage of seed at crop harvest.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* S. Wats.; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv; soybean, *Glycine max* (L.) Merr.

Keywords: harvest weed seed control, seed retention, seed production, cultural practices

Introduction

Current weed management programs rely heavily on herbicides for success. However, an overreliance on herbicides aids in the evolution of herbicide resistance (Gressel and Segel 1978; Maxwell et al. 1990). As a result, herbicide-resistant weeds are plaguing many weed control programs in crops grown around the world today, and due to this growing problem, many researchers and growers are now focusing on alternative methods of weed control that can aid in this battle. In Australia, on-going research has focused on testing the efficacy of late-season strategies aimed at reducing entry of weed seed into the soil seedbank of the troublesome weeds rigid ryegrass (*Lolium rigidum* Gaud.) and wild radish (*Raphanus raphanistrum* L.). These tactics are known as HWSC because the seed is captured and often destroyed using one of several methods including narrow-windrow burning; burning of chaff piles collected with a chaff cart; seed destruction with a Harrington Seed Destructor, or use of a bale-direct system to physically remove weed seed from fields (Walsh and Powles 2007; Walsh et al. 2013). A reduction in weed seed returns to the soil seedbank is important in decreasing future weed populations and ultimately decreasing resistance selection by herbicides. Little is known about the efficacy of HWSC systems on problematic weeds in the United States (U.S.). If successful in U.S. crop production systems, the implementation of HWSC tactics will help to diversify and improve current weed control programs (Norsworthy et al. 2012).

One of the single most important factors in the efficacy of HWSC is weed seed retention at crop harvest. If weed seed has shattered prior to harvesting the crop, then weed seed will not be collected by the combine (harvester) to be targeted with HWSC methods. Seed retention of various weeds, such as Palmer amaranth and barnyardgrass, needs to be investigated throughout the growing season and at harvest to determine if HWSC will have a positive impact and to determine to what extent delays in crop harvest may impact weed seed retention.

Palmer amaranth has been referred to as the worst weed in the U.S. (WSSA 2016) and is very costly to mid-southern U.S. crop production. Palmer amaranth can produce as many as 600,000 seeds plant^{-1} (Keeley et al. 1987), this high number of seeds will quickly establish a substantial soil seedbank and allow populations to quickly increase and spread rapidly across a production field (Norsworthy et al. 2014). Furthermore, Palmer amaranth is resistant to several herbicides across various sites of action including Groups 2, 3, 5, 15, and 27 (Heap 2018). Previous research has shown that at soybean maturity in Arkansas, Illinois, Nebraska, Missouri, and Tennessee, Palmer amaranth retained 98.8 to 99.9% of the total seed produced (Schwartz et al. 2016), meaning that there is a high potential for effective HWSC.

Barnyardgrass is another troublesome weed that exhibits resistance to Group 1, 2, 4, 7, and 13 herbicides (Heap 2018). Barnyardgrass can produce up to 34,000 seeds plant^{-1} when emerging early in a corn (*Zea mays* L.) crop (Bosnic and Swanton 1997). This weed is typically problematic in rice (*Oryza sativa* L.) production systems; however, many growers utilize a rice-soybean rotation in an attempt to control barnyardgrass in the soybean crop. However, if a large soil seedbank is present then ultimately barnyardgrass will be increasingly problematic in soybean. Previous research has shown that allowing barnyardgrass to infest a soybean crop can cause significant yield decreases of 0.25% for each barnyardgrass plant present per m row (Vail and Oliver 1993).

The objective of this research is to determine the seed production characteristics, percentage of seed retained on Palmer amaranth and barnyardgrass at soybean maturity, and the impact of delayed harvest on seed retention. It is hypothesized that Palmer amaranth and barnyardgrass will both retain a high percentage of total seed production at soybean maturity.

Materials and Methods

Field experiments were conducted at the University of Arkansas Agricultural Research and Extension Center in Fayetteville, Arkansas, in 2015. Experiments were established on a soil characterized as a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) with 34% sand, 53% silt, 13% clay, 1.5% organic matter, and a pH of 6.9. Pioneer 95L01 soybean (maturity group IV Liberty-Link cultivar) was planted May 19, 2015. The two experiments, one for Palmer amaranth and the other for barnyardgrass, were adjacent to one another to have similar environmental conditions, and the experiments were kept weed-free throughout the growing season by hand weeding. Each experiment consisted of two separate sampling methods.

One sampling method (Collection Method 1) was a non-destructive harvest collection that involved placing four greenhouse trays (F1721 Tray, T.O. Plastics, Inc. Clearwater, MN) referred to in this experiment as seed traps, measuring 0.51 m x 0.40 m (0.82 m^2 total with four traps), around the base of eight randomly chosen Palmer amaranth and eight randomly chosen barnyardgrass plants. Seed traps were installed on August 21, 2015 and continued through October 29, 2015. Seed was collected weekly from these trays throughout the growing season. The seed traps were emptied using a Dirt Devil Gator 9.6V cordless portable vacuum (TTI Floor Care North America, Glenwillow, Ohio), and samples were returned to the Altheimer laboratory for counting at each collection period. At the conclusion of the experiment, the eight plants that had been sampled weekly throughout the growing season were harvested to obtain a final seed count and determine a percentage of seed shed over time. This sampling method allowed for consistency of sampling the same plants throughout the entire experiment.

The second sampling method (Collection Method 2) was a destructive harvest collection that consisted of collecting eight Palmer amaranth plants and ten barnyardgrass plants each week in an effort to quantify seed production throughout the growing season by counting the number of seed per plant. The idea was that the number of seed per plant would begin to decrease as seed shattered from plants.

Both experiments were conducted following the same sampling and collection procedures; however, establishment of the weed populations that were sampled differed. Palmer amaranth seedlings were allowed to emerge naturally with the soybean crop, whereas barnyardgrass was initiated by sowing barnyardgrass seeds in the greenhouse on the day of soybean planting (May 19, 2015) and transplanting to the field 3 to 4 weeks after planting. In each experiment, the sampled plants were either thinned or transplanted to one plant every 1.2 m of row. Soybean maturity (R8) was noted for both experiments on October 1, 2015.

Weather data were obtained from a weather station approximately 300 m from the experiment site. Cumulative precipitation, maximum wind speeds, and growing degree days (GDD) (Equation 1) were averaged by week for each experiment. GDD calculations started for Palmer amaranth when seed fill began on July 21, 2015, and for barnyardgrass when a majority of panicles in the field were at 75% seed fill on July 13, 2015. The base temperatures used for GDD calculation, 16.7 C and 13.9 C for Palmer amaranth and barnyardgrass, respectively, were taken from previous literature, which indexed the base temperature for seed germination of various weed species (Steinmaus et al. 2000). Parameters were calculated to determine the impact, if any, that environmental conditions had on seed retention in this experiment.

(Equation 1). $GDD = \frac{T_{max}+T_{min}}{2} - T_{base}$

Where GDD = growing degree days, T_{max}= maximum daily temperature, T_{min}= minimum daily temperature, and T_{base}= Base temperature for plant development as taken from literature.

Statistical Analyses. Data for each experiment were averaged by species each week to obtain the means and standard errors for each sampling method. Additionally, polynomial regressions were fit to describe seed production per plant over time. Data were fitted to a model using the FIT MODEL platform in JMP Pro 13 (SAS Institute Inc., Cary, NC).

Results and Discussion

Palmer Amaranth Seed Production. Random plant collections of Palmer amaranth started on August 14, 2015, with number of seeds plant^{-1} ranging from 1,900 to 32,400 (± 4,100). Seed production increased until October 13, 2015 (12 days after soybean maturity), which at this time ranged from 8,300 to 85,000 (± 12,900) seeds plant^{-1} (Figure 2.1). The four plant collections conducted beyond this date yielded an average decrease in seed plant^{-1}, and on November 25, 2015 (last collection), seed production ranged from 13,500 to 50,900 (± 5,000) seeds plant^{-1} (Figure 2.1). Based on these data, when Palmer amaranth is allowed to emerge with a soybean crop, seed production can continue to increase beyond soybean maturity if the growing conditions are supportive and the crop is not harvested in a timely manner. Previous research has shown similar results, with Palmer amaranth plants producing an average of 28,140 to 58,231 seeds by soybean maturity in Arkansas (Schwartz et al. 2016).

Palmer Amaranth Seed Shatter. Palmer amaranth retained a high percentage (97%) of seed production throughout the reproductive development phase. Weekly collections did not identify a large decrease in seed retention. Soybean maturity in the experiment occurred on October 1, 2015, at which time average seed retention had only decreased to 97.6% (Figure 2.2). These results align with previously published research that reported Palmer amaranth seed retention of

98.8 to 99.9% of seed at soybean maturity (Schwartz et al. 2016). Similarly, Walsh and Powles (2014) found that weed species such as wild radish, wild oat (*Avena fatua* L.), brome grass (*Bromus* spp. Scop.), and ryegrass retained 77 to 99% of seed at wheat (*Triticum aestivum* L.) maturity in Australia.

In order to capture the effects of delayed harvest, assessment of seed retention continued until October 29, 2015 (28 days after soybean maturity). On October 29, Palmer amaranth retained 91.2% of total seed production. Even though a delayed harvest would result in loss of some seed, a high percentage of seed would be collected during harvest for possible HWSC.

Barnyardgrass Seed Production. Barnyardgrass plant collections started earlier than those of Palmer amaranth due to the earlier flowering time of barnyardgrass. Plant collections were initiated July 24, 2015, with plants producing 1,700 to 11,500 (± 1,100) seeds plant^{-1}. No attempt was made to quantify the viability of the seed collected from each plant, but most seeds did appear firm, and a high percentage was likely viable at the first date of collection. Barnyardgrass seed production quickly peaked August 14, 2015, with seeds plant^{-1} ranging from 2,700 to 22,200 (± 1,700) before decreasing with subsequent collections (Figure 2.3). At soybean maturity on October 1, 2015, seeds plant^{-1} ranged from 700 to 2,700 (± 300). This decrease in number of seeds plant^{-1} indicates that seed shedding has occurred before soybean maturity. Collections continued after soybean maturity and at the last collection on October 29, 2015, seeds plant^{-1} had further decreased and ranged from 100 to 3,800 (± 500) (Figure 2.3). These results are similar to previous research that showed barnyardgrass produced 16,500 to 35,500 and 2,900 to 39,000 seeds plant^{-1} in cotton (*Gossypium hirsutum* L.) and rice, respectively, when emerging with the crop (Bagavathiannan et al. 2012).

Barnyardgrass Seed Shatter. Barnyardgrass assessments from the seed traps showed that barnyardgrass starts to shatter at least 1.5 months prior to soybean maturity. Assessment of seed traps began August 18, 2015 and continued until October 29, 2015 (28 days after soybean maturity). From installment of the traps to soybean maturity on October 1, 2015, barnyardgrass seed retention decreased to 43% of total seed production (Figure 2.4). Furthermore, assessments that continued until October 29, 2015, revealed that seed shatter continued to occur, with seed retention declining to 35% with a 28-day delay in soybean harvest (Figure 2.4). Decreases in seed retention align with results from Collection Method 1 where seeds plant^{-1} decreased over time. Additionally, the low percentages of seed retention at soybean maturity indicate that HWSC may not be a strong tactic to substantially decrease the amount of barnyardgrass seed returned to the soil seedbank; albeit, some seed destruction may still have a positive long-term impact on lessening the selection for herbicide resistance.

Weather Impacts on Seed Shatter. Total GDD for Palmer amaranth and barnyardgrass was 1235 and 1327, and precipitation amounts were 447 mm and 313 mm, respectively (Tables 2.1 and 2.2). Weather is an important contributing factor in plant growth and development (Nussbaum et al. 1985; Jha and Norsworthy 2009; Jha et al. 2010), and it is probable that weather does have an effect on the rate of seed shatter and retention. Rainfall and wind speed were higher during the period from September 4th through 11th when seed shed was high for barnyardgrass. Also, high rainfall amounts occurred during the period August 14th through 21st, which may have contributed to seed shatter.

Practical Implications. Weed seed retention will be a major factor in determining the potential efficacy of HWSC and, as shown in this study, seed production and retention will differ by species. Based on the results presented here, when grown in soybean, Palmer amaranth has a favorable seed production time frame and a very high (97.6%) seed retention rate at soybean maturity. It is also important to note that while the trays were capturing seed shed from Palmer amaranth plants in Collection Method 2, an increase in seed production was still being observed using Collection Method 1. This suggests that although Palmer amaranth may be shedding some seed, axillary branches may be flowering later than that of the main inflorescence. Barnyardgrass responded differently from Palmer amaranth by retaining a lower percentage (43%) of seed at soybean maturity. Both collection methods showed a decrease in seed per plant and retention for barnyardgrass throughout the growing season. The decreased seed retention of barnyardgrass compared to Palmer amaranth at soybean maturity could be attributed to barnyardgrass being a day-neutral plant while Palmer amaranth is a short-day plant. Data from these experiments are ample evidence that there is strong potential to decrease the soil seedbank through implementation of HWSC tactics at soybean maturity; albeit, these tactics would appear to have a greater impact on Palmer amaranth than barnyardgrass.

Literature Cited

Bagavathiannan MV, Norsworthy JK, Smith KL, Neve P (2012) Seed production of barnyardgrass (*Echinochloa crus-galli*) in response to time of emergence in cotton and rice. J Agr Sci-Cambridge 150:717-724

Bosnic AC, Swanton CJ (1997) Influence of barnyardgrass (*Echinochloa crus-galli*) time of emergence and density on corn (*Zea mays*). Weed Sci 45:276-282

Gressel J, Segel LA (1978) The paucity of plants evolving genetic resistance to herbicides: Possible reasons and implications. J Theo Bio 75:349-371

Heap I (2018) The international survey of herbicide resistant weeds. Online. http://www.weedscience.org. Accessed March 21, 2018

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

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

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

Maxwell BD, Roush ML, Radosevich SR (1990) Predicting the evolution and dynamics of herbicide resistance in weed populations. Weed Technol 4:2-13

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

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci (Special Issue I) 60:31-62

Nussbaum ES, Wiese AF, Crutchfield DE, Chenault EW, Lavake D (1985) The effects of temperature and rainfall on emergence and growth of eight weeds. Weed Sci 33:165-170

Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284-290

Steinmaus SJ, Prather TS, Holt JS (2000) Estimation of base temperatures for nine weed species. J Exp Bot 51:275-286

Vail GD, Oliver LR (1993) Barnyardgrass (*Echinochloa crus-galli*) interference in soybeans (*Glycine max*). Weed Technol 7:220-225

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27:431-436

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332-338

Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. Weed Technol 28:486-493

[WSSA] Weed Science Society of America. 2016 Weed Survey. http://www.wssa.net. Accessed March 21, 2018

Tables and Figures

Table 2.1. Weather data[a] collected for the Palmer amaranth seed retention experiment conducted at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2015.

Time period	Growing degree days	Precipitation	Average max. wind speed
	16.7 C[b]	mm	m s^{-1}
Jul 21-Aug 14	244	110	2.52
Aug 15-Aug 21	285	55	2.61
Aug 22-Aug 28	318	31	3.28
Aug 29-Sept 4	381	26	3.04
Sept 5-Sept 14	444	48	3.55
Sept 15-Sept 18	473	0	4.47
Sept 19-Sept 25	500	2	1.96
Sept 26-Oct 1	517	0	2.68
Oct 2-Oct 13	516	2	2.65
Oct 14-Oct 22	524	25	3.90
Oct 23-Oct 29	507	15	3.68
Oct 30-Nov 11	460	50	3.93
Nov 12-Nov 25[c]	361	85	5.03

[a] Weather data were obtained from weather station located near the experiment location.
[b] Growing degree day (GDD) was calculated using a 16.7 C base temperature from July 21, 2015.
[c] First frost occurred on November 21, 2015.

Table 2.2. Weather data[a] collected for the barnyardgrass seed retention experiment conducted at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2015.

Time period	Growing degree days	Precipitation	Average max. wind speed
	13.9 C[b]	mm	m s^{-1}
Jul 13-Jul 24	165	86	2.87
Jul 25-Jul 31	263	0	2.61
Aug 1-Aug 7	350	11	2.24
Aug 8-Aug 14	431	13	2.84
Aug 15-Aug 21	492	55	2.61
Aug 22-Aug 28	545	31	3.28
Aug 29-Sept 4	627	26	3.04
Sept 5-Sept 14	718	48	3.55
Sept 15-Sept 18	758	0	4.47
Sept 19-Sept 25	805	2	1.96
Sept 26-Oct 1	838	0	2.68
Oct 2-Oct 13	871	2	2.65
Oct 14-Oct 22	905	25	3.90
Oct 23-Oct 29	908	15	3.68

[a] Weather data were obtained from a weather station located near the experiment location.
[b] Growing degree day (GDD) was calculated using a 13.9 C base temperature from July 13, 2015.

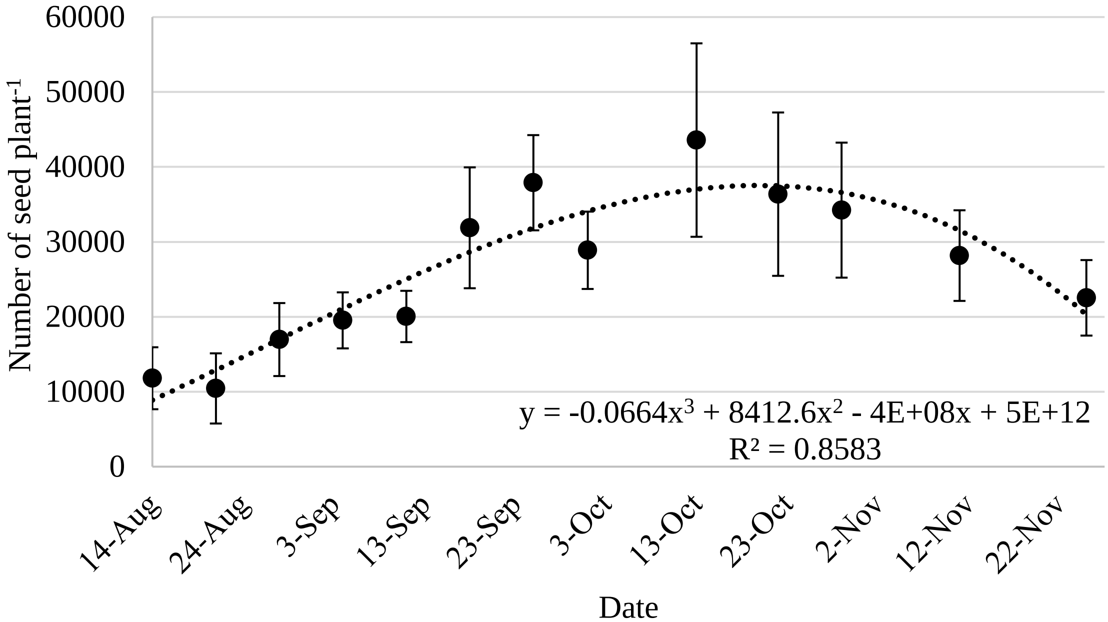

Figure 2.1. Palmer amaranth seed number plant^{-1} from a soybean field as measured from weekly random plant collections in 2015 at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. Points represent the means for that collection time and bars above and below the points represent the standard error.

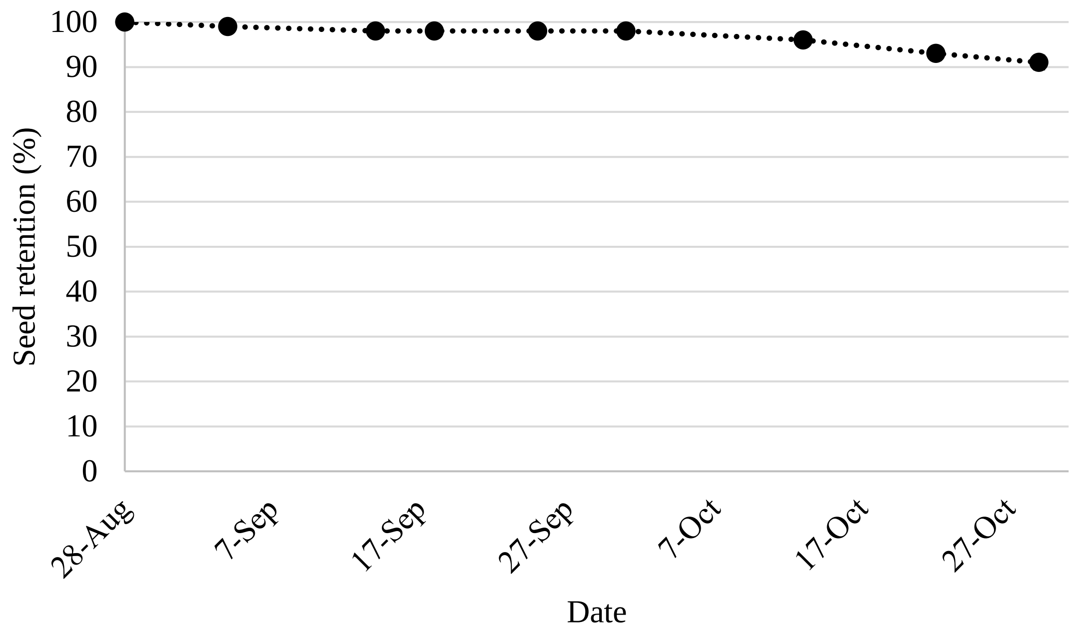

Figure 2.2. Palmer amaranth seed retention from a soybean field assessed by using seed traps in 2015 at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. Points represent the means at that collection time and bars above and below the points represent the standard error.

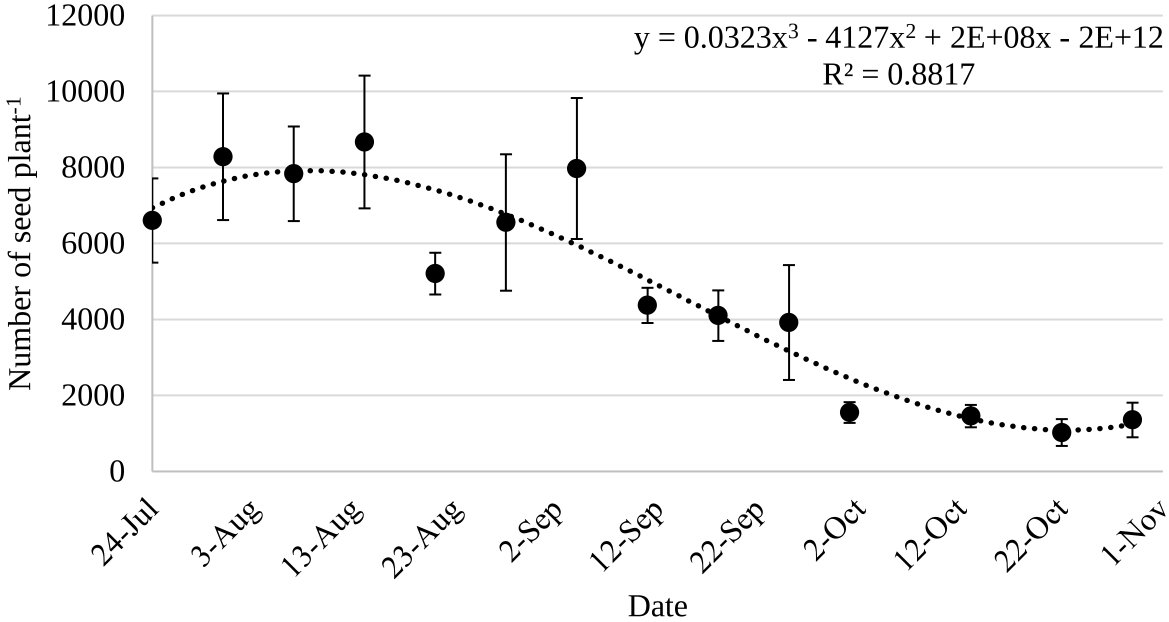

Figure 2.3. Barnyardgrass seed number plant^{-1} from a soybean field as measured from weekly random plant collections in 2015 at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. Points represent the means at that collection time and bars above and below the points represent the standard error.

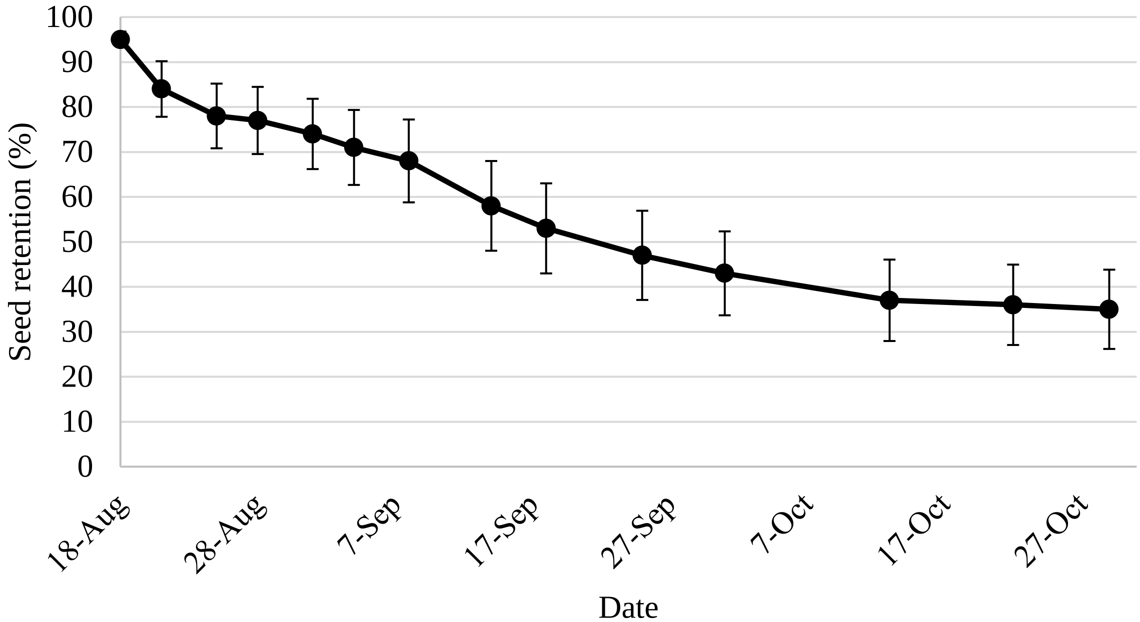

Figure 2.4. Barnyardgrass seed retention from a soybean field assessed by using seed traps in 2015 at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. Points represent the means at that collection time and bars above and below the points represent the standard error.

Chapter Three

Distribution of Common Cocklebur and Palmer Amaranth Seed in the Combine at Soybean Harvest

Abstract

Harvest weed seed control (HWSC) tactics are being investigated to aid in herbicide resistance management by reducing the number of weed seed entering the soil seedbank. Weed seed retention and the location in which weed seeds exit the combine are two important factors that can influence the potential for HWSC success. An experiment was conducted in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, Arkansas, to determine where the seeds of common cocklebur and Palmer amaranth exit the combine during soybean harvest. Soybean plots containing infestations of common cocklebur and Palmer amaranth were harvested with a commercial combine and the grain, chaff (top sieve), and straw (rotor) fractions collected. The number of seed of both weeds was determined in each fraction. The grain fraction contained between 3% and 24% of common cocklebur and 6% of Palmer amaranth. Furthermore, it was determined that 76% and 94% of common cocklebur and Palmer amaranth seeds that entered the combine at harvest exited in the chaff plus straw fractions, respectively, with a large quantity (59-89%) of the weed seed being contained in the chaff fraction. These results point to the potential success of being able to destroy weed seed as they exit the combine during harvest and choosing the best HWSC method.

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

Key words: harvest weed seed control, chaff collection, soil seedbank, cultural practices

Introduction

Harvest weed seed control (HWSC) is a relatively new non-chemical control strategy that is aimed at lowering the returns of weed seed to the soil seedbank during harvest (Walsh et al. 2013). The success of HWSC strategies is highly dependent on weed seed retention at crop harvest. Previous research on weed seed retention in an Australian wheat (*Triticum aestivum* L.) crop has shown that troublesome weed species such as brome grass (*Bromus* spp. Scop.), wild oat (*Avena fatua* L.), annual ryegrass (*Lolium rigidum* Gaud.), and wild radish (*Raphanus raphanistrum* L.) retain 77 to 99% of seeds at crop maturity (Walsh and Powles 2014). Additionally, work on seed retention in the United States has shown that Palmer amaranth and tall waterhemp (*Amaranthus tuberculatus* (moq.) Sauer) retain 95 to 99% of their total seed production at soybean maturity while other troublesome species such as giant ragweed (*Ambrosia trifida* L.) retain approximately 75% of the total seed production at soybean maturity (Goplen et al. 2016; Schwartz et al. 2016). The high seed retention of these species means that there is a potential for weed seed to enter the combine during the harvest operation.

The modern combines are very efficient processors of the material (grain and crop residues) collected during crop harvest. When setup and operated effectively, anything that is not grain, including stems, leaves, pods, and weed seeds, exits the combine in the straw and chaff fractions. Combines have efficient residue spreading systems that ensures the redistribution of these residues back across the field. If weeds are present during the harvest operation and their seed enter the combine, the weed seed will potentially exit the combine in three different fractions [grain, straw, and chaff]. Weed seed that enters the grain bin can cause a decrease in crop quality along with dockage fees at the elevator; however, weed seed that accumulates in the grain is removed from the field and does not enter the soil seedbank. On the contrary, weed seed that is expelled from the combine in the straw and chaff fractions returns to the soil seedbank, where seed can lie dormant and germinate in subsequent years.

In recent years, a machine called the Harrington Seed Destructor (HSD) was commercialized in Australia. The HSD is designed to pulverize chaff in an effort to destroy weed seed that would normally be returned back to the soil seedbank (Walsh et al. 2012; Walsh et al. 2013). Testing of the HSD in Australia during wheat harvest has shown that it can destroy 93 to 99% of wild radish, annual ryegrass, wild oat, and brome grass seeds present in chaff (Walsh et al. 2012). The original HSD was sold as a tow-behind unit; however, engineering development has led to the HSD being incorporated into the combine as a unit called the integrated Harrington Seed Destructor (iHSD). Successful integration of the iHSD into modern combines could result in increased adoption due to ease of use and increasing widespread herbicide resistance. Limitations will exist with the iHSD system as this system is only designed to process the chaff fraction exiting the combine (M.J. Walsh, personal communication). Thus, in order to run at maximum efficiency and have the potential to destroy the greatest amount of weed seed, it is critical to know where the greatest percentage of weed seed exits the combine. Previous research by Shirtliffe and Entz (2005) and Broster et al. (2016) has shown that a high percentage of weed seeds exit in the chaff fraction with ($\geq$ 74%) of wild oat seed and greater than 90% of annual ryegrass seed exiting the combine in the chaff fraction. Additionally, according to Walsh and Parker (2002), 75% of wild radish seeds exit the field by way of the grain fraction at wheat harvest; however, 20% of the remaining seeds exit the combine in the chaff fraction.

Common cocklebur is a large-seeded broadleaf that produces burs with two seeds per bur. Burs are approximately 1 to 3.5 cm in length and classified as long and oval or oblong (Bryson and DeFelice 2009). Common cocklebur has been found to produce over 4,400 burs plant^{-1}

(Bararpour and Oliver 1998), creating the potential for long-term weed infestations if left uncontrolled. Additionally, research on common cocklebur where severe infestations (3,300 to 26,000 plants ha^{-1}) have been left untreated has shown that significant soybean yield decreases of 10 to 52% can occur (Barrentine 1974).

Palmer amaranth, another broadleaf weed, has a small seed that measures 1.0 to 1.3 mm in diameter (Bryson and DeFelice 2009). Palmer amaranth can cause devastating yield losses and/or complete crop loss when left uncontrolled (Norsworthy et al. 2014). Each Palmer amaranth plant can produce as many as 600,000 seeds, and previous research has shown that when as many as 10 plants m^{-1} of row of Palmer amaranth are present, soybean yield can be reduced up to 68% (Keeley et al. 1987; Klingaman and Oliver 1994).

Controlling common cocklebur and Palmer amaranth is essential for maintaining yield potential. Common cocklebur has documented resistance to acetolactate synthase (Group 2) inhibitors while Palmer amaranth has a more troublesome history with documented resistance to acetolactate synthase (Group 2), 5-enolpyruvylskimate-3-phosphate synthase (Group 9), microtubule (Group 3), photosystem II (Group 5), 4-hydroxyphenylpyruvate dioxygenase (Group 27), and protoporphyrinogen oxidase (Group 14) inhibitors (Heap 2018). The longevity in the soil, amount of seed produced, and the documented resistance cases of common cocklebur and Palmer amaranth make these species prime targets for HWSC.

The seed production of various weeds, including common cocklebur and Palmer amaranth, coupled with potential yield or crop losses from plants in successive years, is a cause of concern and a crucial reason as to why the soil seedbank must be managed (Norsworthy et al. 2012). Previous research conducted by Norsworthy et al. (2016) has shown that HWSC, when implemented with herbicide programs, can be effective in lowering the Palmer amaranth soil seedbank. Based on the previously cited research and the efficiency of modern combines, it is hypothesized that a majority of weed seed will exit in the chaff fraction. A study was conducted to determine where seed of Palmer amaranth and common cocklebur exit the combine during soybean harvest, and if weed seed size has an effect on location of exit.

Materials and Methods

A field study was conducted in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, Arkansas, using Credenz 4950LL soybean cultivar. Four 9.1- by 9.1-m soybean plots that were infested with common cocklebur and Palmer amaranth were selected each year. A Case IH 2388 commercial combine (CNH Industrial N.V., Amsterdam, Netherlands) with a 9.1-m platform head was used for this experiment. The commercial combine was annually used to harvest soybean production fields, with the combine operator and farm manager properly setting up the equipment each year prior to harvest. Large tarps were attached to collect straw material exiting the harvester from the rotor and chaff material coming off the top sieve. In addition, a bulk grain bag was attached to the transfer auger to capture all incoming grain from the plots. This setup allowed for each of the three fractions (grain, straw, and chaff) to be caught independently for analysis. After harvesting each plot, fractions were bagged separately and brought back to the University of Arkansas Altheimer Laboratory in Fayetteville, Arkansas, for further analysis. For straw and chaff fraction analyses, one quarter of each fraction was set aside to obtain the number of common cocklebur and Palmer amaranth seeds in the fraction. Common cocklebur seeds were removed from each fraction by hand and counted. After common cocklebur removal, each one-quarter fraction was then ground using a plant grinder to facilitate the counting of Palmer amaranth seed. Each ground fraction was weighed and Palmer amaranth seed in five 1 g subsamples of chaff were counted.

Analysis of grain fractions was conducted in a similar manner, with the exception of the entire grain fraction being manually sorted through for common cocklebur seed collection. After common cocklebur removal, the grain fraction was sieved to remove any small plant material and Palmer amaranth seed. The material that passed through the sieves was then ground using a plant grinder and weighed before taking a 1 g subsample to obtain the number of Palmer amaranth seed collected in each grain fraction.

Fraction biomass was another parameter assessed to determine the exact amount of biomass that exits in the straw and chaff fractions. The weight of material obtained when counting Palmer amaranth seed present in the fractions enabled for a calculation of fraction biomass. By looking at fraction biomass, conclusions can be drawn as to whether the same amount of biomass always exits in the straw and chaff fractions or, if different, whether biomass may have an impact of the amount of seed contained within that fraction.

Statistical Analyses. The data were collected from four plots in a field and analyzed. This experiment was analyzed as a single factor, randomized completely block design with four blocks. The factor levels for the combine fraction were the grain, straw, and chaff portions of soybean. Total seed counts for each weed species were subjected to ANOVA using the FIT MODEL platform in JMP Pro 13 (SAS Institute Inc., Cary, NC) with means separated using Fisher's protected LSD at an alpha level of 0.05.

Results and Discussion

Common Cocklebur. Fraction analyses for common cocklebur burs were conducted with data being averaged across both years. The chaff fraction was responsible for carrying a vast majority (75 ± 2.14%) of the common cocklebur burs. The straw fraction contained 12 ± 1.20% and the grain fraction contained 13 ± 1.83%. Interestingly, common cocklebur burs were slightly more prolific in the grain fraction than that of the straw fraction over both years. This could potentially be attributed to a few causes; the maturity of the cocklebur burs at harvest or the size and weight of the burs.

Palmer Amaranth. Fraction analyses for Palmer amaranth seed were similar in both 2014 and 2015, and data were averaged across years. Similar to common cocklebur, the chaff fraction contained the greatest number of Palmer amaranth seed (85 ± 3.68%) (Table 3.1). The straw and grain fractions had a much lower percentage of Palmer amaranth seed, 9 ± 3.22% and 6 ± 2.43%, respectively.

Fraction Biomass. The total biomass in each fraction differed between years. In 2014, when excluding the grain fraction, the weight expelled from the combine in the chaff and straw fractions was similar at 7,614 g (54%) and 6,447 g (46%), respectively (Table 3.2). However, in 2015, the weight of chaff and straw was not similar, and in fact, the straw fraction accounted for 17,290 g (70%) of the total 24,729 g from the chaff and straw fractions combined (Table 3.2). Increased amounts of biomass could also have contributed to the reason that common cocklebur seeds were found more frequently in the straw fraction in 2015.

Practical Implications. The testing of two different weed species with large and small seed sizes yielded similar results over two years. A high percentage (87% and 94%, respectively) of common cocklebur and Palmer amaranth seeds when the straw and chaff fractions are combined means that the seeds of these weed species are normally distributed across the field during harvest. The results from this experiment align with previous research, which found that wild oat seeds mainly exited the combine in the chaff fraction during wheat harvest (Shirtliffe and Entz 2005). The experiment presented here, coupled with Shirtliffe and Entz (2005) and Walsh and

Parker (2002), points to the high likelihood of weed seed, regardless of species, exiting the combine mainly in the chaff fraction at harvest.

Successful implementation and adoption of the iHSD could significantly reduce returns of weed seed to the soil seedbank at harvest. Results from both common cocklebur and Palmer amaranth show that when the iHSD is widely available, operation parameters that allow the chaff fraction to be processed will result in the destruction of most common cocklebur and Palmer amaranth seed.

Current herbicides must be stewarded to prolong effectiveness and decrease the number of new cases of herbicide resistance (Norsworthy et al. 2012). Soil seedbank management using HWSC tactics such as narrow-windrow burning or the use of new iHSD technology has the potential to be of great value toward the management of resistant species.

Literature Cited

Bararpour MT, Oliver LR (1998) Effect of tillage and interference on common cocklebur (*Xanthium strumarium*) and sicklepod (*Senna obtusifolia*) population, seed production, and seedbank. Weed Sci 46:424-431

Barrentine WL (1974) Common cocklebur competition in soybeans. Weed Sci 22:600-603

Broster JC, Walsh MJ, Chambers AJ (2016) Harvest weed seed control: the influence of harvester set up and speed on efficacy in south-eastern Australia wheat crops. Australasian Weeds Conference 6:38-41

Bryson C, DeFelice M, eds (2009) Weeds of the South. 1st edn. University of Georgia Press. Pp. 34, 116

Goplen JJ, Sheaffer CC, Becker RL, Coulter JA, Breitenbach FR, Behnken LM, Johnson GA, Gunsolus JL (2016) Giant ragweed (*Ambrosia trifida*) seed production and retention in soybean and field margins. Weed Technol 30:246-253

Heap I (2018) The international survey of herbicide resistant weeds. Online. http://www.weedscience.org. Accessed March 21, 2018

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

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

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

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540-550

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (Special Issue I):31-62

Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284-290

Shirtliffe SJ, Entz MH (2005) Chaff collection reduces seed dispersal of wild oat (*Avena fatua*) by a combine harvester. Weed Sci 53:465-470

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. Weed Technol 27:431-436

Walsh MJ, Harrington RB, Powles SB (2012) Harrington seed destructor: A new nonchemical weed control tool for global grain crops. Crop Sci 52:1343-1347

Walsh M, Parker W (2002) Wild radish and ryegrass seed collection at harvest: chaff carts and other devices. Pgs 37-38 Agribusiness Crop Updates. Perth Western Australia: Department of Agriculture Western Australia

Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. Weed Technol 28:486-493

Tables and Figures

Table 3.1. Common cocklebur and Palmer amaranth seed distribution from a Case 2388 combine at the Northeast Research and Extension Center in Keiser, Arkansas, during soybean harvest averaged over 2014 and 2015.[a]

Fraction	Common cocklebur			Palmer amaranth		
	Burs fraction^{-1}		%	Seeds fraction^{-1}		%
Chaff	2,360	a	75	585,000	a	85
Straw	387	b	12	63,000	b	9
Grain	402	b	13	38,000	b	6

[a] Letters are for separating means within a column based on Fisher's protected LSD (P = 0.05).

Table 3.2. Distribution of weed and soybean biomass from the straw, chaff, and grain fractions taken from (or 'exiting') a Case 2388 combine at the Northeast Research and Extension Center in Keiser, Arkansas, during soybean harvest in 2014 and 2015.

	2014		2015	
Fraction	Including grain	Excluding grain	Including grain	Excluding grain
	-------------------- % of total --------------------			
Chaff	27	54	15	30
Straw	23	46	36	70
Grain	51	-	49	-

Chapter Four

Effect of Narrow-Windrow Burning of Soybean Chaff on Weed Seed Viability

Abstract

Herbicide resistance is causing a shift in weed management programs to include non-chemical control methods. Non-chemical weed control includes management strategies such as tillage, cover crops, harvest weed seed control (HWSC), and other weed control options that do not involve the use of herbicides. One HWSC strategy, known as narrow-windrow burning, has been investigated at the University of Arkansas to determine the potential fit in a soybean production system. In Australia, narrow-windrow burning has been shown to be effective in destroying annual ryegrass and wild radish seed. Two experiments were conducted in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, Arkansas. One experiment was to determine the amount of heat produced from narrow windrows of soybean biomass and the effect that the heat had on Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory seed. The second experiment was to determine the effect that wind speed has on the burning of soybean biomass through the use of artificial wind from a leaf blower. This experiment showed that narrow-windrow burning could potentially be a successful tactic if employed at soybean harvest. The weed seed placed within the narrow windrows were completely destroyed by narrow-windrow burning. Additionally, it was determined that wind speed has some effect on narrow-windrow burning because high wind speeds can reduce the efficacy of the burns, likely because of a quicker burn. When conditions are suitable, narrow-windrow burning could be an inexpensive way to lower the amount of weed seed that would normally enter the soil seedbank at harvest.

Nomenclature: Italian ryegrass, *Lolium multiflorum* Lam.; Palmer amaranth, *Amaranthus palmeri* S. Wats.; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv.; johnsongrass, *Sorghum halepense* (L.) Pers.; pitted morningglory, *Ipomoea lacunosa* L.

Keywords: harvest weed seed control, soil seedbank, narrow-windrow burning, cultural practices

Introduction

Chemical weed control options have been decreasing for the last two decades because of herbicide resistance. However, a shift toward weed control programs that involve the use of nonchemical strategies in conjunction with current herbicide programs is beginning to become more prevalent. Slowing the evolution of herbicide resistance involves implementing several different techniques, some of which may include tillage, rotating and mixing herbicide sites of action, cover crops, and implementing a weed control technique known as HWSC (Norsworthy et al. 2012). HWSC is aimed at lowering returns of weed seed to the soil seedbank at crop harvest. A reduction in the number of weed seed in the soil seedbank will ultimately help to lower the selection pressure for resistance currently placed on herbicides.

Weeds that have escaped chemical control methods and are often allowed to continue to grow and produce seed, become major contributors to the soil seedbank. Palmer amaranth, the most troublesome weed in the mid-southern U.S., has been found to retain more than 97% of the total seed production for the growing season at soybean maturity (Schwartz et al. 2016). Weed seed that is retained and enters the combine during harvest is normally redistributed across fields, thereby helping to replenish the soil seedbank each year (Shirtliffe and Entz 2005; Walsh and Powles 2007). Research has shown that the seed of weeds, such as Palmer amaranth and common cocklebur (*Xanthium strumarium* L.), collected by the combine during soybean harvest, exit in the chaff and straw fractions (Green, unpublished data). Using HWSC tactics, capturing and destroying these seed are paramount to decreasing the soil seedbank.

In Australia, HWSC is widely used, with narrow-windrow burning being the most commonly used option (Walsh et al. 2017). In Australia, researchers have conducted experiments to test the efficacy of burning narrow windrows as opposed to burning standing wheat stubble

(*Triticum aestivum* L.) on problematic species such as rigid ryegrass (*Lolium rigidum* Gaud.) and wild radish (*Raphanus raphanistrum* L.). For the narrow-windrow burns, temperatures at the soil surface were high enough to destroy the seeds of rigid ryegrass and wild radish; however, burning standing stubble left after harvest did not produce the required duration of high temperatures to destroy the seeds of these species (Walsh and Newman 2007; Walsh et al. 2013). The low cutting height and high amount of biomass that enters the combine during harvest make soybean a favorable candidate to potentially burn and destroy seed from weed escapes in the field.

The most troublesome weed of soybean in the mid-southern United States is Palmer amaranth (Riar et al. 2013). Palmer amaranth is known to be resistant to multiple herbicide sites of action and can produce a large number of seed (Heap 2018; Keeley et al. 1987). Large numbers of seed, coupled with resistance, makes Palmer amaranth a very important weed to manage. A successful HWSC program that destroys the seed of Palmer amaranth will be beneficial to lowering the amount of seed returned to the soil seedbank, and previous research shows that narrow-windrow burning can be successful in lowering the population of Palmer amaranth (Norsworthy et al. 2016).

Understanding the efficacy of narrow-windrow burning in soybean requires that multiple weed seeds, ranging from small to large, be tested. Other notable weeds of concern would be species such as barnyardgrass (small-seeded grass), johnsongrass (large-seeded grass), and pitted morningglory (large-seeded broadleaf). Barnyardgrass is considered the most troublesome weed in rice (*Oryza sativa* L.) and ranks in the top ten most troublesome weeds in soybean (SWSS 2012; SWSS 2013). Like Palmer amaranth, barnyardgrass has been shown to be resistant to multiple herbicide sites of action (Heap 2018). Johnsongrass is considered the most troublesome weed in grain sorghum (*Sorghum bicolor* L. Moench) and corn (*Zea mays* L.) (SWSS 2012). Johnsongrass has been shown to be resistant to glyphosate in the state of Arkansas (Heap 2018); however, johnsongrass can cause substantial yield loss if left untreated in a field. Pitted morningglory is also ranked in the top ten most troublesome species of multiple crops including soybean, corn, and grain sorghum (SWSS 2012; SWSS 2013). Pitted morningglory can cause significant yield reduction in soybean (Howe III and Oliver 1987; Norsworthy and Oliver 2002), interfere with harvest, and persist in the soil seedbank (Egley and Chandler 1983).

Testing efficacy of narrow-windrow burning on Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory in soybean chaff will enable a conclusion to be drawn as to how well this HWSC tactic will work in soybean on a broad array of weed seed. It is hypothesized that narrow-windrow burning will be successful in destroying seed of major weed species of U.S. soybean production systems due to the larger amount of biomass associated with soybean harvest.

Materials and Methods

Field experiments were conducted at the University of Arkansas Northeast Research and Extension Center in Keiser, AR, in 2014 and 2015 in a production field of Credenz 4950LL soybean grown under irrigated conditions to assess the heat intensity and efficacy of heat on killing the seed of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory. Just prior to harvesting, five 2-m rows of soybean were hand harvested from the experimental site to determine soybean yield. Because the amount of soybean biomass will likely affect the heat intensity of burning, narrow-windrows with increasing levels of biomass were created by harvesting increasingly wider soybean plots (4.8 to 9.2 m) with a Case 2388 combine fitted with a 9.1 m wide header. This range in plot widths was equivalent to 5 to 10 soybean rows where one soybean row was added (0.96 m width) for each increase in plot width. The five rows harvested represented a low-yielding environment, and the 10 rows represented a normal yield for a typical irrigated, high-yielding soybean. After harvesting, five burns for each harvested swath were set up and the different amounts of harvest residue biomass were collected from 1 m of row near where each burn was to occur. Biomass samples were immediately weighed in the field and were returned to the Altheimer Laboratory in Fayetteville to be dried. Just prior to burning, one hundred seeds of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory were placed at the soil surface beneath the narrow windrow in separate 5-cm-diameter aluminum tins to assess the effectiveness of the burn in killing these seeds. The temperature at the location of the weed seed was recorded every second throughout the burn using an Omega Engineering Type K thermocouple and data logger (Omega® Engineering Inc., Stamford, Connecticut).

The data logger allowed for a calculation of heat index (HI) and effective burn time (EBT). HI is a measurement of heat above ambient, which is figured here by summing the temperature above ambient for each second during a burn. EBT is similar to HI but is only the number of seconds that a burn is at or above a specified temperature. For example, in this experiment, EBT 200 is the designation used for the number of seconds that a burn was at or above 200 C. In this experiment, EBT 200 and 300 were calculated. Immediately after burning, the weed seed-containing aluminum tins were collected and returned to the Altheimer Laboratory in Fayetteville for germination and viability assessments. Seeds that were recovered from the burns were completely ash, with the exception of pitted morningglory. To ensure that no seed was missed in the ash, germination tests were conducted in an incubator set at 40 C with a 16 h day and 8 h night for each weed species for 14 days. In preparation for the germination test, the ash from the tins was placed in petri dishes lined with filter paper and moistened with a 1% v/v

Captan solution (Captan 4 Flowable, Drexel, Memphis, TN) as needed. At the end of the 14-day period, petri dishes were examined for any germinated or non-germinated seed. For pitted morningglory, seed were additionally stained using 1% w/v tetrazolium chloride to test for viability.

A second experiment was conducted in 2014 and 2015 to measure the impact of wind speed on HI and EBT using a Stihl BG 55 leaf blower (Stihl Holding AG & Co. KG Waiblingen, Germany). For this experiment, an anemometer was placed near the burn and the leaf blower was positioned to create a predetermined wind speed. An Omega Engineering data logger was placed under the narrow windrow at the time of burning, and temperatures were recorded every one second until temperatures peaked. HI and EBT calculations were calculated based on the data logger readings in the same manner as described in experiment one with the exception that EBT 100 and 200 were used because burn times were substantially reduced.

Statistical Analyses. Data for experiment one were fit to a regression model (Equation 1) using the Fit Model platform in JMP Pro 13 (SAS Institute Inc., Cary, NC):

(Equation 1): $y = B_0 + B_1x_1 + B_2x_2$

where y = response (Heat Index, EBT 200, and EBT 300), B_0 = intercept, B_1= regression coefficient for biomass, and B_2= regression coefficient for wind speed.

Data for experiment two were fit to a linear model (Equation 2) using the Fit Model platform in JMP Pro 13:

(Equation 2): $y = B_0 + B_1x_1$

where y = response (Heat Index, EBT 100, and EBT 200), B_0 = intercept, and B_1 = slope estimate for wind speed.

Results and Discussion

Temperatures Achieved. In experiment one, HI values ranged from a low of 2.08×10^4 to a high of 65.94×10^4 in soybean. These HI values are an order of magnitude higher than those reported for wheat (30.6×10^3) in Australia (Walsh and Newman 2007). For the range of wind speeds in experiment one, wind speed did not have a significant effect on the HI or EBT from any burn. However, as expected, the amount of biomass present at the time of burning did have an effect on HI and EBT (Table 4.1). The greater the amount of biomass, the greater the HI and EBT. Biomass amounts ranged from 1.867 kg m-row for the 10-row harvested width to 1.706 kg, 1.563 kg, 1.341 kg, 1.213 kg, and 1.033 kg m-row for the 9, 8, 7, 6, and 5-row harvested widths, respectively.

In experiment two, wind speed did have an effect (P=0.0152, P=0.0252, P=0.0137) on HI, EBT 100, and EBT 200, respectively (Table 4.2). The wind speed best suited for the longest and highest burn temperatures was between 0.89 and 1.34 m s^{-1}. At wind speeds above 1.34 m s^{-1}, HI, EBT 100, and EBT 200 decreased rapidly.

Weed Seed Survival. During 2014 and 2015, regardless of the HI and EBT achieved, all seeds of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory were killed when the narrow windrows were burned (data not shown). In fact, the seeds of Palmer amaranth, barnyardgrass, and johnsongrass were burned to the point that seeds could be crushed into ash. Pitted morningglory, as expected, was the most resilient of the seeds and remained intact however, these seeds were non-viable. These data align with those of Walsh and Newman (2007) and Lyon et al. (2016) who reported that a high percentage of wild radish (96%) and ryegrass (99%) could be killed with narrow-windrow burning in wheat. Figure 4.1 depicts a typical response from narrow-windrow burning of soybean harvest residues.

Practical Implications. Herbicide-resistant weeds will continue to evolve and decrease the effectiveness of chemical control strategies if herbicide programs are not diversified. HWSC, in particular narrow-windrow burning, has been shown to be effective in decreasing the number of weed seed that returns to the soil seedbank in both wheat in Australia and soybean in the United States. The low cost of setting up a narrow-windrow burning chute ($200 US dollars) and the effectiveness of narrow-windrow burning, as shown here, will make this burning strategy a valuable option, as long as permitted burning continues to be allowed in regions where U.S. farmland predominates.

The upside to this strategy is that even if a farmer is already plagued with herbicide-resistant weeds, narrow-windrow burning will still destroy weed seed that would normally be returned to the soil seedbank and thus, over time, decrease the number of weeds present in the field. A decreased seedbank coupled with an effective herbicide program will help to improve weed control throughout the growing season. However, the main limiting factor to narrow-windrow burning is that the amount of weed seed laced within each narrow windrow is dependent on the seed retention of the weed species present. For example, previous research on Palmer amaranth and barnyardgrass shows that each plant retains approximately 97% and 43%, respectively, of the total seed produced by crop maturity (Schwartz et al. 2016; Schwartz-Lazaro et al. 2017). The higher the percentage of seed retention, the more weed seed that will enter the combine at harvest and subsequently be placed into the narrow windrow for burning. Proper diversification tactics and effective herbicide programs are essential for the future of herbicides that are currently in use. Any grower that is looking to diversify their weed-management program should consider implementing narrow-windrow burning to increase diversification of their current weed control program and better target the soil seedbank, two vital components of a successful program (Norsworthy et al. 2012).

Literature Cited

Egley GH, Chandler JM (1983) Longevity of weed seeds after 5.5 years in the Stoneville 50-year buried-seed study. Weed Sci 31:264-270

Heap I (2018) The international survey of herbicide resistant weeds. Online. http://www.weedscience.org. Accessed March 21, 2018

Howe III OW, Oliver LR (1987) Influence of soybean (*Glycine max*) row spacing on pitted morningglory (*Ipomoea lacunosa*) interference. Weed Sci 35:185-193

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

Lyon DJ, Huggins DR, Spring JF (2016) Windrow burning eliminates Italian ryegrass (*Lolium perenne ssp. Multiflorum*) seed viability. Weed Technol 30:279-283

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540-550

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

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (Special Issue I):31-62

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

Schwartz LM, Norsworthy JK, Young BG, Bradley KW, Kruger GR, Davis VM, Steckel LE, Walsh MJ (2016) Tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus palmeri*) seed production and retention at soybean maturity. Weed Technol 30:284-290

Schwartz-Lazaro LM, Green JK, Norsworthy JK (2017) Seed shatter and retention of Palmer amaranth (*Amaranthus palmeri*) and barnyardgrass (*Echinochloa crus-galli*) at and after soybean maturity. Weed Technol 31:617-622

Shirtliffe SJ, Entz MH (2005) Chaff collection reduces seed dispersal of wild oat (*Avena fatua*) by a combine harvester. Weed Sci 53:465-470

[SWSS] Southern Weed Science Society. 2012 Weed Survey-Grass Crops Subsection. South Weed Sci Soc 65:267-288

[SWSS] Southern Weed Science Society. 2013 Weed Survey-Broadleaf Crop Subsection. South Weed Sci Soc 66:275-287

Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crop Res 104:24-30

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27:431-436

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332-338

Walsh M, Ouzman J, Newman P, Powles S, Llewellyn R (2017) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. Weed Technol 31:341-347

Tables and Figures

Table 4.1. Parameter estimates and P-values for the regression models[a] for heat index (HI), effective burn time at 200 C (EBT 200), and effective burn time at 300 C (EBT 300) from a narrow-windrow burning field experiment conducted in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, Arkansas.

	Parameters	Estimates	P-Value
HI	Intercept (B_0)	16,322.0 ± 59,736.5	0.7859[d]
	Slope biomass (B_1)	149323.1 ± 32,431.5[b]	<0.0001
	Slope wind speed (B_2)	-21180.6 ± 12,563.0[c]	0.0987
EBT 200	Intercept (B_0)	142.4 ± 174.6	0.4190
	Slope biomass (B_1)	433.9 ± 94.8	<0.0001
	Slope wind speed (B_2)	-60.9 ± 36.7	0.1044
EBT 300	Intercept (B_0)	-31.0 ± 159.1	0.8464
	Slope biomass (B_1)	310.5 ± 86.4	0.0008
	Slope wind speed (B_2)	-44.1 ± 33.5	0.1944

[a] Model equation: $y = B_0 + B_1 x_1 + B_2 x_2$
[b] Biomass is expressed in kilograms
[c] Wind speed is expressed in m s^{-1}
[d] P-value $\leq$ 0.05 is significant

Table 4.2. Parameter estimates and P-values from a nonlinear regression model[a] for heat index (HI), effective burn time at 100 C (EBT 100), and effective burn time at 200 C (EBT 200) from narrow-windrow burning experiments where wind speed was created using a leaf blower in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, Arkansas.

	Parameters	**Estimates**	**P-Value**
HI	Intercept (B_0)	36,579.5 ± 7,398.9	0.0001[c]
	Slope wind speed[b] (B_1)	-5356.3 ± 2,033.3	0.0152
EBT 100	Intercept (B_0)	151.8 ± 29.0	<0.0001
	Slope wind speed (B_1)	-18.6 ± 7.8	0.0252
EBT 200	Intercept (B_0)	105.7 ± 23.9	0.0004
	Slope wind speed (B_1)	-17.0 ± 6.4	0.0137

[a] Model equation: $y = B_0 + B_1 x_1$
[b] Wind speed is expressed as m s^{-1}
[c] P-value $\leq$ 0.05 is significant

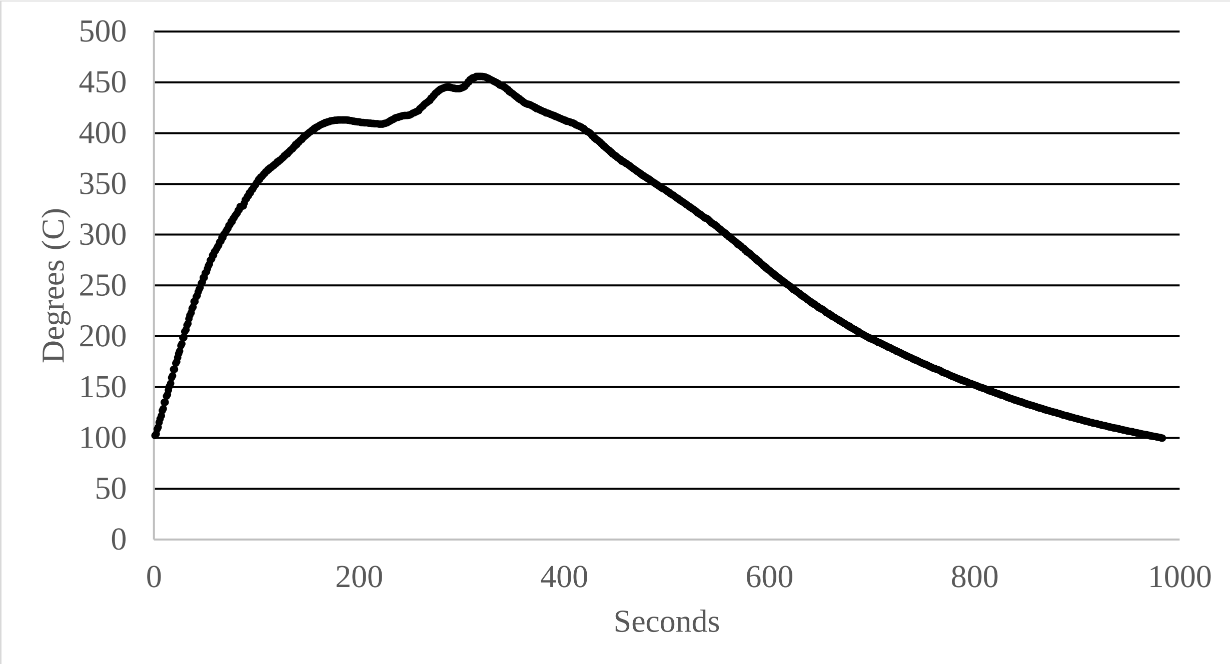

Figure 4.1. Time and temperatures observed from a typical plot while narrow-windrow burning soybean harvest residues at the Northeast Research and Extension Center in Keiser, Arkansas in 2014 and 2015.

Chapter Five

Heat Requirements for Weed Seed Destruction

Abstract

Narrow-windrow burning has been successful in some Australian crops because the heat required kill the seed of Australian weed species is achieved during burning. Little is known about the efficacy of narrow-windrow burning on the seeds of weeds infesting U.S. cropping systems, in particular, the heat required to kill them. An experiment was conducted at the University of Arkansas Research and Extension Center in Fayetteville, Arkansas, using a high-fire kiln that exposed various large- and small-seeded grass and broadleaf weed seeds to temperatures of 200, 300, 400, 500, and 600 C for 20, 40, 60, and 80 seconds to determine the temperature and time needed to kill the seed of each species. At the highest temperature and time tested, only sicklepod had any percentage of survival (<1% average); however, in most cases, the seeds were completely destroyed (ash). The results from this experiment, coupled with the results of narrow-windrow burning of soybean chaff, show that complete loss in viability of weed seed is likely if weed seed is present at harvest, taken into the combine during the harvesting operation, and narrow-windrows burned after harvest. Given the low cost of implementation of narrow-windrow burning and the success of burning on various weed seeds, this strategy is an attractive option for destroying weed seed before they enter the soil profile and become problematic in the future.

Nomenclature: soybean, *Glycine max* (L.) Merr.

Keywords: harvest weed seed control, kiln, weed seed viability, narrow-windrow burning, cultural practices

Introduction

Harvest weed seed control (HWSC) strategies are currently being investigated to determine their potential fit for weed management programs in United States (U.S.) crop production systems. HWSC, more specifically narrow-windrow burning, is a widely adopted practice for destroying rigid ryegrass (*Lolium rigidum* Gaud.) seed and decreasing the soil seedbank when growing wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), and lupin (*Lupinus angustifolius* L.) in Australia (Walsh et al. 2013). In southern U.S. soybean production systems, there is an opportunity to use narrow-windrow burning of chaff and straw residues in an effort to destroy weed seed that escaped a weed management program and are harvested with the crop (Norsworthy et al. 2016). If troublesome weed species in the U.S., such as Palmer amaranth (*Amaranthus palmeri* S. Wats.), can be controlled with HWSC, growers would have an additional option to decrease the number of weed seed in the soil seedbank.

In southern U.S. crop production systems, the most troublesome weed is Palmer amaranth (WSSA 2017). Palmer amaranth has documented resistance to microtubule assembly, acetolactate synthase, 5-enolpyruvylshikimate-3-phosphate synthase, photosystem II, 4-hydroxyphenylpyruvate dioxygenase, and protoporphyrinogen oxidase inhibiting herbicides (Heap 2018). As resistance continues to increase and become more widespread, effective herbicide options decrease. Stewardship of remaining effective herbicide options must be a priority to continue having a successful weed management program (Norsworthy et al. 2012). Proper stewardship requires a grower to abandon a herbicide-only program and diversify management tactics to include cultural practices such as tillage, cover crops, and HWSC.

HWSC can be implemented by using various tactics; including narrow-windrow burning, chaff carts, the bale-direct system, or the integrated Harrington Seed Destructor (iHSD) (Walsh et al. 2013). The low cost of implementing narrow-windrow burning makes this strategy an attractive option; however, the efficacy of narrow-windrow burning on various weed seed that may pass through the combine at harvest is unknown and expected to be different for weed species that differ in size and shape. In previous research conducted at the University of Arkansas, narrow-windrow burning of soybean showed that weed seed destruction is possible on an array of different seed sizes due to the high temperatures (200 – 400 C) and durations (5 – 15 minutes) during burning (Green, unpublished data). According to Walsh and Newman (2007), the destruction of rigid ryegrass and wild radish (*Raphanus raphanistrum* L.) differed with temperature and duration of temperature even though the seeds are similar in size. The objective of this research is to examine the specific temperature and duration requirements needed to kill various weed seeds. This experiment is crucial in estimating the potential efficacy of narrow-windrow burning.

Materials and Methods

An experiment was conducted at the Altheimer Laboratory located in Fayetteville, Arkansas, to determine the temperature and amount of time needed to kill the seed of Palmer amaranth, barnyardgrass [*Echinochloa crus-galli* (P.) Beauv.], johnsongrass [*Sorghum halepense* (L.) Pers.], pitted morningglory (*Ipomoea lacunosa* L.), hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], prickly sida (*Sida spinosa* L.), sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby], velvetleaf (*Abutilon theophrasti* Medik.), and Italian ryegrass (*Lolium multiflorum* Lam.). The species for this experiment were chosen to evaluate burning on small- and large-seeded grasses and broadleaves that may be encountered in soybean production.

Before counting and burning, all seeds were placed in a small aluminum tin and then moved into an oven at 40 C for drying until the weight for each seed lot stabilized so that moisture would not be considered a factor. After drying, viability was determined for the seed of each weed species to ensure that we could capture a curve for decreasing seed viability. Once viability was determined, 100 seeds of each species, with the exception of barnyardgrass, were counted into separate packets for burning. For barnyardgrass, samples of 200 seeds were used because of the lower viability of the available seed lot. The seed samples were then emptied into porcelain crucibles measuring 4 cm in height and 5 cm at the top outside diameter (Cole-Parmer, Vernon Hills, Illinois), placed inside a high-fire kiln (Paragon Industries, L. P. Mesquite, Texas), and subjected to various temperatures (200, 300, 400, 500, and 600 C) and times (20, 40, 60, 80 sec). For the kiln used in this experiment, a burn was considered acceptable if the temperature inside the kiln varied no more than ±10 C of each experimental temperature. The specified temperatures and times for burning seed in this experiment allowed for a calculation of heat index (HI). HI is calculated by summing the temperature achieved above ambient for each second during the burn. The ambient temperature used in this experiment was 23.9 C. The experiment was conducted in two runs with two replications per run. After burning, seeds of pitted morningglory, hemp sesbania, sicklepod, and velvetleaf were scarified or cut with a razor blade and placed between two filter papers soaked with a 1% w/v tetrazolium chloride solution for approximately 24 h before checking for germination and staining. Seeds of Palmer amaranth, barnyardgrass, johnsongrass, prickly sida, and ryegrass were soaked between two filter papers soaked with 1% w/v tetrazolium chloride solution for approximately 24 to 48 h before being crushed to assess staining. A seed was considered viable if the seed had germinated or if 10 percent of the internal seed structure was stained pink to red. Results for live seed were then converted into a percentage of survivors based on the viability of the unburned controls so that a kill rate could be determined for the seed of each weed species.

Statistical Analyses. Data from this experiment were analyzed as a regression model (Equation 1) using FIT MODEL platform in JMP Pro 13 (SAS Institute Inc., Cary, NC):

(Equation 1): $y = B_0 + B_1X_1 + B_2X_2 + B_3X_1X_2$

where y = percent viability, B_0 = intercept, B_1 = temperature, B_2 = time. Additionally, a regression model (Equation 2) to determine the relationship between heat index and percent viability using FIT Y by X in JMP Pro 13:

(Equation 2): $y = B_0 + B_1X_1$

Where y = percent viability, B_0 = intercept, B_1 = slope estimate for heat index.

A determination of lowest heat index where zero was observed was simply chosen once 0% viability was reached and no data points after were > 0%. Furthermore, mean temperatures to obtain 95% kill (5% viability) at 30 and 60 seconds were determined for each species to determine the least to most resistant species to heat using JMP Pro 13.

Results and Discussion

Heat Effects on Weed Seed Viability. Seed viability of Palmer amaranth, barnyardgrass, hemp sesbania, sicklepod, velvetleaf, and ryegrass was affected by an interaction of temperature and duration of exposure to a temperature (Table 5.1). This interaction is similar to one found by Thompson et al. (1997) where the weed seeds of various species were subjected to a known temperature for a specific amount of time. Each species tested in this experiment, with the exception of sicklepod, was destroyed at or before the highest temperature and time tested which was 600 C for 80 seconds (HI = 46,088); however, no seed, regardless of species, was completely destroyed at 200 C for any time tested. As expected, seed size had some impact on the amount of heat needed to kill each of the nine species. For example, small seeded species, such as Palmer amaranth and barnyardgrass, had complete loss in viability when the seed was exposed to temperatures of 400 C for at least 60 seconds (HI = 22,566) or 500 C for 40 seconds (HI = 19,044). However, species with larger seeds, such as pitted morningglory and sicklepod, required more heat to cause or approach complete loss in viability by requiring 500 C for 80 seconds (HI = 38,088) and 600 C for 80 seconds (HI = 46,088), respectively. This type of response is very similar to the response seen in narrow-windrow burning experiments conducted in Keiser, Arkansas in 2014 and 2015 where the smaller seeds (Palmer amaranth, barnyardgrass, and johnsongrass) were destroyed much faster and easier than the larger seeds (pitted morningglory) (Green, unpublished data).

Heat Index and Seed Viability. Heat index was a weak predictor of percent viability in the mid-range of heat indexes tested (Table 5.2). Low HI had little effect on weed seed as expected; however, as HI increases, the HI does not correspond well with percent viability (Figure 5.11). This response would be expected based on R^2 values reported by Walsh and Newman (2007) for a kiln experiment burning rigid ryegrass ($R^2 = 0.76$) and wild radish ($R^2 = 0.44$).

The kill rate determined by Walsh and Newman (2007) for ryegrass (400 C greater than 10 seconds) is lower than the kill rate that was determined in this experiment (400 C greater than 40 seconds). This slight difference in kill rate could be attributed to the different methods used to determine viability. The determination of viability used by Walsh and Newman in 2007 classified a seed as viable if the seed had germinated or remained firm and not decayed.

Previous research has been conducted to test weed seed viability after being exposed to various temperatures and times, such as those seen in solarization techniques. The seeds of barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], tumble pigweed (*Amaranthus albus* L.), annual sowthistle (*Sonchus oleraceus* L.), London rocket (*Sisymbrium irio* L.), common purslane (*Portulaca oleracea* L.), and black nightshade (*Solanum nigrum* L.) were subjected to temperatures ranging from 39 C to 70 C (Dahlquist et al. 2007). As temperature increased for each species, viability decreased, showing that killing weed seed is attainable by heating. Additionally, previous research has also been conducted to determine the efficacy of composting on killing weed seed. According to Wiese et al. (1998), the seeds of pigweed (*Amaranthus* sp. *hybridus* and *palmeri* L.), barnyardgrass, johnsongrass [*Sorghum halepense* (L.) Pers.], kochia [*Kochia scoparia* (L.) Schrad.], sorghum [*Sorghum bicolor* (L.) Moench], and field bindweed (*Convolvulus arvensis* L.) could all be destroyed when the seeds were exposed to temperatures of at least 49 C for three days. Reports from other studies indicate that seeds of plants such as fireweed [*Chamaenerion angustifolium* (L.) Holub], pineappleweed (*Matricaria discoidea* DC.), annual bluegrass (*Poa annua* L.), black nightshade, sowthistle, common chickweed [*Stellaria media* (L.) Vill.], white clover (*Trifolium repens* L.), and speedwell (*Veronica persica* Poir.) could also be destroyed if exposed to a temperature of 55 C for three days (Grundy et al. 1998). These experiments, which involved solarization-type techniques and composting, give similar results by showing that the alleviation of seed viability with heat is attainable even with lower temperatures. Exposure temperatures and times are critical in determining the kill rate of various weed seed.

Practical Implications. This experiment shows that complete loss in weed seed viability is possible through burning. At 600 C for 80 seconds, the calculated heat index value was 46,088. Complete loss in viability and, in most cases, seed destruction was observed at this value. Heat index calculations from narrow-windrow burning experiments in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, Arkansas, showed that values ranged from 20,800 to 659,400, with an average of 242,130 across all burns both years regardless of amount of biomass present. If weed seed is taken into the combine at harvest, and subsequently subjected to narrow-windrow burning, the likelihood is high for destruction of all seeds encountered in soybean production systems. Given the low cost of implementation and the validation of weed seed destruction in narrow-windrow burning using this kiln experiment, it is recommended that growers employ this tactic to lower the return of weed seed to the soil seedbank and thereby reduce selection for herbicide-resistant weeds.

Literature Cited

Dahlquist RM, Prather TS, Stapleton JJ (2007) Time and temperature requirements for weed seed thermal death. Weed Sci 55:619-625

Grundy AC, Green JM, Lennartsson M (1998) The effect of temperature on the viability of weed seeds in compost. Compost Sci Util 6:26-33

Heap I (2018) The international survey of herbicide resistant weeds. Available at: www.weedscience.org. Accessed March 21, 2018

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540-550

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (Special Issue I):31-62

Thompson AJ, Jones NE, Blair AM (1997) The effect of temperature on viability of imbibed weed seeds. Ann Appl Biol 130:123-134

Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crop Res. 104:24-30

Walsh M, Newman P, Powles S (2013) Targeting weed seed in-crop: A new weed control paradigm for global agriculture. Weed Technol 27:431-436

Wiese AF, Sweeten JM, Bean BW, Salisbury CD, Chenault EW (1998) High temperature composting of cattle feedlot manure kills weed seed. Appl Eng Agric 14:377-380

[WSSA] Weed Science Society of America. 2017 Weed Survey. http://www.wssa.net. Accessed March 21, 2018

Tables and Figures

Table 5.1. Parameter estimates and P-values from a multiple regression model[a] for a high-fire kiln experiment conducted on nine species at the Altheimer Laboratory in Fayetteville, Arkansas.

Species	Intercept $(\boldsymbol{B_0})$	P- Value	Temp. (C) $(\boldsymbol{B_1})$	P- Value	Time (sec) $(\boldsymbol{B_2})$	P-Value	Temp. * Time $(\boldsymbol{B_3})$	P-Value
Palmer amaranth	152.1 ± 11.2	< 0.0001	-0.3 ± 0.02	< 0.0001	-0.4 ± 0.1	< 0.0023	0.002 ± 0.001	0.0613
barnyardgrass	142.7 ± 8.9	< 0.0001	-0.2 ± 0.02	< 0.0001	-0.6 ± 0.1	< 0.0001	0.003 ± 0.001	0.0008
johnsongrass	175.3 ± 9.2	< 0.0001	-0.3 ± 0.02	< 0.0001	-0.7 ± 0.1	< 0.0001	-	-[b]
pitted morningglory	192.8 ± 8.4	< 0.0001	-0.3 ± 0.02	< 0.0001	-0.8 ± 0.1	< 0.0001	-	-
prickly sida	188.1 ± 14.0	< 0.0001	-0.3 ± 0.03	< 0.0001	-0.9 ± 0.2	< 0.0001	-	-
annual ryegrass	173.8 ± 9.7	< 0.0001	-0.3 ± 0.02	< 0.0001	-0.6 ± 0.1	< 0.0001	0.001 ± 0.001	0.0976
sicklepod	217.3 ± 9.5	< 0.0001	-0.2 ± 0.02	< 0.0001	-1.1 ± 0.1	< 0.0001	-0.004 ± 0.001	< 0.0001
velvetleaf	201.7 ± 10.9	< 0.0001	-0.3 ± 0.02	< 0.0001	-1.0 ± 0.1	< 0.0001	-	-
hemp sesbania	182.4 ± 7.6	< 0.0001	-0.2 ± 0.01	< 0.0001	-0.9 ± 0.1	< 0.0001	-0.002 ± 0.001	0.0021

[a]Model equation: $y = B_0 + B_1X_1 + B_2X_2 + \; B_3X_3$
[b] - = no significance

Table 5.2. Parameter estimates, P-values, maximum heat index (Max HI), and minimum heat index (Min HI) from a linear regression model[a] for nine weed species from a high-fire kiln experiment conducted at the Altheimer Laboratory in Fayetteville, Arkansas.

Species	**Intercept** $(\boldsymbol{B_0})$	**P-Value**	**Heat Index** $(\boldsymbol{B_1})$	**P-Value**	**Max HI**[b]	**Min HI**[c]
Palmer amaranth	100.5 ± 4.2	<0.0001***[d]	0.0001 ± 0.0008	0.8558	7,044	22,566
barnyardgrass	100.0 ± 5.9	0.0005***	-[e]	-	3,522	22,566
johnsongrass	98.5 ± 7.4	<0.0001***	-0.004 ± 0.001	0.7655	7,522	30,088
pitted morningglory	100.4 ± 5.3	<0.0001***	0.0002 ± 0.0009	0.8136	7,522	34,566
prickly sida	93.3 ± 32.4	0.0348***	0.0019 ± 0.007	0.8015	5,522	23,044
annual ryegrass	104.3 ± 1.0	<0.0001***	-	-	3,522	22,566
sicklepod	114.6 ± 6.9	<0.0001***	-0.0003 ± 0.001	0.8198	7,522	N/A[f]
velvetleaf	105.1 ± 4.3	<0.0001***	0.00007 ± 0.0005	0.8935	11,044	23,044
hemp sesbania	97.5 ± 6.7	<0.0001***	-0.0005 ± 0.001	0.6686	7,522	23,044

[a]Model equation: $y = B_0 + B_1X_1$
[b]Max HI = highest HI achieved before seeing a significant decrease in percent viability
[c]Min HI = lowest HI where viability was zero across all replications
[d]*** = significant at an alpha level of 0.001
[e]- = no P-value obtained due to rapid decrease in percent viability from lowest HI tested
[f]N/A = zero not reached at the highest HI tested

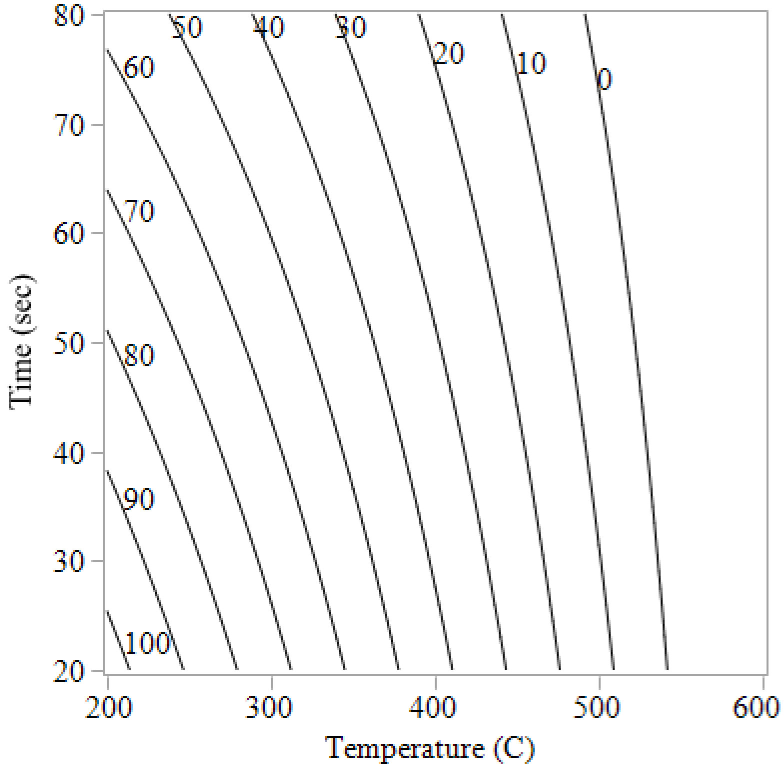

Figure 5.1. Contour map for Palmer amaranth viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

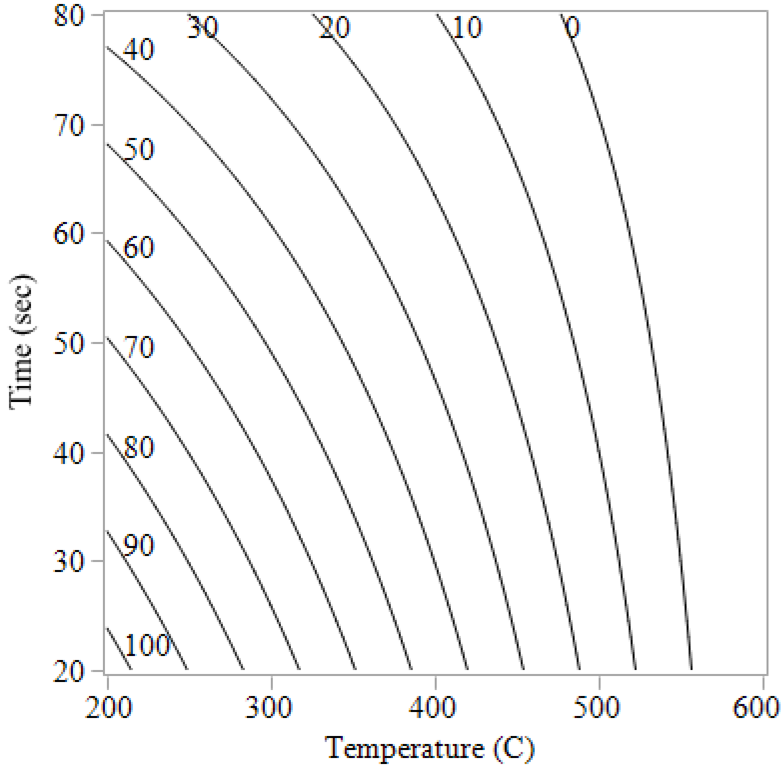

Figure 5.2. Contour map for barnyardgrass viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

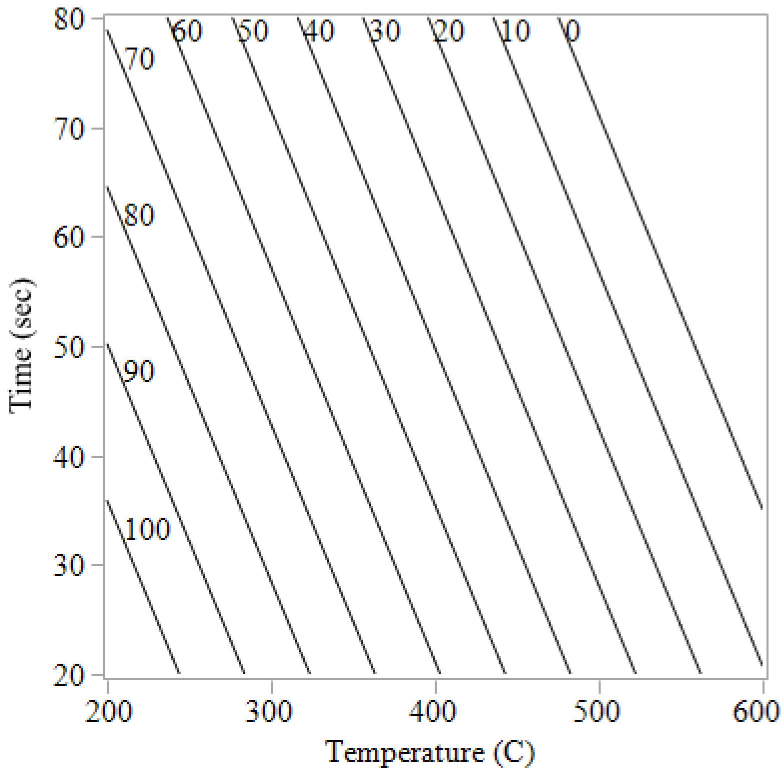

Figure 5.3. Contour map for johnsongrass viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

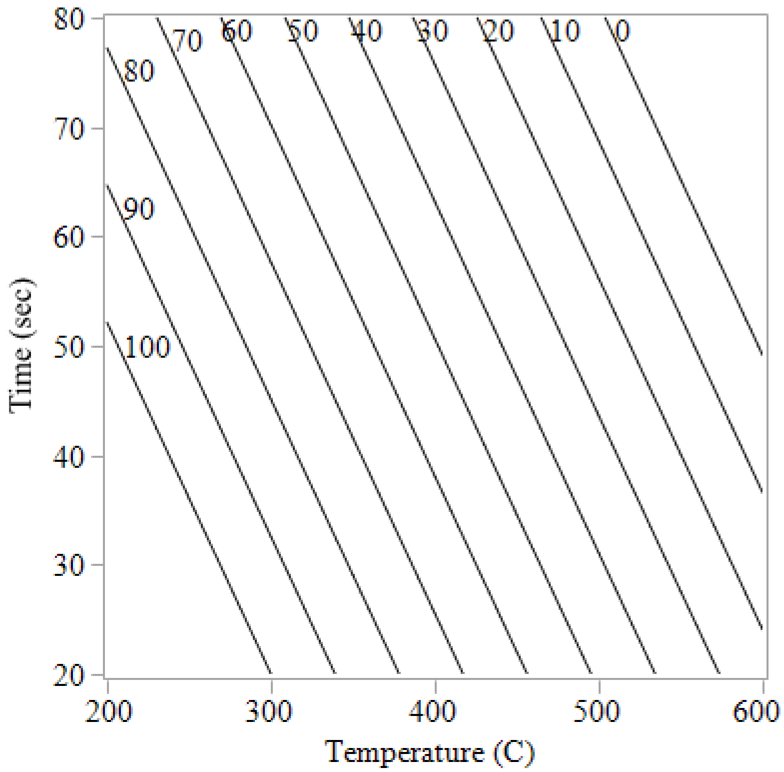

Figure 5.4. Contour map for pitted morningglory viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

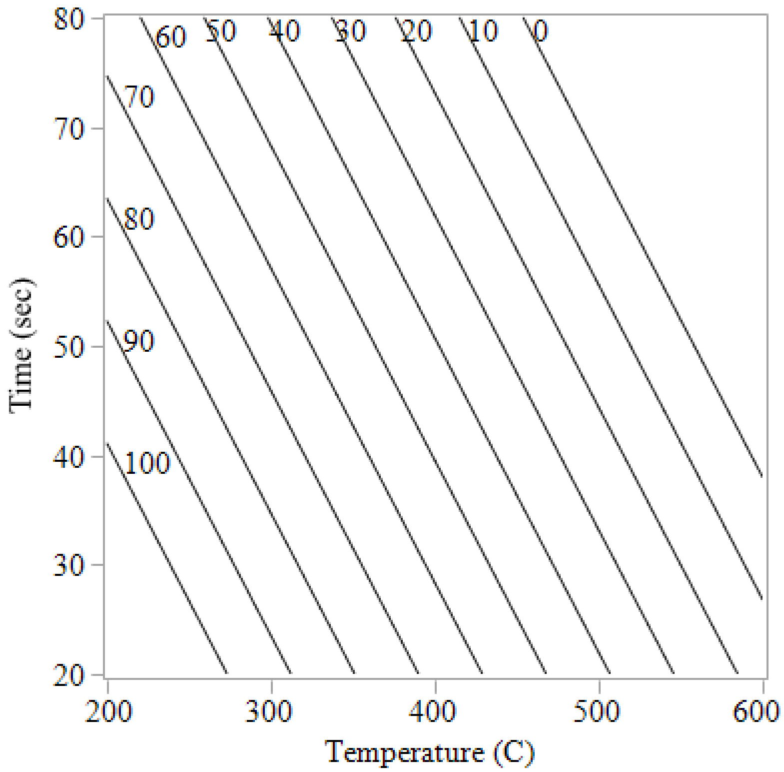

Figure 5.5. Contour map for prickly sida viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

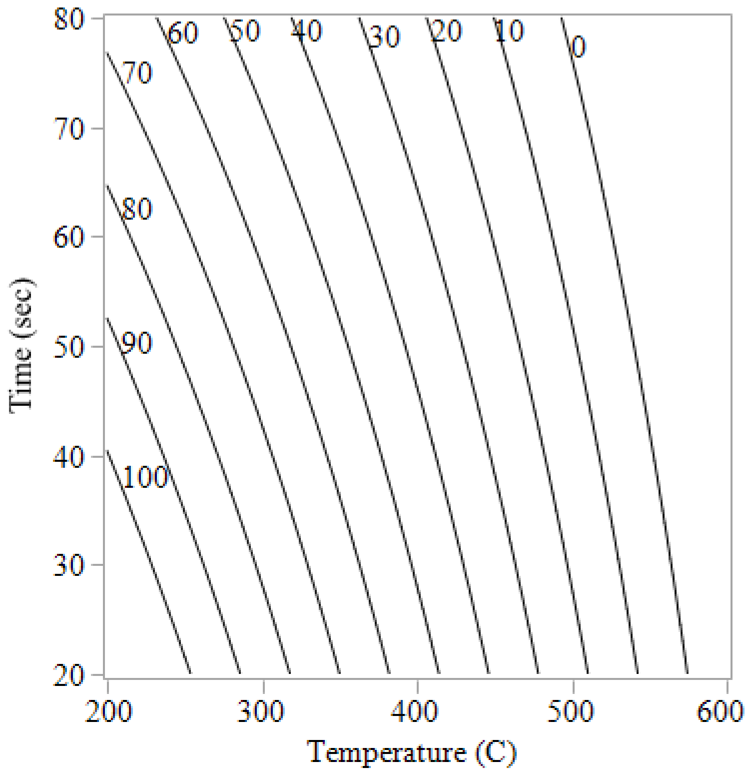

Figure 5.6. Contour map for annual ryegrass viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

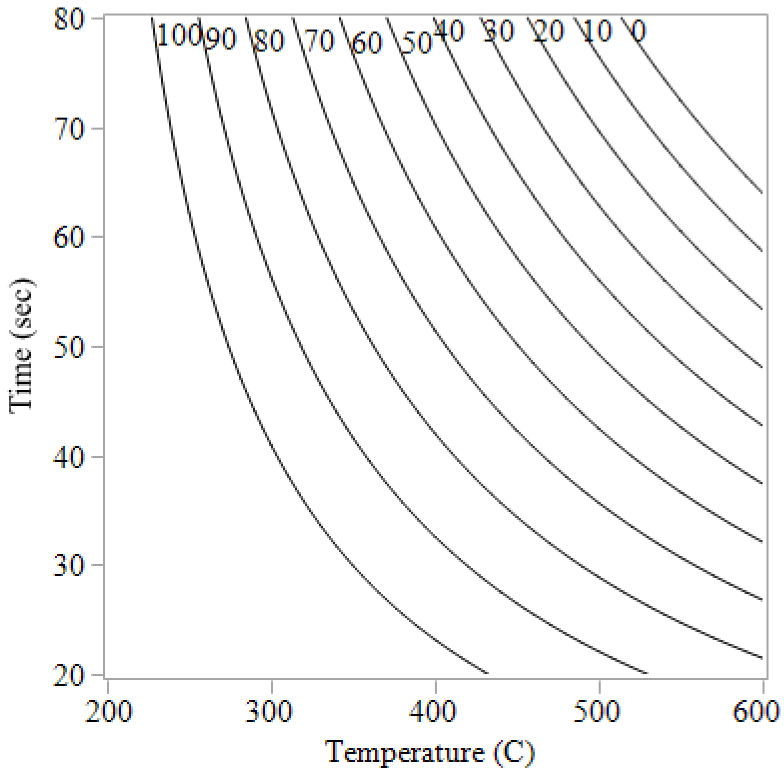

Figure 5.7. Contour map for sicklepod viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

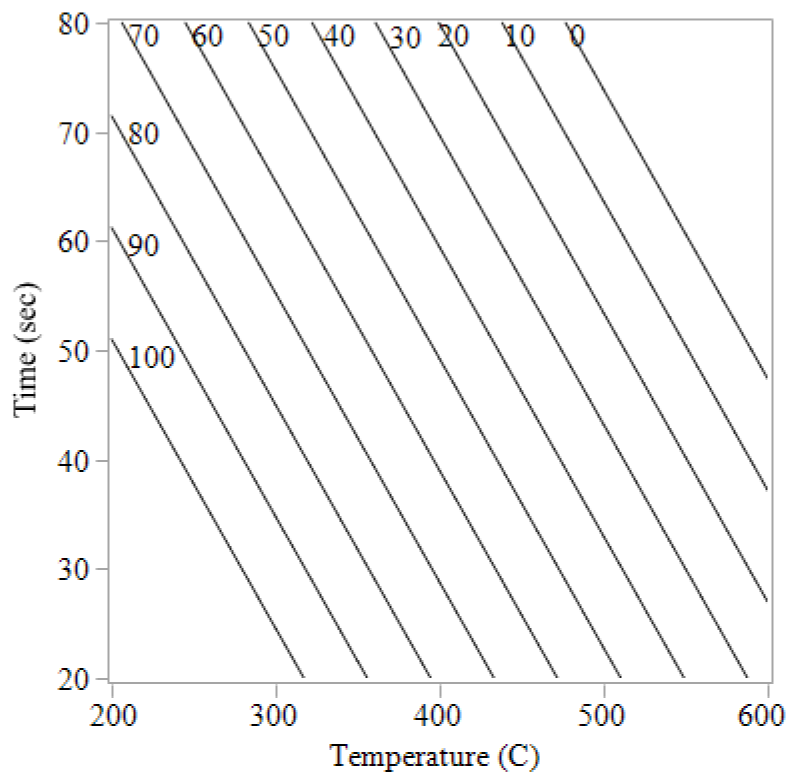

Figure 5.8. Contour map for velvetleaf viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

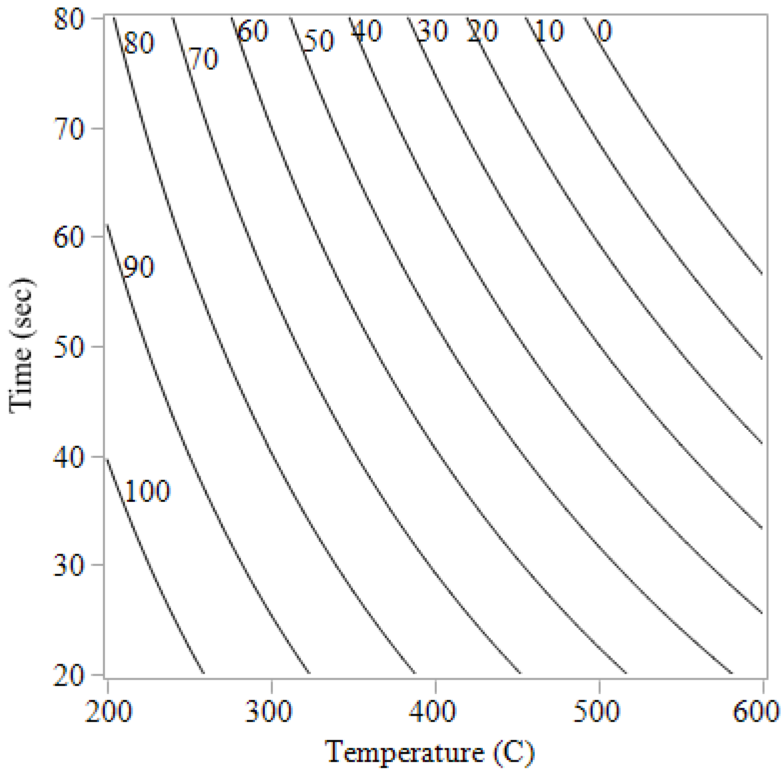

Figure 5.9. Contour map for hemp sesbania viability after exposure to various temperature and heating periods in a high-fire kiln at Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

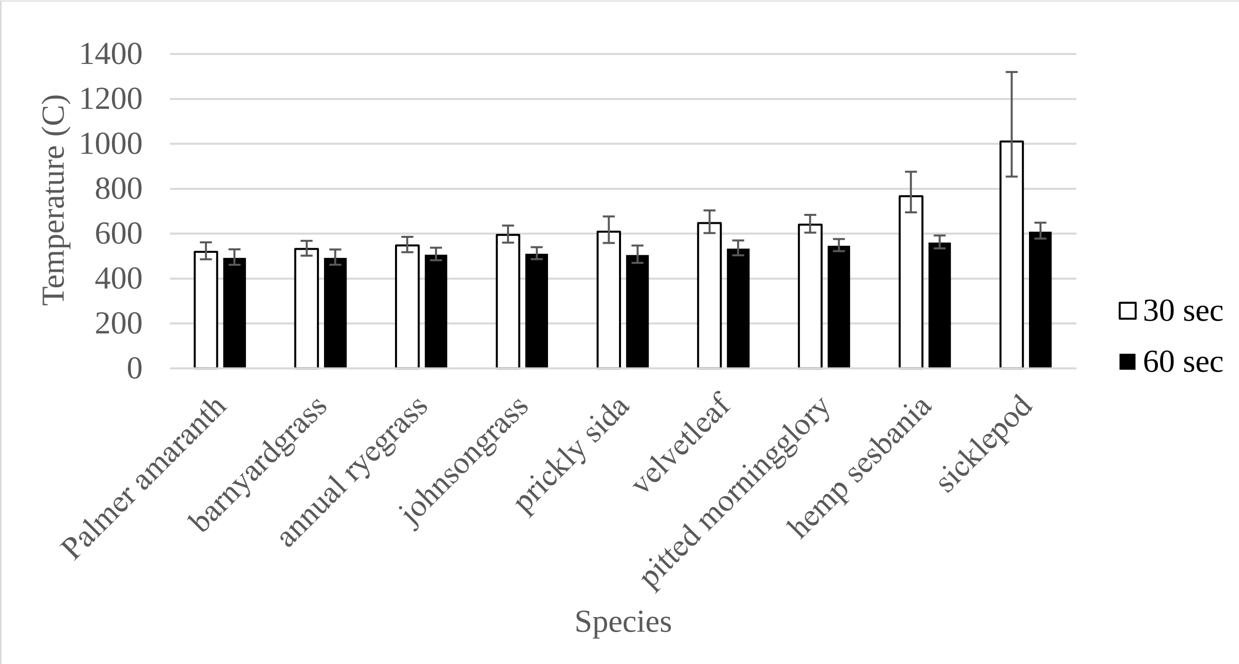

Figure 5.10. Temperature for 95% kill (5% viability) at 30 and 60 seconds for all weed seed tested in a kiln experiment at the Altheimer Laboratory in Fayetteville, Arkansas. Bars represent the mean for 5% viability and the bars above and below the mean represents the standard error.

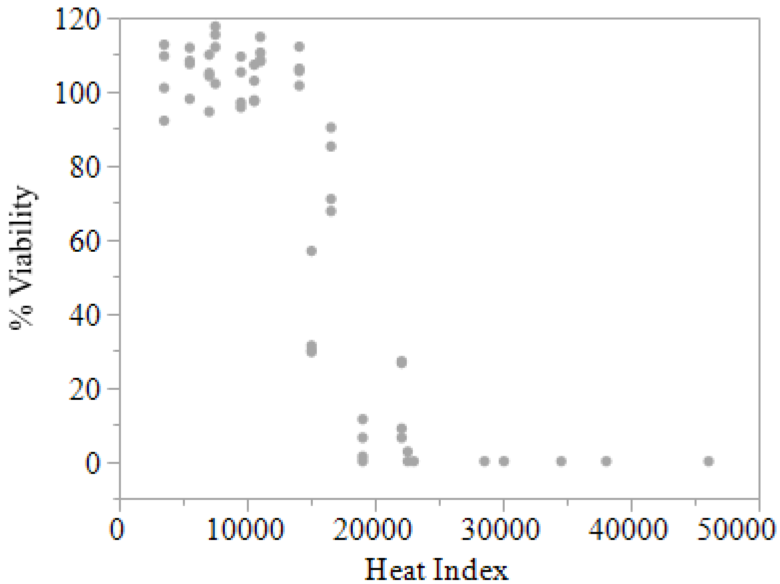

Figure 5.11. Relationship between heat index and percent viability of velvetleaf as an example of the results from the kiln experiment at the Altheimer Laboratory in Fayetteville, Arkansas. (Figure from JMP Pro)

General Conclusions

Harvest weed seed control (HWSC) is a non-chemical control option to lower the soil seedbank and effectively reduce the amount of resistance selection pressure currently placed on herbicides. High seed retention of weed species that escape weed management programs is the first step in determining the potential for the success of HWSC tactics such as narrow-windrow burning. Weed seeds that pass through the combine at harvest are normally redistributed across the landscape, which replenishes the soil seedbank and causes problems in subsequent years. The data presented throughout this thesis show that for weeds such as Palmer amaranth, high seed retention is expected. High seed retention means that if the plant escapes a weed control program and is left in the field at harvest then a high number of seed will enter the combine and subsequently exit in the grain, chaff, or straw fractions. It has been determined that when a combine encounters weeds during soybean harvest, the chaff and straw fractions become heavily laced with weed seed upon exiting the combine; however, it is the chaff fraction that contains most of the weed seed exiting the combine.

Narrow-windrow burning of soybean chaff and straw can be an effective option for destroying weed seed. Weed seeds from species such as Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory have all been rendered nonviable through burning, regardless of the amount of soybean biomass present in these experiments. These results are promising as effective herbicide options continue to decrease. The success, coupled with low cost and ease of implementation, of narrow-windrow burning has given way to the recommendation that this tactic should be employed on farms to combat high soil seedbanks and decrease or delay the onset of herbicide resistance.