INTEGRATION OF HARVEST-TIME AND POST-HARVEST TACTICS FOR INTEGRATED MANAGEMENT OF JOHNSONGRASS (*SORGHUM HALEPENSE*) IN GRAIN SORGHUM (*SORGHUM BICOLOR*)

A Thesis

by

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ABSTRACT

Management of noxious weeds is an evolving task in agriculture, especially with the current state of herbicide resistance in dominant weed species globally. Johnsongrass (*Sorghum halepense*) has been consistently ranked as one of the world's worst weeds, and is considered a high-risk species for the evolution of herbicide resistance (Johnson et al. 2014). Johnsongrass is particularly difficult to control in its crop relative, grain sorghum (*Sorghum bicolor*), due to the genetic similarities between the two species. Novel tactics for integrated management of this species is thus imperative. Harvest weed seed control (HWSC), developed originally in Australia, is an emerging strategy for minimizing viable seed addition to the soil, but its success depends on the proportion of seeds that are retained on the weed and available for capture during crop harvest and the efficiency of the harvest machinery in separating the weed seed for subsequent destruction. There is also a critical need for developing integrated programs that include chemical and non-chemical options for johnsongrass management in grain sorghum. This study had two specific objectives. First, a four-year field survey (2016-2019) was conducted in multiple locations across Texas and Arkansas to assess johnsongrass seed shattering and determine proportion of seeds that are available for capture by the combine during grain sorghum harvest. Johnsongrass produced as high as 5,929 seeds/m^2 in Texas and 808 seeds/m^2 in Arkansas, of which >80% was available for capture (at the harvest height) at the time of grain sorghum harvest. Periodic seed shattering assessments showed that individual johnsongrass plants retained >80% of the seeds within the crop harvest window. For the second objective, a four-year study (2016-19) was conducted in College Station, Texas and Keiser, Arkansas involving multiple combinations of integrated management practices in an acetolactate synthase (ALS)-inhibitor-resistant grain sorghum cultivar (Inzen™), including the use of preemergence and postemergence herbicides, desiccant application prior to harvest, HWSC, disking the field after harvest and treating the regrowth with a graminicide. Johnsongrass plant density and soil seedbank size declined drastically when multiple strategies were combined, compared to a standard herbicide-only program. Results of this study show high feasibility for implementing HWSC as part of an integrated program for managing johnsongrass in grain sorghum in the southern US.

DEDICATION

I would like to dedicate my thesis to the following important people who have supported me throughout the duration of my Masters degree.

Firstly, Dr. Tom Cothren for my original acceptance to Texas A&M in 2013 but for personal reasons I was unable to finish and had to depart prematurely. He opened the door to my dream university at a time that was not ideal for me. I am forever grateful for his acceptance and remorseful for having not completed my studies under his guidance.

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Third, my grandparents and great-grandparents for the introduction into agriculture that stemmed my background and my inquisitive nature to improve agriculture.

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NOMENCLATURE

ACCase	Acetyl CoA carboxylase
ALS	Acetolactate synthase
AR	Arkansas, US
CB	Coastal Bend, TX
CV	Coefficient of variation
DNA	Deoxyribonucleic acid
ET	Economic threshold
FAY	Fayetteville, AR
HWSC	Harvest Weed Seed Control
JG	Johnsongrass (*Sorghum halepense*)
KE	Keiser, AR
MOA	Mechanism/Mode of action
PRE	Pre-emergence
POST	Post-emergence
RGV	Rio Grande Valley, TX
STU	Stuttgart, AR
T#	Treatment followed by treatment number (1, 2, 3, 4, 5, and/or 6)
TX	Texas, US
US	United States
USDA	United States Department of Agriculture

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CHAPTER I

INTRODUCTION

Johnsongrass is the most troublesome weed in grain sorghum production in the southern United States, costing enormous amounts of resources (McWhorter 1989; Miller 2003; Ohadi et al. 2018). Johnsongrass is native to areas east of the Mediterranean Sea, the range of this species now includes all continents except Antarctica and has been known as one of the world's worst weeds (Holm et al. 1977). In row crops, such as sorghum, corn, and cotton, johnsongrass can cause as much as 70% yield loss (Bridges and Chandler 1987; Millhollon 1970) to complete crop failure under severe infestations. Johnsongrass reproduces both by seeds and rhizomes (Horowitz 1972). A single johnsongrass plant can produce about 28,000 seeds (Horowitz 1973), in addition to the production of about 40 to 90 m of rhizomes in a single season (McWhorter 1981). Rhizomes can overwinter if buried deeper (Warwick and Black 1983) and the production of extensive rhizome systems make eradication of this species challenging (McWhorter 1961).

The severity of johnsongrass infestation in sorghum fields and its difficulty to control are mainly due to the lack of selective herbicide options for johnsongrass control (Stahlman and Wicks 2000). Millions of sorghum hectares throughout the nation lack control for johnsongrass because there is currently no postemergence herbicide that can selectively control johnsongrass within a grain sorghum crop (Werle et al. 2016). Thus, johnsongrass infestations cause enormous economic damages to sorghum growers especially in marginal environments where sorghum is valued as a low-input, high-return crop.

Herbicides such as the acetolactate synthase (ALS)-inhibitors (such as nicosulfuron) provide effective control of johnsongrass (Howard 2004; Rosales-Robles et al. 1999a, b). Scientists at Kansas State University have transferred mutations conferring resistance to the ALS-inhibitor nicosulfuron from shattercane to grain sorghum. This herbicide-tolerant cop technology, named as Inzen™ sorghum by Dupont (Wilmington, DE) who acquired its license from Kansas State University, is expected to be available for commercial cultivation soon. Recently, Advanta US has also developed another herbicide-resistant grain sorghum, which is resistant to the ALS-inhibiting herbicide family imidazolinones and expected to be available in the commercial market soon.

While herbicide-resistant crop technologies are expected to provide a valuable tool for johnsongrass control in sorghum, the industry is also concerned about johnsongrass developing resistance to these herbicides, either through random mutation followed by selection or through pollen-mediated gene flow from the resistant sorghum cultivars. Cases of ALS-inhibitor resistance in johnsongrass have already been documented across the states (Werle et al. 2016). In Texas, ALS-inhibitor-resistant johnsongrass (resistance to nicosulfuron and imazethapyr) was documented as early as in 2000 (Green; archived in Heap 2020). Glyphosate resistance was also documented in a johnsongrass biotype collected near West Memphis, Arkansas in 2008 (Riar et al. 2011) and acetyl CoA carboxylase (ACCase)-inhibitors in Virginia in 1995 (Heap 2020).

While herbicide resistance evolution in johnsongrass is a major threat to sorghum production, its invasiveness and the difficulties to control especially in grain sorghum make this species even more troublesome. There is a vital need for developing additional tools for the management of johnsongrass in grain sorghum production fields.

In order to protect the longevity of our current herbicide options that are still effective and achieve economical and sustainable weed management, it is imperative to integrate non-chemical tools in herbicide-dominant weed management systems. Weed (soil) seedbank management is an important element of herbicide resistance management (Liebman and Davis 2009; Walsh et al. 2013). Tremendous opportunities exist to minimize seedbank size by preventing seedbank replenishment from late-season weed escapes through practices implemented at the time of harvest and after harvest (Bagavathiannan and Norsworthy 2012; Walsh and Powles 2007). These approaches can include, but are not limited to, harvest weed seed control (HWSC) for destroying seed before it enters the soil seedbank (Walsh et al. 2013), desiccants for barring weed seed development (Lofton 2019), post-harvest tillage for dehydrating the rhizomes to death (McWhorter and Hartwig 1965), suppressing weed regrowth after crop harvest (Johnson et al. 1997), and others.

The concept of collecting and destroying unshed weed seeds during crop harvest instigated the idea of the HWSC technology; however, this strategy has been only utilized predominantly for annual or rigid ryegrass management in Australia (Walsh et al. 2017a). In the preliminary studies conducted recently across the US, HWSC has shown tremendous potential in reducing weed seedbank size of important troublesome weeds in different cropping systems (Beam et al. 2019; Norsworthy et al. 2020; Shergill et al. 2020a, b). However, they need further confirmation before commercial implementation. Although johnsongrass exhibits seed shattering and produces enormous seeds multiple times in a year, HWSC tactics can be used as a valuable non-chemical tool, if used before substantial portion of seeds are shed, for integrated management of johnsongrass.

Location-specific customized testing of HWSC is crucial as the johnsongrass biotypes may significantly vary in reproductive phenology including seed shattering depending on the location and climatic conditions (Ohadi et al. 2018). Moreover, the commercial HWSC machineries are expensive; their usefulness in capturing and destroying the johnsongrass seeds must be assessed before commercial adoption in a region. Further, its efficiency and compatibility must be tested in combination with other chemical and non-chemical weed control measures before recommending a robust integrated weed management strategy for johnsongrass in grain sorghum production. Therefore, the objectives of the current study were to 1) assess the feasibility (seed retention and capture potential) of implementing HWSC for johnsongrass in grain sorghum in southern US, and 2) evaluate integrated management involving harvest-time and post-harvest tactics for johnsongrass control in grain sorghum.

Review of Literature

Grain Sorghum (*Sorghum bicolor*)

Background

Grain sorghum (*Sorghum bicolor*) is one of the top five cereal crops globally, with versatile uses such as human food, livestock feed, bioenergy, or industrial feedstock. Sorghum is one of the most efficient converters of solar energy and is relatively drought/heat tolerant. In Asia and Africa, sorghum is primarily used as a staple food, while in United States it is mainly used as livestock feed or for ethanol production. The livestock industry is one of the major marketplaces of US sorghum, where it is utilized in feed production for beef, poultry, dairy and swine. Approximately, one third of sorghum produced in the US is used in ethanol plants. In recent years, sorghum is becoming popular in US food markets because of its gluten-free nature. Native to Africa and Asia, sorghum was introduced in the US approximately 200-300 years ago or less and grown along the Atlantic coast (Sezen et al. 2016). From there, cultivation moved towards the drier regions and currently the US sorghum belt extends from southern Texas to South Dakota. Between 2015-2020, an average of 2.3 million hectares were planted annually to grain sorghum (USDA-NASS 2020). Because of its low input cost, drought and heat tolerance, and wide usage and adaptability, sorghum has the potential to replace corn grown for grain and silage in water limited environments.

As sorghum is a multi-purpose crop grown for grain, fodder, silage, syrup and/or other minor products, sorghum breeders have varied objectives depending upon the use of sorghum. Major breeding objectives in sorghum breeding programs involve increased productivity, disease and insect resistance, early maturity, resistance to lodging, less shattering and adaptation to mechanical harvesting. Sorghum hybrids are particularly popular since these are vigorous and more productive than inbreds. In addition to hybrid production by conventional means, it is also possible to transform sorghum using exogenous DNA. Genes associated with herbicide, disease and pest resistance are known and can be used for transgenic sorghum production. Further, ALS-inhibitor resistant non-genetically modified grain sorghum is expected to be released in the market in the coming years. The longevity and sustainability of the novel traits introduced in sorghum is highly dependent on the rate of outcrossing between sorghum and johnsongrass.

Grain sorghum in the United States

Sorghum was most likely introduced to the US via slave trade in 1810 (Quinby 1974). It was nearly a decade later when the United States Department of Agriculture (USDA) and the Texas Agriculture Experiment Station started the testing of sorghum cultivars for their performances in Chillicothe, Texas (Quinby 1974). As grain sorghum is a drought tolerant and low-input crop that grows reasonably well in marginal environments (Hadebe et al. 2017), it occupied more than two million hectares in the US in 2017 (USDA-NASS 2017) (Table 1). This has made sorghum an increasingly popular and profitable crop in large parts of Texas, which ranks second in the nation in grain sorghum production, with more than 610 thousand hectares harvested in 2017 and with a value of $486 million (USDA-NASS 2017). The area under grain sorghum production in neighboring states has recently increased in the Mississippi Delta, particularly in Arkansas in a rotational program (Figure 1).

Table 1. Grain sorghum hectares harvested in the eight largest producing states in 2012 and 2017, data sourced from the USDA-NASS census data (USDA-NASS 2012, 2017)

Year	State	Hectares	CV* (%)
2012	Kansas	851,428	12.3
2012	Texas	768,388	3.4
2012	Oklahoma	81,153	2.8
2012	Colorado	59,875	57.5
2012	South Dakota	55,567	9.3
2012	Arkansas	54,090	3.2
2012	Louisiana	50,625	15.9
2012	Alabama	2,851	28.5
2017	Kansas	983,618	6.8
2017	Texas	610,989	5.6
2017	Colorado	140,079	8.3
2017	Oklahoma	125,581	9.1
2017	South Dakota	61,725	16.2
2017	Louisiana	5,009	44.6
2017	Arkansas	2,826	3.7
2017	Alabama	1,059	(H)

CV, coefficient of variation

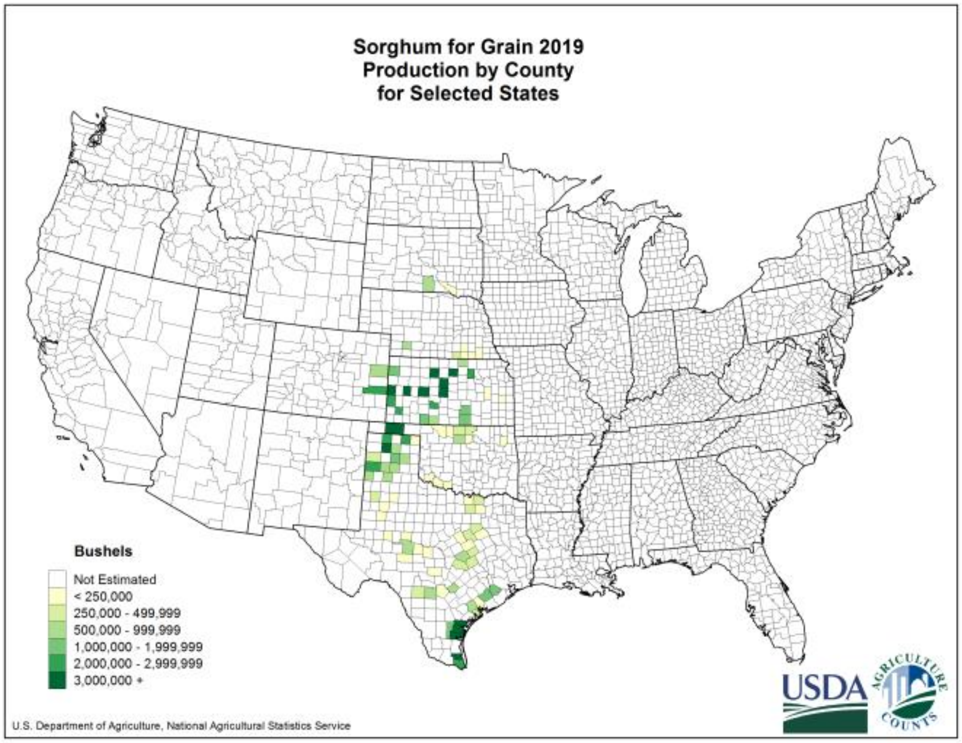

Figure 1. County-level production of grain sorghum in the US in 2019. (USDA-NASS 2019)
Reprinted from United States Department of Agriculture- National Agricultural Statistics Service.

Johnsongrass (*Sorghum halepense*)

Johnsongrass: introduction and severity in the US

Johnsongrass is a perennial, invasive, noxious weed found colonizing throughout the southern US (McWhorter 1989; Miller 2003). It is suspected that johnsongrass was intentionally introduced in the US as a forage crop or unintentionally through seed contamination, but it has since become a troublesome agronomic weed in the US (Holm et al. 1977; McWhorter 1971). The spread of johnsongrass in the US has been attributed mainly to contaminated planting seed, cavalry movement during civil war and planting for erosion control (McWhorter and Hartwig 1972).

Johnsongrass can reach up to 3.5 m in height with profuse tillering. Being a tall growing C_4 plant, johnsongrass has high biomass production potential and can be very competitive with other plant species (Ohadi et al. 2018). Research conducted by Czarnota et al. (2003) showed that root exudates of *Sorghum* spp. are allelopathic and suppressive on other species. In row crops, johnsongrass can cause as much as 70% yield loss (Bridges and Chandler 1987; Millhollon 1970) and even complete crop failure under severe infestations (Figure 2). Both seed and rhizome are the modes of propagation in johnsongrass. It is a profuse seed producer, with as high as 28,000 seeds per plant (Horowitz 1973) and can produce up to 40 to 90 m of rhizomes in a single season (McWhorter 1981). Eradication of johnsongrass from crop fields is extremely difficult due to the rapid proliferation of the rhizomes and overwintering potential (McWhorter 1961; Warwick and Black 1983).

Figure 2. A johnsongrass infested grain sorghum production field near Corpus Christi, Texas. Severe infestation of johnsongrass leading to the complete abandonment of the crop.

Available management options

Herbicides such as the acetolactate synthase (ALS)-inhibitors and glyphosate provide effective control of johnsongrass and have been heavily relied upon for the management of this species (Howard 2004; Rosales-Robles et al. 1999a, b). Currently, atrazine and *S*-metolachlor (with Concep seed safener for sorghum) are the preemergence options for johnsongrass control, whereas glyphosate (applied at the physiological maturity of sorghum) is the postemergence option (Matocha et al. 2008). In other crops, the ALS-inhibitors and glyphosate have been intensively used for johnsongrass control. As a result, resistance evolution against these herbicides has been a significant concern (Smeda et al. 1997). Meyer et al. (2015) reported at least 90% johnsongrass control in Arkansas and Louisiana cotton production by using Fluometuron or fluometuron plus pyrithiobac applied PRE followed by multiple effective mechanisms of action (MOA). In southern states, ALS-inhibitor-resistance (to nicosulfuron and imazethapyr) was first documented in 2000 in Texas (Green; archived in Heap 2020) and glyphosate resistance in 2008 in Arkansas (Riar et al. 2011).

Loss of herbicide options for johnsongrass control

Growers are gradually losing herbicide options due to rapid resistance evolution and it is likely that this trend will continue if sufficient measures are not implemented (Smeda et al. 1997). Moreover, herbicides are lost to resistance at a rate faster than they are replaced with new modes of action (MOAs) (Duke 2012). While herbicide resistance is a localized problem in johnsongrass, the invasiveness of this species and the lack of effective herbicide options for selective control in sorghum makes this species troublesome. The ALS-inhibitor-resistant sorghum technology (Inzen™, developed by DuPont®) provides a new tool for the management of grasses, but not labeled for johnsongrass control (see Zest® herbicide label). However, in reality, it can kill the johnsongrass plants if present in the Zest®-applied fields, and there is a possibility for unintentionally exposing johnsongrass to this herbicide under practical field conditions.

The lack of options for grass control in sorghum may accelerate adoption rate of this technology immediately. Expected heavy use of this technology may compromise the longevity of this technology in terms of resistance evolution. There is a critical need to explore additional tools to diversify management tactics and protect existing tools, while achieving sustainable weed management. It is vital that diversified strategies include more than just diversified herbicide options (Harker et al. 2012). Effective long-term management of johnsongrass might require integration of various management tactics aimed at different demographic stages.

Need for integrating non-chemical options

A key consideration to herbicide resistance management is managing selection pressure (Holt et al. 1993; Norsworthy et al. 2012), which is achieved through diversifying weed management tools, as diversification minimizes selection pressure placed on any single management tool. The importance of integrating non-chemical weed management tools in herbicide resistance management should not be overlooked for two key reasons: firstly, a strategy that is solely based on rotating herbicide MOAs does not address metabolism-based polygenic resistance development in weed populations (Shaner 2014). For instance, cytochrome P450 monooxygenases or glutathione S-transferases can endow enhanced rates of herbicide metabolism (Yuan et al. 2007; Yu et al. 2013). Secondly, a weed management strategy that is based on intensive herbicide use can be economically and environmentally detrimental (Pimental et al. 1992). It is, therefore, imperative to integrate non-chemical tools in herbicide-dominant weed management systems to protect and preserve the herbicide options that are still effective and achieve economical and sustainable weed management.

Focus on weed seedbank management

Weed seedbank management must be an important element of herbicide resistance management (Walsh et al. 2013). Simulation models have emphasized that the risk of herbicide resistance evolution is strongly and positively associated with soil seedbank size (Bagavathiannan et al. 2013; Neve et al. 2011). While soil seedbank management often involves practices for encouraging seed loss through predation and microbial decay (Davis 2006; Gallandt 2006), tremendous opportunities also exist to minimize seedbank size by preventing seedbank replenishment from late-season weed escapes through practices implemented at the time of harvest and after harvest (Bagavathiannan and Norsworthy 2012; Walsh and Newman 2007). Liebman and Davis (2009) demonstrated that minimizing seedbank replenishment by 40% can have a substantial impact on weed population dynamics. Tillage can be an effective non-chemical strategy in managing johnsongrass rhizomes through dehydration (McWhorter and Hartwig 1965).

Preventing seedbank replenishment can greatly impact weed population dynamics because this process represents the most important reason for weed persistence in production fields (Walsh et al. 2017b). However, efforts to minimize seedbank replenishment from late-season escapes do not improve current-season yields, and therefore are often viewed unnecessary. Traditional weed control recommendations have been based on the economic threshold (ET) concept, which advocates control only when weed densities exceed a yield loss threshold. However, the ET concept does not adequately address the likelihood of weed seed production and seedbank addition, which might increase future weed management costs and also elevate the risk of herbicide resistance evolution (Norris 1999; Bagavathiannan and Norsworthy 2012).

For invasive weeds such as johnsongrass, even a few seeds allowed to go back to the soil can be too many. Thus, minimizing viable seed production in weed escapes (both at and after harvest as applicable) must be regarded as a key aspect of seedbank management. For perennial weeds such as johnsongrass with substantial seed and rhizome production, depleting underground rhizome reserves should be combined with seedbank management tactics for effective long-term management of this species (Johnson et al. 2003; Jordan et al. 1997). While we recognize that the term 'seedbank management' does not necessarily imply rhizome management, in this study we investigate the management of both propagules using diverse tactics.

Harvest-time and post-harvest seedbank management

The crop harvesting operation typically facilitates the removal and dispersal of seeds from uncontrolled weeds (Shirtliffe and Entz 2005). At the same time, it presents an excellent opportunity to collect and destroy any unshed weed seeds, yet this strategy has been only utilized predominantly for ryegrass management in Australia (Walsh et al. 2017b). There exists enormous potential to utilize HWSC tactics in global agriculture under different situations (Walsh et al. 2013), which is being tested under preliminary trials across the US (Beam et al. 2019; Norsworthy et al. 2016, 2020; Shergill et al. 2020a, b). In the southern US, HWSC tactics can be used as a valuable non-chemical tool for integrated management of some of the most troublesome and economically damaging weeds such as johnsongrass, among others.

Several tactics could be used at the time of crop harvest to collect and destroy weed seeds using HWSC strategies. A chaff-cart (Figure 3a) attached to the rear of the harvester could achieve up to 85% efficiency in removing ryegrass seeds in Australian wheat (Walsh and Parker 2002). Baling equipment (Figure 3b) could be attached to the harvester to bale the chaff along with weed seeds that could be later fed to confined livestock (Walsh and Powles 2004). Windrowing chaff as it exits the combine, followed by high temperature burning (Figure 3c) can also kill weed seeds. Estimates show that crop residue burning could eliminate up to 98% of annual ryegrass seeds collected in the windrows (Fettell 1998; Walsh and Newman 2007). Additionally, a farmer-developed Harrington seed destructor (Figure 3d) has been successfully used to destroy weed seeds before they return to the soil. In field evaluations, the Harrington seed destructor consistently destroyed between 95 and 98% of ryegrass seed present in wheat, lupin (*Lupinus* spp.), and barley (*Hordeum vulgare* L.) chaff (Walsh et al. 2012).

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For invasive weeds such as johnsongrass, even a few seeds allowed to go back to the soil can be too many. Thus, minimizing viable seed production in weed escapes (both at and after harvest as applicable) must be regarded as a key aspect of seedbank management. For perennial weeds such as johnsongrass with substantial seed and rhizome production, depleting underground rhizome reserves should be combined with seedbank management tactics for effective long-term management of this species (Johnson et al. 2003; Jordan et al. 1997). While we recognize that the term ‘seedbank management’ does not necessarily imply rhizome management, in this study we investigate the management of both propagules using diverse tactics.

Figure 3. Examples of harvest-time weed seed management tactics practiced in Australia: a) chaff cart, b) bale-direct system, c) narrow-windrow burning, and d) Harrington Seed Destructor (photo credit: MJ Walsh, AHRI)

There is a critical research need to generate weed biology and ecology information in conjunction with knowledge on harvest machineries for facilitating the adoption of HWSC for johnsongrass in southern US agriculture. Seedbank management tactics practiced after harvest may augment practices adopted at the time of harvest in minimizing seedbank size and aid effective long-term management. The efficacy of weed seed destruction depends on the amount of weed seed retained. For johnsongrass, in addition to the seed production during crop growth, regrowth following crop harvest has the potential to produce viable seed, particularly in early-harvested crops in southern Texas.

Even in situations where mature seed production does not occur prior to killing frost, the underground rhizomes continue to proliferate if not intervened by management practices. Johnsongrass regrowth depletes underground reserves of rhizomes (Anderson et al. 1960; McWhorter 1981; Sturkie 1930), but the rhizome proliferation resumes closer to flowering (Keeley and Thullen 1979). It is critical that the rhizomes must be destroyed before they proliferate in order to suppress the aboveground johnsongrass density. Therefore, the overarching hypothesis of this research is that the harvest-time practices such as HWSC and post-harvest non-chemical practices such as shredding/mowing followed by delayed tillage can be integrated with herbicides applied during the cropping season, including desiccants prior to harvest, to negatively impact both seed and rhizome production in johnsongrass.

CHAPTER II

FEASIBILITY ASSESSMENT FOR IMPLEMENTING HARVEST-TIME MANAGEMENT TACTICS FOR JOHNSONGRASS (*SORGHUM HALEPENSE*) IN GRAIN SORGHUM (*SORGHUM BICOLOR*)

Introduction

Rapid evolution and spread of herbicide resistance in dominant weed species (Heap 2020) have severely threatened the sustainability of several agronomic production systems. Within the south-central region, Arkansas and Texas represent two important agricultural states where crop production and profitability have been severely threatened by the evolution and spread of herbicide-resistant weeds. While Palmer amaranth (*Amaranthus palmeri* S. Wats.) has been in the spotlight in recent years and much research has been devoted to managing this single species (Norsworthy et al. 2020; Werner et al. 2020), there are other equally troublesome weed issues in the region in specific cropping situations that have not received enough research attention. Specifically, johnsongrass (*Sorghum halepense* L.) is the most troublesome weed in grain sorghum production in the region, costing enormous amounts of resources (Ohadi et al. 2018).

Johnsongrass is an invasive, perennial, and aggressive weed species that proliferates both from seeds and overwintering rhizomes (Miller 2003; Ohadi et al. 2018). Johnsongrass closely resembles shattercane and cultivated sorghum genetically and physiologically. Young plants may also look like shattercane, sorghum, corn or sudangrass in field conditions (Klein and Smith 2020). Johnsongrass seeds are dark reddish brown to black when matured and are 3-5 millimeters long and oval-shaped (Curran and Lingenfelter 2007). The underground rhizomes are thick and cream colored with an occasional tint of purple. A single johnsongrass plant can produce about 28,000 seeds (Horowitz 1973), in addition to the production of up to 40 to 90 m of rhizomes in a single season (McWhorter 1981). The plant can reach up to 2 meters in height (sometimes more, as observed in Texas environments). The inflorescence is purple in color with an open panicle type. Johnsongrass is an indeterminate plant, with first flowering in Southeast Texas occurring as early as April and continuing through fall.

The HWSC tactic, developed and adopted widely in Australia, aims to collect and destroy weed seeds during crop harvest, thwarting the soil weed seedbank enrichment. With a little modification in the harvesting machinery, the chaff mixed with weed seeds exiting the combine are either removed from the field or destroyed *in situ* (Walsh et al. 2014). Success of HWSC depends largely on the extent of seed retained in weed plants at the time of crop harvest; maximum retention leads to effective collection and subsequent destruction (Walsh et al. 2018). Reproductive phenology, magnitude of seed shattering/retention, and height comparison between the seedheads of weed and crop are some of the critical factors that determine the feasibility of implementing HWSC for effective weed management in a particular crop-weed scenario (Walsh et al. 2018). Seedbank management tactics practiced after harvest may be augmented by the practices adopted at the time of harvest in minimizing seedbank size and thus, can aid effective long-term management. There is a critical research need to understand this aspect to support the adoption of HWSC tactics for managing johnsongrass in grain sorghum production. The aim of this study was to document the biology and ecology knowledge of johnsongrass in southern US grain sorghum production as it relates to the implementation of HWSC.

Materials and Methods

Sampling sites and design

Johnsongrass samples were collected from two regions in Texas, identified as the Rio Grande Valley (RGV) and Coastal Bend (CB), and three locations in Arkansas, identified as Keiser (KE), Fayetteville (FAY), and Stuttgart (STU) (Figure 4). Within each region, at least three grain sorghum fields that showed considerable johnsongrass infestation at harvest were identified during the survey and sampled using methods mentioned below during 2017, 2018, and 2019 in Texas and 2017 and 2018 in Arkansas.

The field survey routes were created using a Google® satellite map overlay within an itinerary planning program (ITN Converter v1.88-1.94) to identify cultivated fields within a region. A waypoint was placed and compiled into an itinerary and was optimized with the program software. At least 15-20 waypoints were identified within a region to allow for the best chance of finding grain sorghum fields with significant johnsongrass infestation (Figure 5A). In each field, samples were collected from three 1 m^2 quadrats.

Seed production potential and seed retention/shattering in johnsongrass

In each of the three quadrats per field, observations were made separately from above and below the combine cutting height. The combine height is usually 30 cm below the base of the sorghum panicle in a standing crop as typically used by farmers across the regions, which prevents the clogging of plant material in the combine (Figure 5B). First, percent johnsongrass seed maturity on the panicles was estimated based on the seed coat color turning from dark orange to dark black (i.e. 40% maturity indicates that 60% of the florets have immature seed). For additional precaution, a seed was considered mature if it was hard when pressed between fingers.

Seed shattering percentage for the entire quadrat was estimated by observing the top of the panicles, as johnsongrass seed matures first at the top. Then, seed shattering (%) was visually rated based on the proportion of empty rachis within the entire panicle. All the mature johnsongrass seed heads (with one or more mature seed) above and below the combine cutting heights were clipped and placed in two separate paper bags and labelled accordingly. It was likely that only a little or negligible mature seed were available or shattering occurred below the cutting height. The harvested seed was dried at 40° C for 72 hours and hand thrashed. Mature and intact seed were extracted using a South Dakota seed blower (Seed Blower Equipment Company, Des Plaines, IL) set at 4.8 cm opening for 5 minutes. The seed blower was calibrated using various sources of seed from the survey by recording the time required for effective seed extraction. Percent seed retention was calculated as follows:

Above the cutting height: if the number of mature seeds extracted above cutting height of a panicle is *x* and the seed shattering was estimated as *y* (%), then:

Total mature seed produced by the plant above cutting height

$$= x / [(100 - y) / 100]$$

Number of seeds shattered above cutting height

$$= total\ mature\ seed\ produced - mature\ seed\ extracted$$

Below the cutting height: if the number of mature seeds extracted below cutting height was *x* and the seed shattering was estimated as *y* (%), then

Number of seed shattered below cutting height

$$= x / [(100 - y) / 100]$$

Number of seeds shattered below cutting height

$$= total\ mature\ seed\ produced - mature\ seed\ extracted$$

The total mature seed produced within quadrat

$$= total\ seed\ collected + total\ seed\ shattered$$

Percentage of seed available for HWSC at harvest is then calculated as

$$= \left(\frac{total\ seed\ collected\ at\ harvest\ above\ cutting\ height}{total\ mature\ seed\ produced\ (above + below + shattered)}\right) * 100$$

The total seed not available for HWSC at harvest =

$(seed\ shattered\ above\ cutting\ height)\ +$

$(total\ mature\ seed\ produced\ below\ cutting\ height, which\ includes\ shattered\ seed)$

Percentage of seed not available for HWSC at harvest

$$= \left(\frac{(total\ seed\ not\ available\ for\ HWSC)}{total\ mature\ seed\ produced\ (above + below + shattered)}\right) * 100$$

Johnsongrass weekly seed shattering during crop maturity and harvest

The goal was to determine the influence of harvest date on the potential for seed capture. The experiment was conducted in two locations: College Station, TX and Fayetteville, AR. Seed collection trays were placed underneath johnsongrass plants to capture shattered seed. A total of four square-shaped trays of 25 cm*25 cm size [Hummert International (Item No. 11005100)] with a layer of landscaping cloth (Model: LLF350BA) were placed under each johnsongrass plant, for a total of eight randomly selected plants. The number of seeds captured in the trays was extracted and counted at weekly intervals starting a week before johnsongrass seed maturity until three weeks after the first opportunity for sorghum harvest before termination of the study.

Additionally, sorghum maturity stage at each week of observation was documented. At termination of the experiment, all seed heads from each plant were carefully harvested, threshed and the number of retained seeds was counted. The data were used to calculate % seed retention over the period of observation.

Effect of sieve size on weed seed collection in combine harvester

The goal was to determine johnsongrass seed fraction exiting out of the large, upper screen; small, lower screen; and fraction with sorghum seed in the combine. This experiment was conducted in one location: Keiser, AR in 2017 with four replications (plot size: 12 m x 9.14 m). Samples were collected from three fractions: the material exiting out of the upper sieve (fraction 1), lower sieve (fraction 2), and grain auger (fraction 3). However, apparently no johnsongrass seed was observed in the grain auger, hence tis fraction was excluded from the analysis. For this study, grain sorghum was planted in a naturally occurring johnsongrass patch to simulate a real-world scenario and the areas with high johnsongrass density within the plots were selected for combine operation. A swath of 12 m (combine header width) was used for sampling. Johnsongrass seed in each of the two fractions was extracted, counted, and weighed (g); and percent seed viability was determined. The volume (m^3) and weight (g) of the chaff material for the first two fractions were measured to estimate chaff to seed weight ratio.

Data analysis

All data were analyzed using JMP PRO 14 (SAS Institute Inc., Cary, NC). Seed shattering (%), seed production potential, and seed retention (%) of johnsongrass during grain sorghum harvest are illustrated using boxplots. Weekly johnsongrass seed shattering during sorghum maturity is described using a 3-parameter sigmoidal curve based on cumulative seed shattering (%) over a 11-week period using SigmaPlot software (version 14.0, Systat Software, Inc., San Jose, CA). Analysis of variance (ANOVA) was carried out to examine the effect of sieve size on weed seed collection in combine. Prior to ANOVA, normality of residuals was checked using the Shapiro-Wilk test in JMP. Means were separated based on the Tukey's Honestly Significant Difference test at α=0.05.

Results and discussion

Seed production potential and seed retention/shattering in johnsongrass

Johnsongrass seed shattering (%) observed immediately before grain sorghum harvest varied largely across the states as well as across the regions within a state (Figure 6A). In Fayetteville (FAY), Arkansas, seed shattering varied 0-15% and 0-5% during the 2017 and 2018 seasons, respectively, whereas in Keiser (KE), johnsongrass shed 0-30% of the seed in 2017, but shattering was negligible in 2018. Shattering was also negligible in Stuttgart (STU) in 2017. In the Rio Grande Valley (RGV), Texas, johnsongrass shed 10-50% of the total seed in 2017, whereas, 0-20% in 2018 and 0-35% in 2019. However, in the Coastal Bend (CB), seed shattering varied from 10 to 50% in 2017, 5 to 15% in 2018, and 0 to 50% in 2019.

Although persistence of johnsongrass and its ability to compete with the crop are largely attributed to the vigorous rhizome system, the invasiveness and spread of such weeds in infesting new areas are often associated with the prolific seed production and seed shattering at maturity (Dlugosch and Parker 2008), leading to rapid seedbank replenishment. However, in the current study, johnsongrass mature panicles did not exhibit high shattering prior to crop harvest in the locations surveyed. Lyon (in Walsh et al. 2018) documented <50% seed shattering in Italian ryegrass prior to wheat harvest in Washington. Walsh and Powles (2014) reported a 30% seed shattering in jointed goatgrass, 15% in annual ryegrass, 33% in cheatgrass, and 16% in wild oat in Australian cropping system; whereas Schwartz-Lazaro et al. (2017a) reported 59-68% seed shattering in barnyardgrass in Arkansas. In Canadian agriculture, Tidemann et al. (2016) suggested that wild oat must shatter <20% seed for successful implementation of HWSC. Therefore, the information generated in this study is highly crucial in deciding whether HWSC could be a potential tool for weed seed destruction in this region.

The estimated mature seed production in FAY was 341 to 1268 seeds/m^2 in 2017 and 352 to 743 seeds/m^2 in 2018. Mature seed production varied from 326 to 808 seeds/m^2 and 341 to 952 seeds/m^2 in KE, and 388 to 468 seeds/m^2 and 0 seeds/m^2 in STU, respectively in 2017 and 2018 (Figure 6B). Mature seed production was significantly greater in Texas, which was 857 to 10,118 seeds/m^2, 315 to 5962 seeds/m^2, and 159 to 5929 seeds/m^2 in CB, and 603 to 3993 seeds/m^2, 1384 to 3151 seeds/m^2, and 932 to 3921 seeds/m^2 in RGV in 2017, 2018, and 2019, respectively. Some of the major advantages of johnsongrass as a weed are that it is both a self- and cross-pollinated species, producing enormous number of seeds (Keeley and Thullen 1979). It can produce 28,000 to 80,000 seeds/plant in a single season across geographical regions (McWhorter 1961). Liu et al. (2019) reported that johnsongrass produces 356 to 1852 seeds/plant in Argentina. As johnsongrass is characterized with faster seed germination, rapid seedling emergence, and greater foliage growth, the quantity of seed produced per unit area plays a critical role in subsequent johnsongrass infestation in crop fields (Klein and Smith 2020). As high seed production in weeds followed by shattering leads to a rapid increase of the soil seedbank (Walsh et al. 2018), it is pertinent to assess the seed production potential of johnsongrass before effective harvest-time interventions can be advocated.

Out of the total mature seed produced, johnsongrass plants retained 45 to 70% and 69 to 80% in FAY, respectively in 2017 and 2018; whereas in KE, 75 to 100% and 69 to 80% seeds respectively in 2017 and 2018, and in STU, 88 to 100% seeds in 2017 were retained during grain sorghum harvest (Figure 6C). In CB, 50 to 90%, 85 to 100%, and 75 to 100% seeds were retained in 2017, 2018, and 2019, respectively; whereas, 60 to 95%, 80 to 100%, and 65 to 100% seeds were retained in RGV in 2017, 2018, and 2019, respectively. Though it has been believed that johnsongrass seed shattering is high (Dlugosch and Parker 2008), our findings don’t support that notion. As reviewed by Walsh et al. (2018), 96% seed was retained by johnsongrass, 69-84% by wild oat, 77%

by bromegrass, and 85% by rigid ryegrass during crop maturity, which indicate a high HWSC potential in managing these weeds in those regions. The relative time of johnsongrass seed maturity and the extent of seed retention as recorded in this case, therefore, provide critical information in order to facilitate the implementation of HWSC strategies during grain sorghum harvest (Walsh et al. 2018).

Johnsongrass weekly seed shattering toward grain sorghum maturity and harvest

Johnsongrass infesting sorghum fields began maturing in mid-July in the south-central region, as observed in this study. Both location and year impacted the magnitude of weekly seed shattering in johnsongrass (Figure 7). In AR, johnsongrass started shedding seeds the third week of July and all seeds were shed before mid-September, whereas in TX shattering started the first week of August and completed almost at the same time as that of AR. Johnsongrass shows a profuse tillering habit and the reproductive tillers produce large numbers of seeds that may readily shatter on maturity (Johnson et al. 1997). Thus, determining both the seed shattering window for johnsongrass along with the sorghum harvest maturity was necessary. It is evident from this study that a major proportion (>80%) of johnsongrass seeds can be captured during sorghum harvest, within the harvest window of mid-July to mid-August in Southeast Texas. This indicates great potential for using HWSC in this region. Schwartz et al. (2016) reported that Palmer amaranth and tall waterhemp retained greater than 95% and 99%, respectively, of their seed at soybean harvest in Arkansas, which is ideal for HWSC to be effective.

Effect of sieve size setting on weed seed collection in the combine harvester

Sieve size of the combine showed significant effects on the chaff to johnsongrass seed ratio and johnsongrass seed count/chaff weight (kg) exiting from the combine (Figure 8). When chaff was collected exiting the bottom sieve, it had a greater proportion of johnsongrass seeds in the total chaff as compared to that collected exiting the top sieve (Figure 8A). This was reflected in the seed count/chaff weight: 2463 johnsongrass seeds/kg of chaff were found in chaff materials exiting the bottom sieve as compared to the significantly less seeds (850 seeds/kg of chaff) from the top sieve (Figure 8B). Combine setting can be manipulated to alter the airflow; combine add-ons can also significantly influence the amount of weed seeds that can be collected and destroyed during crop harvest (Clarke 2020). More studies are vital on this aspect. Based on the quantity of chaff harvested by the combine in an acre, the total weight of chaff per unit area was calculated to be roughly 0.5 kg/m^2 (data not presented separately). So, from 1 m^2 area, an average of 1232 seeds (50% of 2463) and 425 (50% of 850) seeds were removed respectively by the bottom and top sieve for destruction via HWSC. This indicates high potential for removing johnsongrass seed in the combine during sorghum harvest.

The efficacy of HWSC mainly depends on two factors: the proportion of weed seeds retained at the time of crop harvest and the effectiveness of the combine harvester in collecting and separating weed seeds for subsequent destruction (Walsh et al. 2017a).

Walsh and Powles (2007) and Walsh et al. (2012) reported that 95% of seed was removed via chaff carts and 93% was killed using a Harrington Seed Destructor in wild radish in Australia, whereas Schwartz-Lazaro et al. (2017b) reported 100% destruction of giant ragweed seed using an integrated Harrington Seed Destructor in Arkansas. Lyon et al. (2016) in Washington reported that 58% of Italian ryegrass seed was retained during wheat harvest, which was removed as chaff followed by narrow windrow burning leading to nearly 100% weed seed control. Beam et al. (2019) reported that the potential number of seeds that can be removed by a HWSC operation in Italian ryegrass ranged from 7,559 to 11,095 seed m^{-2} in Virginia. As no such studies have been conducted in johnsongrass in sorghum production, the current study provides unique information that will help justify HWSC implementation in the southern states.

Conclusions

Johnsongrass produced more seeds in Texas as compared to Arkansas. In both states, a greater proportion of the total seeds produced was available to be captured at the time of crop harvest. Weekly assessment of seed shattering showed that individual johnsongrass plants retained a high fraction of the total seeds within the crop harvest window, that can then be captured and destroyed by HWSC. In the combine, chaff exiting the bottom sieve captured significantly more johnsongrass seeds than that by the top sieve, indicating the advantage of collecting and destroying chaff exiting the bottom sieve. Results of this experiment confirms the potential of implementing HWSC for johnsongrass control in the southern United States, though the implementation of HWSC is highly time-sensitive. An economic analysis would have guided a more informed decision; however, there are several cost-effective HWSC options such as chaff-lining that can be implemented. Moreover, the cost of seed impact mills is also rapidly declining, making it an economically attractive option especially for large operations. Thus, there is a high potential for utilizing HWSC for managing johnsongrass in the study region.

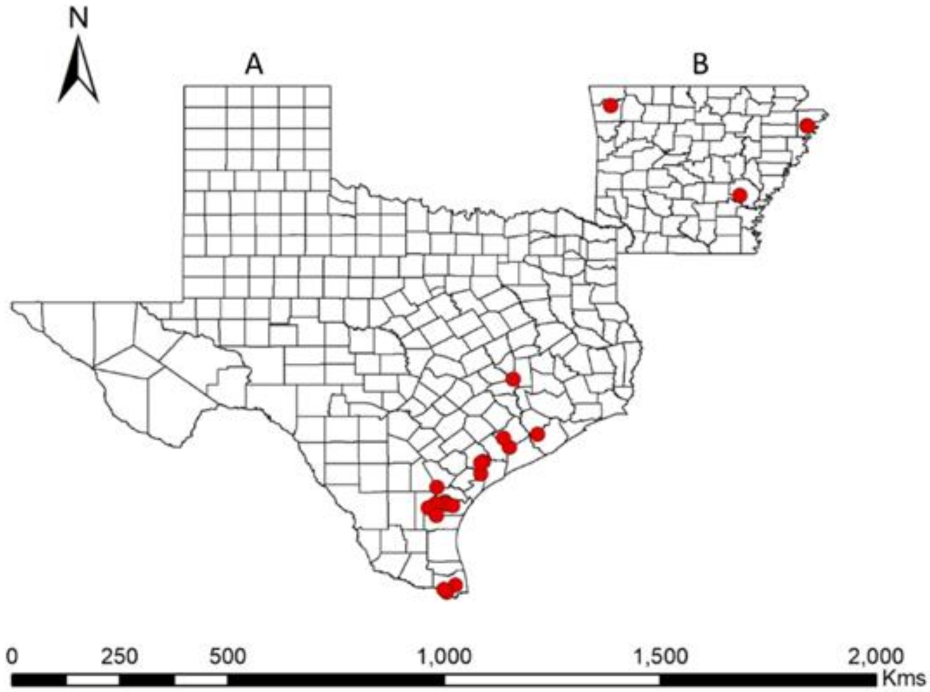

Figure 4. Geocoordinates of johnsongrass survey locations across the grain sorghum fields in (A) Texas during 2017, 2018, and 2019 and (B) Arkansas during 2017 and 2018.

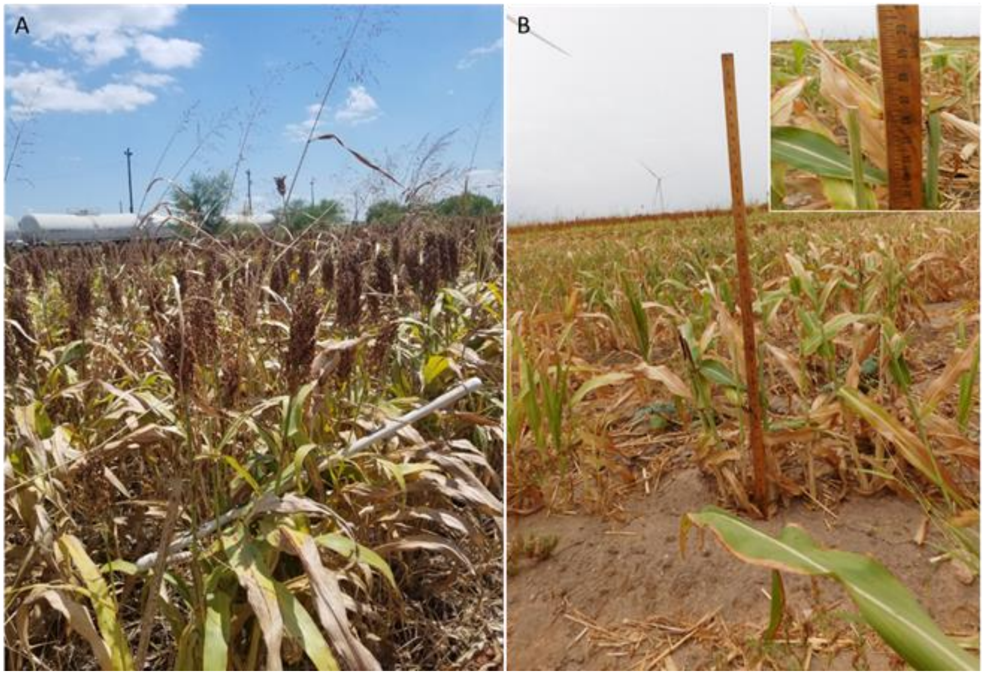

Figure 5. A) Johnsongrass in a mature grain sorghum field and B) grain sorghum harvest height. The harvest height for sorghum is usually 30 cm below the panicle.

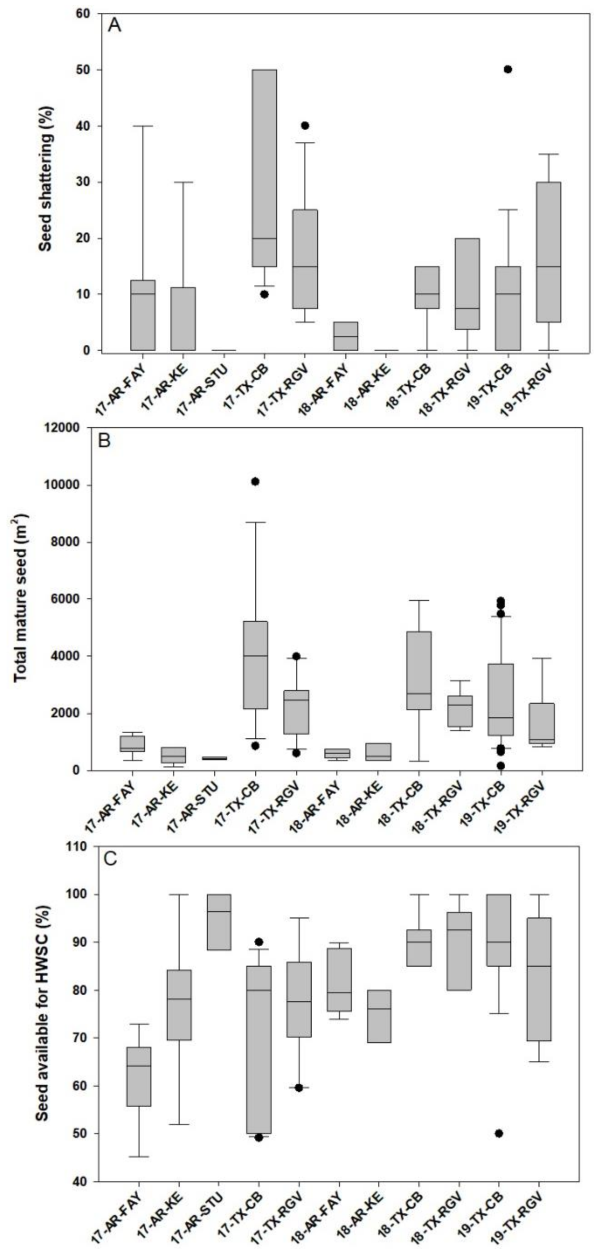

Figure 6. Seed shattering (%) (A), total mature seed/m^2 (B), and seed retention (%) (available for HWSC) (C) of johnsongrass plants at grain sorghum harvest stage across the survey sites in Texas during 2017, 2018, and 2019, and Arkansas during 2017 and 2018.
In the codes on x-axis, for example in 17-AR-FAY, 17 is year of sample collection (2017), AR is state name (Arkansas) and FAY is the region name. In Texas (TX), Rio Grande Valley (RGV) and Coastal Bend (CB) regions were surveyed, whereas in Arkansas (AR), Keiser (KE), Fayetteville (FAY), and Stuttgart (STU) were surveyed.

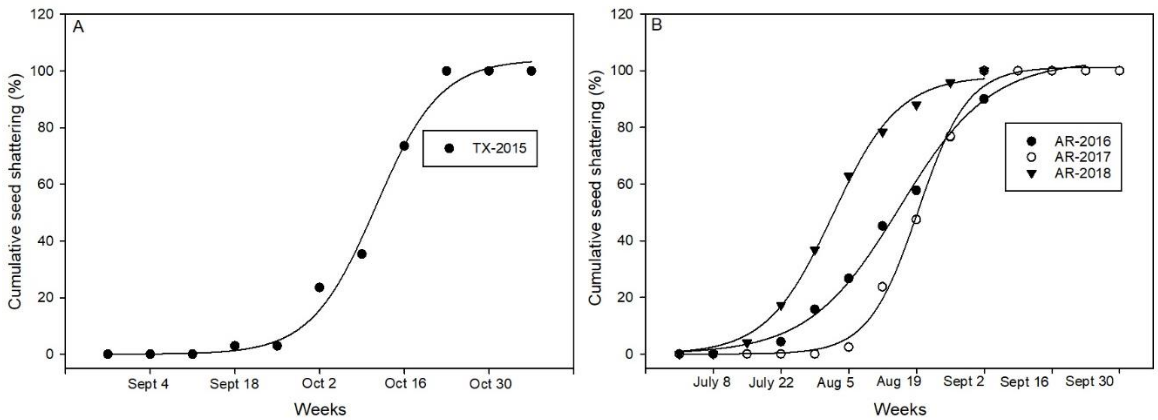

Figure 7. Weekly johnsongrass seed shattering during sorghum maturity in different years in College Station, TX (A) and Keiser, AR (B). Typical sorghum harvest window in the region is between mid-July and end of August.

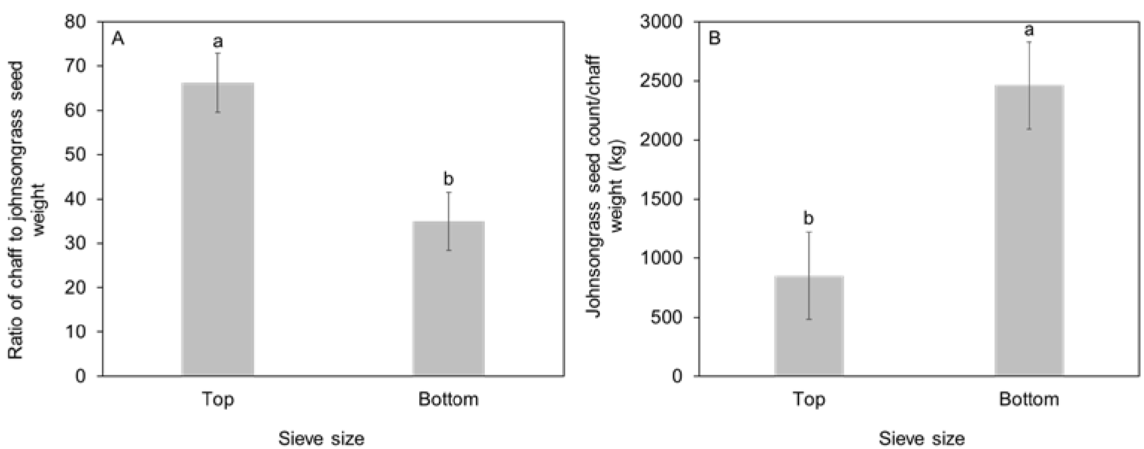

Figure 8. Effect of sieve size setting of combine on A) ratio of chaff to johnsongrass seed weight (kg/kg) and B) johnsongrass seed count/ kg of chaff collected during sorghum harvest in Arkansas. Bars topped with different letters within each panel indicate significant difference between the treatments (α=0.05).

CHAPTER III

EVALUATION OF HARVEST-TIME AND POST-HARVEST TACTICS ON JOHNSONGRASS [*SORGHUM HALEPENSE* (L.) PERS.] CONTROL IN GRAIN SORGHUM [*SORGHUM BICOLOR*] IN THE SOUTHERN US

Introduction

Johnsongrass is a perennial, invasive, and noxious weed found colonizing throughout the southern United States (US) and is the most troublesome weed in grain sorghum production in the region, costing enormous resources (McWhorter 1989; Miller 2003; Ohadi et al. 2018). Native to areas east of the Mediterranean Sea, the range of this species now includes all continents except Antarctica and is known as one of the world's worst weeds (Holm et al. 1977).

Johnsongrass is the major weed in sorghum fields and is an extremely difficult-to-control weed in sorghum due to the lack of herbicide options (Stahlman and Wicks, 2000). There is no postemergence herbicide that can control johnsongrass in grain sorghum, meaning that johnsongrass remains inadequately controlled in millions of sorghum hectares throughout the nation (Werle et al. 2016). Thus, johnsongrass infestation causes enormous economic damages to sorghum growers especially in marginal environments where sorghum is valued as a low-input, high-return crop.

Weed (soil) seedbank management is an important element of herbicide resistance management (Liebman and Davis 2009; Walsh et al. 2013), which often involves practices for encouraging weed seed loss through predation and microbial decay (Davis 2006; Gallandt 2006). Tremendous opportunities exist to minimize seedbank size by preventing seedbank replenishment from late-season weed escapes through practices implemented at the time of harvest and after harvest (Bagavathiannan and Norsworthy 2012; Walsh and Powles 2007), such as Harvest Weed Seed Control (HWSC) for destroying before they enter soil seedbank (Walsh et al. 2013), desiccants for suppressing seed development (Lofton 2019), post-harvest tillage for dehydrating rhizomes to death (McWhorter and Hartwig 1965), killing of regrowth after crop harvest (Johnson et al. 1997) etcetera. While we recognize that the term 'seedbank management' does not necessarily imply rhizome management, for perennial weeds such as johnsongrass which overwinters/survives by rhizome production, depleting underground rhizome reserves must be combined with seedbank management tactics for effective management of this species.

The current study aims at assessing the efficiency of johnsongrass seed removal, one of the HWSC tactics, in combination with current herbicide programs and other non-chemical options for johnsongrass control in grain sorghum production in Texas and Arkansas, where johnsongrass is abundant and a major threat to sorghum production.

Materials and Methods

Experimental location, layout, and treatment details

A large-scale field experiment was conducted from 2016 to 2018 in College Station, Texas and in Keiser, Arkansas. In 2019, no grain sorghum was planted but final data were collected. Fields were selected with a history of sufficient johnsongrass infestation so that the control efficiency of the treatments could be realized. In Texas, Inzen™ sorghum cultivar was planted in April and harvested in August, whereas in Arkansas it was planted in May and harvested in September. In Arkansas, grain yield was assessed in each plot by harvesting a single row along the length of the plot (110 m) 7-10 day after application of the desiccant (glyphosate 1262 g a.e. ha^{-1}). The experimental design was a randomized complete block design (RCBD) with four replications, with a grain sorghum seeding rate of 190,000 seeds ha^{-1} in continuous sorghum production. Based on existing cultivation practices, the plot size was as such: College Station, TX- 8 m (8 rows on 1.016 m centers) x 110 m; Keiser, AR- 7.5 m x (8 rows on 0.97 m centers) x 200 m. The total crop area including buffers was 2.11 hectares at the College Station site and 3.75 hectares at the Keiser site.

To simulate a worst-case scenario, additional ALS-inhibitor resistant johnsongrass plants were introduced within each plot. Seeds of the putative resistant population (sourced from Nebraska, John Lindquist and Rodrigo Werle) were planted in flats filled with potting soil mixture (LC1 Potting Mix, Sun Gro Horticulture Inc., Agawam, MA, USA). The flats were maintained in the Norman Borlaug Center for Southern Crop Improvement Greenhouse Research Facility at Texas A&M University at 26/22ºC day/night temperature and a 14-hour photoperiod. The johnsongrass seedlings at 15 cm height were sprayed with nicosulfuron at a rate of 35.1 g a.i. ha^{-1} to confirm resistance to the ALS-inhibitor. Upon confirmation, 15 and 10 surviving plants of this resistant population were transplanted to each plot in both locations, and a 70% survival rate was observed after transplanting.

For both the locations, combinations of standard herbicide programs and HWSC (in the form of chaff removal) were used for the study. Treatments included were:

A. Treatment 1 (T1)- *S*-metolachlor PRE (Dual II Magnum® 1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}) on 30-cm tall sorghum plants (standard practice in conventional sorghum);

B. Treatment 2 (T2)- *S*-metolachlor PRE (Dual II Magnum® 1071 g a.i. ha^{-1}) followed by atrazine (1122 g a.i. ha^{-1}) + nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30-cm tall sorghum plants (standard Inzen™ program);

C. Treatment 3 (T3)- *S*-metolachlor PRE (Dual II Magnum® 1071 g a.i. ha^{-1}) followed by atrazine (1122 g a.i. ha^{-1}) + nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30-cm tall sorghum plants (standard Inzen™ program) + glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest;

D. Treatment 4 (T4)- *S*-metolachlor PRE (Dual II Magnum® 1071 g a.i. ha^{-1}) followed by atrazine (1122 g a.i. ha^{-1}) + nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30-cm tall sorghum plants (standard Inzen™ program) + glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest + chaff removal at harvest (removal of johnsongrass mature seed panicles);

E. Treatment 5 (T5)- *S*-metolachlor PRE (Dual II Magnum® 1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}) + nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30-cm tall sorghum plants (standard Inzen™ program) + glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest + seed removal at harvest (removal of johnsongrass mature seed panicles) + shredding and disking the field after harvest and treat the johnsongrass regrowth with clethodim (Select® 140 g a.i. ha^{-1}) at 30 cm height; and

F. Treatment 6 (T6)- *S*-metolachlor PRE (Dual II Magnum® 1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}) + nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30-cm tall sorghum plants (standard Inzen™ program) + glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest + shredding and disking the field after harvest and treat the johnsongrass regrowth with clethodim (Select® 140 g a.i. ha^{-1}) at 30 cm height.

All the treatments were applied at the rate of 140 L ha^{-1} (15 gallons $acre^{-1}$) following recommend application timings. Fertilizer was applied as needed.

Data collection

Johnsongrass plant density

Johnsongrass plant density per unit area was estimated by placing seven random quadrats (1 m^2 each) at the spots with representative johnsongrass density within each plot during spring and fall each year. The plants without rhizomes were considered seedlings (germinated from seeds) and plants with rhizomes as rhizomatous plants (Figure 9).

Reproductive Traits

Total mature johnsongrass seeds produced in seven random quadrats (1 m^2) were estimated immediately prior to sorghum harvest in each year. In order to do this, 100 randomly selected johnsongrass mature panicles were collected before the onset of shattering both in TX and AR during 2016 and 2018. Panicles were measured to the nearest half cm from the lowest branched raceme to the tip of panicle. Samples were dried for 72 hours at 40° C prior to counting. Each branch was separated and counted for potential mature seed that could be produced as well as mature seed that was already produced at the time of collection.

The panicle length and number of seeds were recorded for each panicle and a regression equation was developed to calculate the seed count cm^{-1} panicle length separately for both locations. For estimation of seed production in the plots, total number of panicles were counted in each quadrat and all panicles were measured for their length with at least one mature seed. The quadrats were randomly placed within the plot so that it captures average plant densities for infested areas. Plot percent infested densities as well as percent seed shattered were also observed. These observations allowed for the estimation of total seed production or fecundity ha^{-1} within a treatment plot with the following equation:

$$\frac{Fecundity}{ha} = [\{(average\ panicle\ length\ (cm) \\ *(seed\ count\ per\ cm\ of\ panicle\ length) \\ *average\ panicles\ per\ m^2\} * \ 10000] * percent\ plot\ maturity$$

Prior to desiccant application, the johnsongrass seed production was estimated per the above equation after measuring the length of mature panicles as well as by recording a plot maturity estimation.

Soil seedbank dynamics

Soil samples were collected with a posthole digger to a depth of 15 cm with 13-cm core diameter during the early growing season in 2016-2019. In each plot, 16 random soil cores across the entire plot were collected, four cores were pooled into a single sample, thus yielding four composite soil samples/plot in total. Soil samples were soaked in water for a 24-hour period in a 5-gallon bucket to loosen the hard soil before washing. After adding water to the soil, a paint mixer attached to a cordless power drill was used to break up the clods and this process was repeated after 24 hours before straining solution through sieves. Soil samples were poured over three sieve sizes in the order of 3.35mm (No. 6) followed by 2.36 mm (No. 8) and then 850 µm (No. 20) (VWR international Inc., Radnor, PA). Johnsongrass and other seeds were collected between the second and third sieves 0.85-2.36 mm and were dried for 24 hours. They were then spread over a white surface to identify and count johnsongrass seeds per sample.

Data analysis

All data were analysed using JMP PRO 14 (SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) was carried out to examine the effects of the various combinations of herbicide programs and HWSC tactics on the aboveground density and reproductive traits of johnsongrass. Prior to conducting the ANOVA, all the data were checked for normality using the Shapiro-Wilk test in JMP PRO 14 (SAS Institute Inc., Cary, NC). Means were separated based on the Tukey's Honestly Significant Difference test with α=0.05. Figures with statistical analysis were created using SigmaPlot (version 14.0, Systat Software Inc., San Jose, CA).

Results and Discussion

Johnsongrass plant density

Initial johnsongrass density was high across the plots, which varied from 113,200 to 161,100 plants ha^{-1} in College Station and 174,000 to 211,000 plants ha^{-1} in Keiser (Figure 10). During the first spring, both seedling and rhizomatous johnsongrass plants were observed, whereas, during summer and fall, the majority of the plants were rhizomatous. Combination of herbicide programs and HWSC tactics showed significant effects on johnsongrass aboveground density at both the locations (Figure 10). After one year of treatment imposition, johnsongrass density significantly declined in all the treatments, except T1 (treatement based on only *S*-metolachlor), as observed during spring in College Station (Figure 10A), whereas, in Keiser, both T1 and T2 failed to reduce johnsongrass density (Figure 10B). *S*-metolachlor applied as PRE was reported to control johnsongrass effectively in corn in Italy (Scarabel et al. 2014) and in Texas (Ghosheh and Chandler 1998), whereas, *S*-metolachlor followed by atrazine was effective for controlling johnsongrass in grain sorghum in Arkansas (Barber et al. (2015).

Most of the grassy weeds are controlled by PRE herbicides such as *S*-metolachlor in grain sorghum (Peerzada et al. 2017; Werle et al. 2016). However, inadequate or no control of johnsongrass in T1 plots in this experiment indicates that this standard practice is no longer a robust option for johnsongrass control in southern US. This is likely due to the dominance of rhizomatous johnsongrass in the plots, which are not sensitive to PRE herbicides.

Until the introduction of Inzen™ technology, no POST options were available for johnsongrass control in grain sorghum due to genetic similarity between grain sorghum and johnsongrass (Barber et al. 2015; Johnson and Norsworthy 2014). In our study, T2 which involved the Inzen™ technology, was not sufficient for controlling johnsongrass. Results of this experiment indicate that there is a need to integrate additional management, including chemical and non-chemical options within the Inzen™ sorghum production system. Similar concerns were reported by Werle et al. (2016) for Nebraska, Kansas, and Arkansas johnsongrass populations.

In the second year (spring 2017), plots under T1 maintaned the highest johnsongrass densities in College Station, whereas in Keiser T1 and T2 showed similarly high densities. In spring 2018, johnsongrass density started to increase in plots under T1 and T2 and they were significantly greater in number than the other treatements. In T3 to T6 johnsongrass plant densities varied, but were significantly lower than that in T1 and T2. In Keiser, T1 showed the greatest johnsongrass density followed by T2 and they were significantly greater than the rest of the treatments during fall 2017; however, 2018 data could not be collected due to continuous wet field conditions. Overall, johnsongrass density progressivley decreased in Keiser across the treatments; cold winters and relatively low persistence of the species in that environment could be attributed to this overall decline, as suggested by Rosales-Robles et al. (2003). In 2019, i.e. after three years of continuouly imposing treatments, there was an increase in johnsongrass density in College Station in T1 and T2 plots. Lack of an effective herbicide for selective johnsongrass control in grain sorghum could be the main reason for increased jonsongrass density in T1, especially considering the fact that *S*-metolachlor and atrazine do not provide PRE activity on rhizomatous johnsongrass, and no POST activity on any kind of emerged johnsongrass (Scarabel et al. 2014, Ghosheh and Chandler 1998). It clearly indicates that harvest-time and post-harvest weed control measures are imperative for adequate control of johnsongrass in grain sorghum.

In this study, T3 to T6 were equally effective in reducing johnsongrass plant densities significantly and were comparabale across the years of observation (Figure 10A). Nicosulfuron-based herbicide program controlled johnsongrass reasonably well when combined with additional harvest-time and post-harvest interventions. The success of T3 treatment in this study, which involved both PRE and POST herbicides combined with a fall-applied glyphosate as a desiccant is supported by previous studies (Ghosheh and Chandler 1998, Lofton 2019). Johnson et al. (1997) and Lofton (2019) suggested a second application of the desiccants if regrowth occurs; however, this was not required in the current study. Plots under T4 that simulated the effects of HWSC by chaff removal at sorghum harvest was numerically the best treatment among T3 to T6. After two years of continuous application of the treatments, T4 showed 1 and 6 johnsongrass plants ha^{-1} in spring 2018 and 2019, respectively as compared to 4 and 20 plants ha^{-1} in T5 and 1 and 10 johnsongrass plants ha^{-1} in T6. These results indicate that the additional treatment of disking and shredding plots followed by treating johnsongrass regrowth with clethodim (T5), did not provide any additional johnsongrass control over T4.

There are several reports that claim that leaving fields undisturbed during winter after deep-disking helps control johnsongrass rhizomes in different cropping systems (McWhorter and Hartwig 1965), as the rhizomes assist with overwintering and regrowth if buried deeper and left undisturbed (McWhorter 1981; Warwick and Black 1983). The rhizomes deplete upon regrowth (Anderson et al. 1960), but proliferate closer to flowering (Keeley and Thullen 1979). Therefore, rhizomatous johnsongrass must be controlled before or after the regrowth starts. In this study, glyphosate as desiccant provided the extended control, nullifying the added benefit of T5. Moreover, shredding and disking the field after harvest and treating the johnsongrass regrowth with clethodim (T5) may be valuable in the absence of a desiccant application and HWSC, which is reaffirmed as the T5 and T6 were almost equally effective. The benefit of HWSC in controlling weed infestation over a period of time, as shown in other production systems (Shergill et al. 2020), stands true for johnsongrass management in grain sorghum.

Seedling vs rhizomatous plants

Knowing the source of new johnsongrass plants, whether from seed or rhizome, is a key factor while managing them in the field in the long-run. Prior to applying treatments in the College Station site, the proportion of rhizomatous plants varied from 37 % to 58 % of the total plants observed during spring, with no significant difference among treatments (Figure 11). In the second year, the proportion of rhizomatous plants increased across the treatments; however, T1 showed the highest proportion followed by T2, whereas the other treatments had significantly lower proportion of rhizomatous plants. Remarkably, in spring 2018, the proportion of rhizomatous plants drastically increased across the treatments.

The increase in rhizomatous plants could also be due to the competitive displacement of seedling johnsongrass by rhizomatous plants (intra-specific competition). In the terminal year, the plots under T1 (and T6) maintained the highest proportion of rhizomatous plants, whereas T4 showed significantly lower proportion than other treatments. However, most of the plants were rhizomatous across the treatments, as they were in spring 2018. This indicates that the additional harvest-time and post-harvest treatments were successful in managing johnsongrass. Although the number of surviving plants was low, the species continues to persist by adapting to rhizomatous propagation, which makes their eradication from a region challenging (McWhorter and Jordan 1976; McWhorter 1961).

Reproductive traits

Johnsongrass panicle density, measured before sorghum harvest in August in College Station varied from 18,200 ha^{-1} in T6 to 68,000 ha^{-1} in T1 (Table 2). In the second year, i.e., summer 2017, the panicle number significantly increased in T1 and T2 plots, but other treatments maintained the numbers comparable to that of the last year.

Inadequate control of johnsongrass in T1 and appearance of ALS-inhibitor resistant johnsongrass in T2 plots might be contributing to the increase in these plots. However, presence of ALS-inhibitor-resistance did not impact other treatment plots wherein additional harvest and post-harvest time interventions were carried out. After two years of continuous treatment implementation, plots under T1 and T2 showed increased number of johnsongrass plants; however, the harvest-time and post-harvest interventions in T3 to T6 plots displayed positive impacts in controlling johnsongrass. In particular, herbicide programs in combination with HWSC and post-harvest operations (T5) showed the lowest panicle density by number, though it was at par with T3, T4, and T6 in Keiser. In College Station, T4 and T6 produced no panicles, indicating the complementary effects of HWSC vs disking/shredding the plots followed by treating the regrowth.

Prolific tiller production in johnsongrass aids the aggressive invasiveness of this species, which complicates control measures (Werle et al. 2016). Although it directly depends on the aboveground pant density, the reduction in panicle density in response to harvest-time and post-harvest treatments promises a great potential in reducing/eradicating johnsongrass at vegetative as well as reproductive stages. Rosales-Robles et al. (1999a) reported 36 johnsongrass panicles m^{-2} in a nontreated check which was reduced to 1 panicle m^{-2} under clethodim management system in Texas cotton production, whereas Meyer et al. (2015) reported a 92% reduction in panicle numbers under clethodim application in a midsouth cotton production system.

The regression equations based on data obtained from 100 panicles in both locations showed reasonably high regression coefficients: R^2=0.7 and 0.6, respectively in College Station and Keiser (Figure 12). Number of seeds produced by the johnsongrass plants in College Station was calculated by the respective equation, which then directly used panicle number and length to calculate potential seed production. After one year, the number of seeds increased in T1, T2, and T4 plots, whereas, it decreased in T3, T5 and T6 plots (Table 2). The highest reduction in seed production potential was achieved in T5 (from 7 million seed ha^{-1} to 3.8 million ha^{-1}) after two years of applying the HWSC treatments within the herbicide programs, whereas the number increased from 33 million ha^{-1} to 77 million ha^{-1} in T1 and 12 million ha^{-1} to 31.6 million ha^{-1} in T2.

Reports suggest that a single johnsongrass plant can produce about 28,000 seeds in the absence of any control measures (Horowitz 1973) and high seed production provides the greatest potential for the establishment and spread of johnsongrass (Keeley and Thullen 1979). In this experiment, *S*-metolachlor followed by atrazine application (T1) was not able to control potential seed production in johnsongrass, rather it increased the number. It indicates that a huge seedbank replenishment will occur if effective control measures are not implemented for johnsongrass control, which in turn will produce enormous plants in next season (Peerzada et al. 2017). Herbicide programs combined with harvest-time and post-harvest management strategies can provide effective johnsongrass control, especially with the introduction of HWSC (Green 2019). HWSC provides significant control in several cropping systems across countries by removing weed seeds at crop harvest (Walsh et al. 2018). The effectiveness of HWSC (specifically, narrow windrow burning) in efficient control of johnsongrass seedbank enrichment has been reported by Green (2019) in midsouth cotton production, which corroborates our results.

Soil seedbank size

At end of the experiment, the integration of HWSC and other harvest-time and post-harvest interventions provided significantly greater johnsongrass seedbank reduction over the traditional herbicide programs alone at both study sites (Figure 13). In College Station, there was a significant increase in johnsongrass seedbank size in T1, with limited reduction in T2, whereas all other treatments showed continuous decline in soil seedbank size over the years. In Keiser, all the treatments showed reduction in the soil seedbank size; however, T1 and T2 had greater seedbank size across the observation timings. In College Station, the reduction in seedbank in T1 and T2 was mainly due to the presence of higher proportion of rhizomatous plants, which might have reduced seedbank size by intra-specific competition. In T3 to T6, seedbank size declined due to the treatment effects (desiccant application + seed removal). In Keiser, a similar trend was observed. Reduced seedbank size also resulted in low aboveground density of johnsongrass in T3-T6 towards the end of the experiment.

Johnsongrass seed can survive 2-5 years in the soil seedbank depending on the burial depth (Concenco et al. 2012; Looker 1981). Simulation models have emphasized that the risk of herbicide resistance evolution is strongly and positively associated with soil seedbank size (Bagavathiannan et al. 2013; Neve et al. 2011). It is important to exhaust a soil seedbank with stringent agronomic strategies for effective and long-term control of johnsongrass (Peerzada et al. 2017). The standard herbicide application in Inzen™ sorghum technology was inadequate for sustainable long-term management of johnsongrass in the current study. However, the use of a desiccant and post-harvest interventions can significantly reduce soil seedbank size (Green 2019). Johnson and Norsworthy (2014) reported a 98% and 99% reduction of viable seed production in johnsongrass after application of clethodim and glyphosate. As far as we know, this is the first study of its kind on the use of HWSC for targeting johnsongrass seedbank. The benefit of a desiccant in terminating johnsongrass before viable seed production has been reported previously in sorghum (Barber et al. 2020; Lofton 2019).

Sorghum grain yield

Although overall yield levels were on the lower side in this experiment, Texas grain sorghum yield assessed at the end of experiment was the highest in plots under T5 (1840 kg ha^{-1}) followed by T6 (1458 kg ha^{-1}) and T4 (1185 kg ha^{-1}); the lowest yield was observed in T1 (534 kg ha^{-1}) followed by T2 (951 kg ha^{-1}) and T3 (1101 kg ha^{-1}) (Figure 14). The johnsongrass density directly impacted sorghum grain yield, leading to the highest grain yield in plots with HWSC and shredding operations. Rosales-Robles et al. (1999a) and Bridges and Chandler (1987) reported a 93% and 70% yield reduction, respectively by johnsongrass infestation in Texas cotton production. In this experiment, a 71% yield reduction was observed with the standard program (T1) as compared to the best treatment with additional harvest-time and post-harvest operations (T5). Therefore, it is important that diversified weed management programs must include non-chemical options and should not be merely based on multiple herbicides (Harker et al. 2012).

Conclusion

Johnsongrass presents a significant threat to grain sorghum production in the southern United States, despite the use of currently available PRE and POST herbicides, as indicated by this study. Rapid spread of ALS-inhibitor-resistance in johnsongrass can limit the adoption of Inzen™ sorghum technology. In addition to the best herbicide program available currently, use of harvest-time and post-harvest intervention is deemed necessary to achieve best control of johnsongrass in southern US grain sorghum production. Although the combination of herbicide and other non-chemical tools satisfactorily controlled johnsongrass in sorghum production, proportion of rhizomatous plants increased in the treated plots, indicating the need for improved rhizome control strategies in the long-run. Overall, the combined implementation of Inzen™ technology, desiccant application, HWSC, and disking/shredding of plots followed by treating the regrowth show great potential for successful johnsongrass management in grain sorghum production in the southern US.

Table 2. Johnsongrass panicle density and seed production hectare^{-1} as affected by different treatments in College Station, TX

Treatment[‡]	Number of panicles ha^{-1} ('000)			Number of seeds ha^{-1} ('000)		
	2016	2017	2018	2016	2017	2018
T1	68.0^{A*}	148.7^{A}	154.1^{A}	33512^{A}	70066^{A}	77128^{A}
T2	30.0^{B}	54.2^{B}	68.3^{B}	12073^{B}	26825^{B}	31661^{B}
T3	28.8^{B}	39.2^{BC}	18.5^{C}	10526^{B}	18827^{B}	10734^{B}
T4	30.6^{B}	27.1^{C}	25.6^{C}	12490^{B}	9347^{B}	10641^{B}
T5	20.9^{C}	10.9^{C}	6.6^{C}	7016^{B}	4997^{B}	3881^{B}
T6	18.2^{C}	19.6^{C}	11.1^{C}	6964^{B}	7921^{B}	5579^{B}

[‡] Treatments included were: T1- *S*-metolachlor PRE (1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}+1% crop oil concentrate) on 30 cm sorghum plants (standard practice in conventional sorghum); T2- T1+ nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30 cm sorghum plants (standard Inzen™ program); T3- T2+ glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest; T4- T3+chaff removal at harvest (removal of johnsongrass mature seed panicles); T5- T4+shredding/disking the field after harvest and treat the johnsongrass regrowth with clethodim (140 g a.i. ha^{-1}) at 30 cm height; and T6- T5 except no chaff removal at harvest.

*Within each column, means followed by different letters indicate significant differences between treatments based on Tukey's Honestly Significant Difference test at (α=0.05).

Figure 9. Rhizomatous (A) and seedling (B) johnsongrass plants observed in the sorghum fields during the spring.

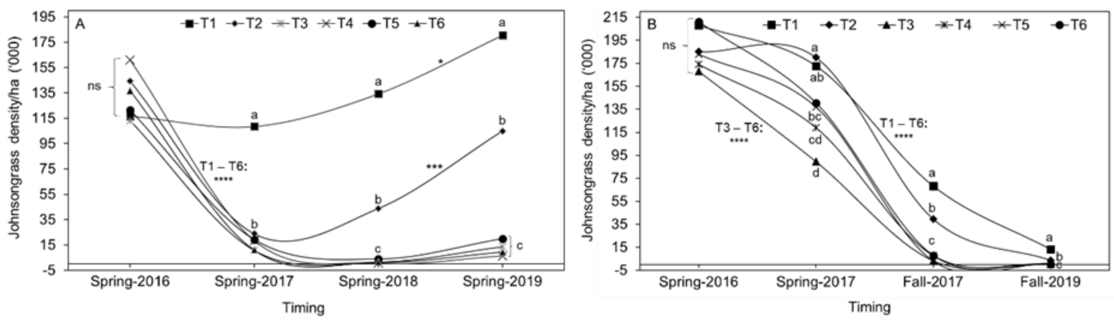

Figure 10. Impact of integrated weed management treatments on johnsongrass population density ha^{-1} (includes seedling and rhizomatous plants) in the experiments conducted at A) College Station, Texas and B) Keiser, AR.
The spring observation timing corresponds to about a month after grain sorghum planting, whereas the fall observation corresponds to the timing after all treatments were implemented in the plots. Treatments included were: T1- S-metolachlor PRE (1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}+1% crop oil concentrate) on 30 cm sorghum plants (standard practice in conventional sorghum); T2- T1+ nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30 cm sorghum plants (standard Inzen™ program); T3- T2+ glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest; T4- T3+chaff removal at harvest (removal of johnsongrass mature seed panicles); T5- T4+shredding/disking the field after harvest and treat the johnsongrass regrowth with clethodim (140 g a.i. ha^{-1}) at 30 cm height; and T6- T5 except no chaff removal at harvest. Within a specific time of observation, different letters indicate significant differences between the treatments based on Tukey's Honestly Significant Difference test (α=0.05). Asterisk (*) indicates significant difference between two consecutive timings for the same treatment (*, $p<0.05$; ***, $p<0.001$; ****, $p<0.0001$; ns, non-significant).

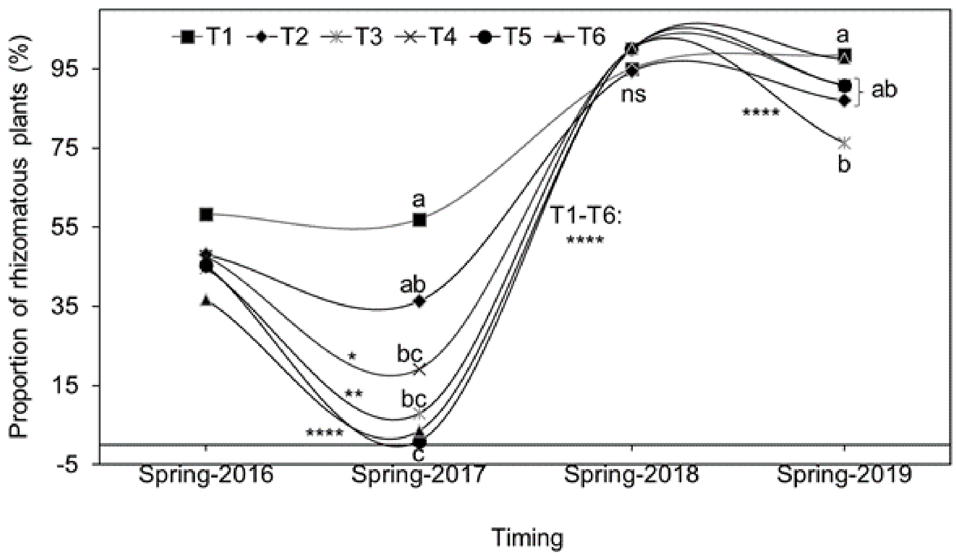

Figure 11. Impact of integrated weed management treatments on the proportion of rhizomatous plants among the total johnsongrass plants (rhizomatous + seedling) at the experiment conducted in College Station, TX.

Treatments included were: T1- S-metolachlor PRE (1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}+1% crop oil concentrate) on 30 cm sorghum plants (standard practice in conventional sorghum); T2- T1+ nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30 cm sorghum plants (standard Inzen™ program); T3- T2+ glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest; T4- T3+chaff removal at harvest (removal of johnsongrass mature seed panicles); T5- T4+shredding/disking the field after harvest and treat the johnsongrass regrowth with clethodim (140 g a.i. ha^{-1}) at 30 cm height; and T6- T5 except no chaff removal at harvest. Within a specific time of observation, different letters indicate significant differences between the treatments based on Tukey's Honestly Significant Difference test (α=0.05). Asterisk (*) indicates significant difference between two consecutive timings for the same treatment (*, $p<0.05$; ***, $p<0.001$; ****, $p<0.0001$; ns, non-significant).

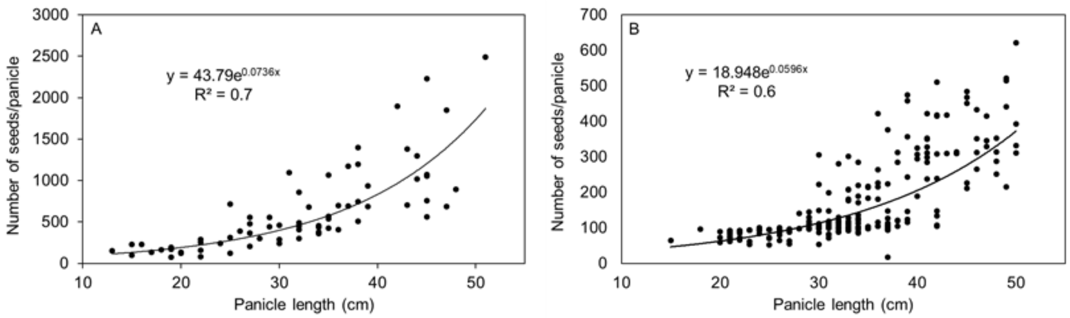

Figure 12. Relationship between johnsongrass panicle length and seed production recorded over 2017 and 2018 growing seasons in College Station, TX (A), and 2016 to 2018 growing seasons in Keiser, AR (B)

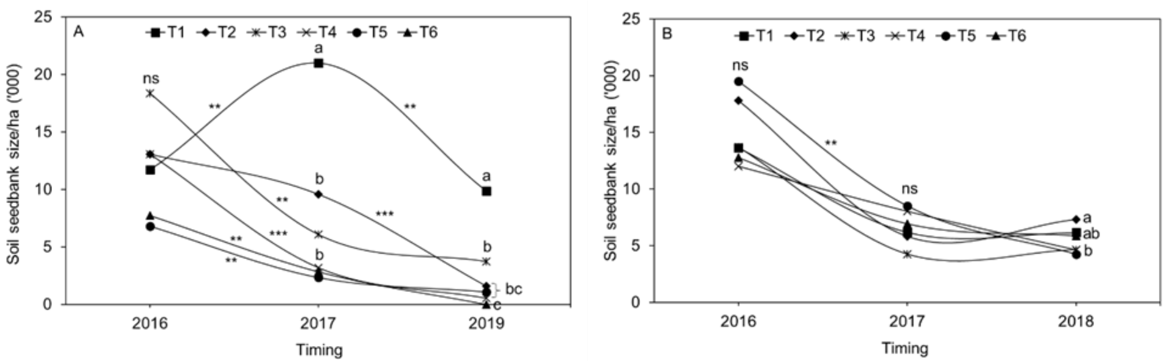

Figure 13. Impact of integrated weed management treatments on johnsongrass soil seedbank size in experiments conducted at A) College Station, TX and B) Keiser, AR. Soil seedbank samples were collected prior to sorghum planting each spring. Treatments included were: T1- *S*-metolachlor PRE (1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}+1% crop oil concentrate) on 30 cm sorghum plants (standard practice in conventional sorghum); T2- T1+ nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30 cm sorghum plants (standard Inzen™ program); T3- T2+ glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest; T4- T3+chaff removal at harvest (removal of johnsongrass mature seed panicles); T5- T4+shredding/disking the field after harvest and treat the johnsongrass regrowth with clethodim (140 g a.i. ha^{-1}) at 30 cm height; and T6- T5 except no chaff removal at harvest. Within a specific time of observation, different letters indicate significant differences between the treatments based on Tukey's Honestly Significant Difference test (α=0.05). Asterisk (*) indicates significant difference between two consecutive timings for the same treatment (*, $p<0.05$; ***, $p<0.001$; ****, $p<0.0001$; ns, non-significant).

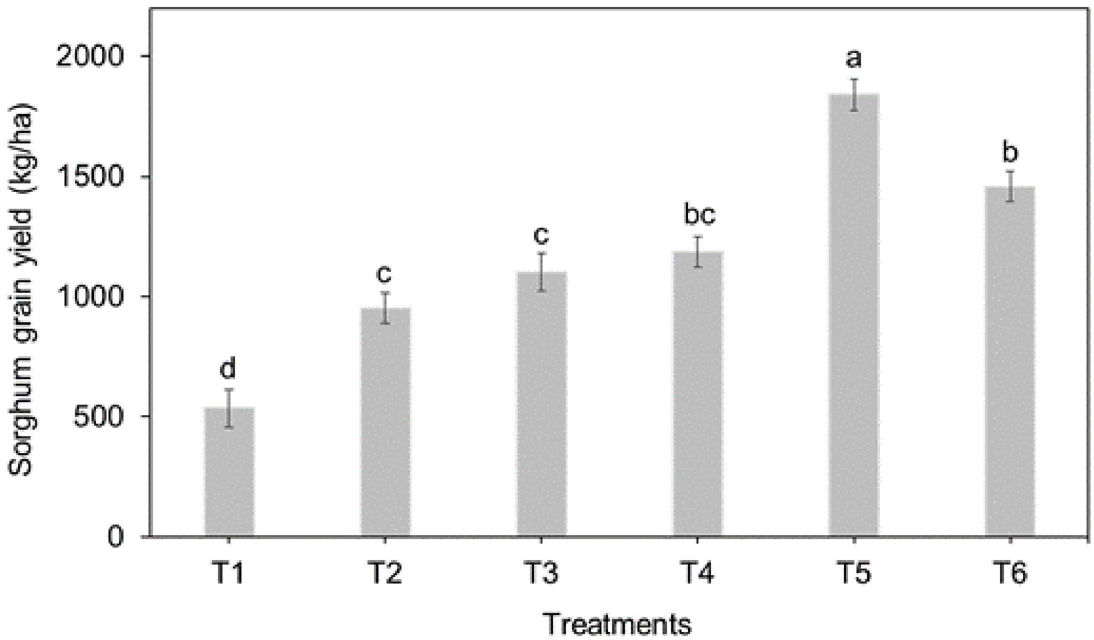

Figure 14. Impact of integrated weed management treatments on sorghum grain yield in College Station, TX in 2018.

Treatments included were: T1- *S*-metolachlor PRE (1071 g a.i. ha^{-1}) followed by Atrazine (1122 g a.i. ha^{-1}+1% crop oil concentrate) on 30 cm sorghum plants (standard practice in conventional sorghum); T2- T1+ nicosulfuron (Zest® 35.1 g a.i. ha^{-1}) POST on 30 cm sorghum plants (standard Inzen™ program); T3- T2+ glyphosate (1262 g a.e. ha^{-1}) as desiccant prior to harvest; T4- T3+chaff removal at harvest (removal of johnsongrass mature seed panicles); T5- T4+shredding/disking the field after harvest and treat the johnsongrass regrowth with clethodim (140 g a.i. ha^{-1}) at 30 cm height; and T6- T5 except no chaff removal at harvest. Bars topped with different letters indicate significant difference between the treatments based on the Tukey's Honestly Significant Difference test (α=0.05).

CHAPTER IV

CONCLUSIONS

The study examined the feasibility of a harvest weed seed control (HWSC) tactic, in combination with the available herbicide and mechanical options for johnsongrass (*Sorghum halepense*) management in southern US grain sorghum (*Sorghum bicolor*) production. The HWSC tactic, which aims to collect and destroy weed seeds at the time of crop harvest, has been shown elsewhere to be effective in managing troublesome weeds. In this study, the assessment of relative maturity time, seed production potential, seed shattering window, and seed retention in the johnsongrass plants with respect to grain sorghum maturity and harvest time indicates that a large percentage of johnsongrass seeds are retained for effective capture by the harvest machinery. Evaluation of harvest-time (HWSC) and post-harvest tactics on johnsongrass control indicates that, in addition to the best herbicide programs available currently the integration of harvest-time and post-harvest intervention is imperative for sustainable control of johnsongrass in southern US grain sorghum production, especially given the rapid spread of herbicide resistance in this species. Further, the increase in the proportion of rhizomatous plants across the treatments indicates the need for better rhizome control strategies in the long-run. Overall, the implementation of Inzen™ technology, in combination with a desiccant application, HWSC, and shredding/disking plots followed by treating the regrowth is very effective in long-term management of this species. Further research is imperative on the types of HWSC that are practical in this cropping system as well as the long-term economic benefits of implementing HWSC.

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