Weed Technology

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Research Article

Cite this article: Schwartz-Lazaro LM, Korres NE, Bararpour T, Bagavathiannan M, Green J, Norsworthy JK (2022) Population dynamics of naturally occurring weed flora in response to crop rotation and HPPD-inhibiting herbicide-based treatments. Weed Technol. **36**: 426–435. doi: 10.1017/wet.2022.40

Received: 12 October 2021
Revised: 26 April 2022
Accepted: 12 May 2022
First published online: 26 May 2022

Associate Editor:
Prashant Jha, Iowa State University

Nomenclature:
barnyardgrass; *Echinochloa crus-galli* (L.) P. Beauv.; broadleaf signalgrass; *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster; johnsongrass; *Sorghum halepense* (L.) Pers.; large crabgrass; *Digitaria sanguinalis* (L.) Scop.; morningglory; *Ipomoea* spp.; Palmer amaranth; *Amaranthus palmeri* S. Watson; prickly sida; *Sida spinosa* L.; corn; *Zea mays* L.; cotton; *Gossypium hirsutum* L.; soybean; *Glycine max* (L.) Merr.

Keywords:
Monoculture; crop rotation; integrated weed management; soil seedbank; weed ecology; weed management; herbicide resistance

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Population dynamics of naturally occurring weed flora in response to crop rotation and HPPD-inhibiting herbicide-based treatments

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Abstract

A 3-yr field study was conducted in Keiser, AR, to investigate the response of the naturally occurring weed flora, dominated by Palmer amaranth, under various combinations of 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicide-based programs and crop rotation sequences. In the first year, corn plots were established with three corn HPPD-based herbicide programs designed to represent a range of efficacies and selection pressures for resistance. In the following two years, corn as monoculture or with soybean and/or cotton crops was included in the rotation sequence for selected herbicide programs. Weed emergence, weed biomass, and soil seedbank were assessed through the entire experimental period. The results show that crop rotation, especially a rotation sequence with corn followed by (fb) soybean fb cotton, and the lowest-risk herbicide program involving seven sites of action over the course of the entire crop rotation was effective in reducing the emergence of naturally occurring weeds, including Palmer amaranth, prickly sida, morningglory species, and grass weeds (broadleaf signalgrass, large crabgrass, barnyardgrass, and johnsongrass) by 88.3%, 57.5%, 28.7%, and 76.3%, respectively. Treatments without crop rotation (corn as monoculture for 3 consecutive years) and poor herbicide programs, with one site of action, increased weed emergence, notably of Palmer amaranth and prickly sida, by 73.5% and 74.1%, respectively. The soil seedbank showed a similar trend to weed emergence. This study highlights the fact that reducing the weed seedbank cannot rely on one management practice but requires a multitactic approach with various control methods. HPPD-inhibiting herbicide programs seem to be effective on Palmer amaranth when coupled with crop rotation and should be used with other best management practices.

Introduction

The acquisition of detailed knowledge of weed response to various management approaches will enhance our understanding of the multifunctional interactions that influence weed distribution and will improve our efforts for effective management (Korres et al. 2019). The cosmopolitan nature of Palmer amaranth, barnyardgrass, broadleaf signalgrass, johnsongrass, large crabgrass, morningglory, and prickly sida, along with yield reductions caused by their competition, are well documented (EPPO 2018; Korres et al. 2017; Van Wychen 2019, 2020; Webster and Nichols 2012).

Palmer amaranth is one of the most problematic broadleaf weeds in North America, especially in the midsouthern United States, owing to its rapid growth rate, prolific seed production, adaptability, and propensity to evolve resistance to several herbicide sites of action (SOAs) (Heap 2021; Korres and Norsworthy 2017; Schwartz-Lazaro et al. 2018; Van Wychen 2016). Currently Palmer amaranth has developed resistance to eight different SOAs, including acetolactate synthase inhibitors (Weed Science Society of America SOA Group 2), microtubule inhibitors (Group 3), synthetic auxins (Group 4), photosystem II inhibitors (Group 5), 5-enolpyruvylshikimate-3-phosphate synthase inhibitors (Group 9), protoporphyrinogen oxidase inhibitors (Group 14), long-chain fatty-acid elongase inhibitors (Group 15), and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (Group 27) (Heap 2021; Jhala et al. 2014). Therefore there is a need to evaluate herbicide options to manage Palmer amaranth and other problematic *Amaranthus* species (Tranel et al. 2011).

Non-new herbicide SOAs have been commercialized in recent years (Duke 2012). HPPD-inhibiting herbicides are one of the most recently developed commercialized SOAs developed in the 1980s (Lee et al. 1997; Van Almsick 2009). HPPD catalyzes the oxidative decarboxylation of 4-hydroxyphenylpyruvate to form homogentisate (Dreesen et al. 2018). HPPD is a key enzyme for the catabolism of tyrosine, hence the formation of fumarate and acetoacetate (Dreesen et al. 2018). It also holds an important role for the biosynthesis of plastoquinone, an essential cofactor for phytoene desaturase, a key enzyme in the biosynthesis of carotenoids (Norris et al. 1995) and an essential component of the photosynthetic electron transport chain in photosystem II. Prevention of carotenoid synthesis has direct effects on chloroplast development and photosynthesis (Pallett et al. 1998). These herbicides are also known as bleachers because they prevent pigment biosynthesis and impair chloroplast development, leaving the tissue white on susceptible plants (Dreesen et al. 2018; Grossmann and Ehrhardt 2007). HPPD inhibitors like mesotrione and tembotrione are the most commonly used herbicides for weed control in corn owing to their broad-spectrum weed control; mixing compatibility with other herbicides, such as atrazine; preemergence and postemergence activity; and crop safety (Bollman et al. 2008; Fleming et al. 1988; Gitsopoulos et al. 2010; Mitchell et al. 2001; Nurse et al. 2010; Swanton et al. 2007). Globally, only two species, Palmer amaranth and waterhemp (*Amaranthus tuberculatus* [Moq.] Sauer), have known resistance to this SOA, and both are found in the United States (McMullan and Green 2011).

The overreliance on a single herbicide SOA, reduced herbicide rates, and lack of crop rotation can lead to added selection for herbicide resistance evolution (Norsworthy et al. 2012). Effective control of Palmer amaranth in corn, for example, requires the application of preemergence followed by postemergence herbicides with distinct SOAs, herbicide rotation, and crop rotation (Chahal et al. 2017; Chahal et al. 2018a).

Crop rotation is a weed management approach that can facilitate the control of problematic weeds by exploiting the morphophysiological differences and production practices of the crop grown and by allowing rotation of the herbicides used in the cropping sequence (Harper 1956), resulting in reduced selection pressure for herbicide resistance through stress modifications and mortality factors, which directly affect weed population dynamics (Weisberger et al. 2019). Problem weeds in one crop are often effectively controlled in other crops (Johnson and Coble 1986). Soil and crop management, such as crop rotation, tillage systems, application of herbicides, and other agricultural practices, affect weed seedbanks and weed emergence (Barberi et al. 1998; Buhler et al. 2001; Marshall et al. 2003; Sjursen 2001). In addition, two or more years of crop rotation where seed production of the target weed is prevented greatly reduced weed populations (Schwartz-Lazaro and Copes 2019). Nevertheless, crop rotations have systematically allowed the removal of easily controlled weeds while allowing other species to become well established (Johnson and Coble 1986), hence the importance of population dynamics in understanding the evolution of herbicide resistance, and the ability to accurately predict how management strategies would impact resistance is paramount.

Knowledge of weed biology and ecology related to weed biomass production, weed seedbank, and weed population dynamics, such as the information provided in this article, can be used to develop and potentially predict how management strategies may affect the population (Korres et al. 2019). Therefore the objective of this study was to understand the population dynamics of the naturally occurring weed flora, dominated by Palmer amaranth, under various combinations of HPPD-based herbicide treatments and crop rotation sequences.

Materials and Methods

Experimental Site

A 3-yr trial was conducted at the Northeast Research and Extension Center in Keiser, AR (35.66927°N, 90.08105°W), from 2015 to 2017. The experiment had a randomized complete block design with three replications, with some of the treatments being nested, whereas repeated measures were conducted for some of the variables mentioned in the following paragraphs. Experiments were established on a Sharkey clay (very-fine, smectite, thermic Chromic Epiaquerts) with a pH of 6.7 and 1.7% organic matter. Plot size was 7.7 × 183 m in all years on 96.5-cm-wide rows. The field, prior to the experiment, was under soybean production for 2 yr.

Crop Management

In 2015, corn was planted into all plots with varying herbicide programs, with the subsequent years including soybean and cotton rotation for selected herbicide programs (Table 1). Each treatment consisted of varying herbicide programs (Table 2) and crop rotation sequences: two treatments with continuous corn monoculture; two treatments with corn and soybean rotation, the latter shifting between year 2 and year 3; one corn and cotton occurring in the second year; and one with corn, soybean, and cotton, in that sequence, for each of the years in the 3-yr rotation sequence. Each crop was irrigated and fertilized as needed to optimize yield potential. Corn, soybean, and cotton crop planting dates, seeding rates, and harvest dates were all within recommended time frames for Arkansas (Table 3). The herbicide programs were designed to represent a range of efficacies and selection pressures for resistance, with the weakest being continuous corn with reduced rates of HPPD-inhibiting herbicides (Program 6).

Data Collection

In fall 2015, 30 soil cores, 10.8 cm wide and 15.2 cm deep, were collected in a W pattern across each plot to determine a baseline of the soil seedbank. Soil cores were also taken in fall 2016, 2017, and 2018. Soil samples were stored at −20 C for at least 6 wk before each sample was thawed, deaggregated, stirred, and distributed over commercial potting mix in a 28 × 55 cm plastic tray. The trays containing the soil samples were placed on a greenhouse bench and irrigated daily to field capacity. Seedlings were identified and counted over 4 wk, after which soils were then allowed to dry and the irrigation and germination cycle repeated. After the second germination cycle, soils were stored at 5 C or frozen prior to a third germination cycle to aid in breaking the dormancy cycle (Korres 2005).

Subsequently, each spring, one permanent covered and one permanent uncovered 1-m^2 subplot were placed 1 m apart into each plot at approximately 30, 91, and 152 m between crop rows 2 and 3 and 6 and 7 for a total of six subplots per plot (two at each distance down the row). At each application, the covered subplots were protected with a 2-m^2 tarp to act as a control for that specific herbicide program. Once the application was made, the tarp was removed. Weeds in each subplot were counted by species every 2 wk and removed for weed density determination from planting until harvest. Prior to harvest, total weed biomass from additional predetermined 1-m^2 areas was collected.

Table 1. Weed control treatments from 2015 to 2017.[a,b]

Treatment ID	Weed control treatment (crop rotation × herbicide program)	Herbicide program 2015	2016	2017
1	Corn–corn–soybean rotation, where the first year of corn has heavy reliance on HPPD herbicides	Corn #2	Corn #3	Soybean
2	Effective herbicide program in a corn–soybean–cotton rotation	Corn #3	Soybean	Cotton
3	Effective herbicide program in a corn–cotton–corn rotation	Corn #3	Cotton	Corn #3
4	Effective herbicide program in a corn–soybean–corn rotation	Corn #3	Soybean	Corn #3
5	Highly effective HPPD herbicide program in continuous corn	Corn #3	Corn #3	Corn #3
6	Poor HPPD herbicide program in continuous corn	Corn #1	Corn #1	Corn #1

[a]An explanation of the herbicide programs for each crop can be found in Table 2.
[b]Abbreviation: HPPD, 4-hydroxyphenylpyruvate dioxygenase.

Table 2. Herbicide treatment programs for corn, soybean, and cotton from 2015 to 2017.[a]

Herbicide program	Herbicide	Trade name	Timing[b]	Rate	Manufacturer	Adjuvant
				g ai (ae) ha^{-1}		
Corn #1	Mesotrione fb tembotrione	Callisto® fb Laudis®	EPOST fb MPOST	52.5 fb 46	Syngenta Crop Protection fb Bayer Crop Science	NIS + NIS
Corn #2	Mesotrione fb tembotrione	Callisto® fb Laudis®	PRE fb MPOST	105 fb 92	Syngenta Crop Protection fb Bayer Crop Science	NIS
Corn #3	*S*-metolachlor/ atrazine/ mesotrione fb thiencarbazone/ tembotrione + atrazine + glufosinate	Lexar® fb Capreno® + AAtrex® + Liberty®	PRE fb MPOST	1,480/1,480/190 fb 758 + 1,120 + 1,540	Syngenta Crop Protection fb Bayer Crop Science + Syngenta Crop Science + Bayer Crop Science	NIS
Soybean	Flumioxazin fb glufosinate + fomesafen/*S*-metolachlor fb glufosinate	Valor® fb Liberty® + Prefix® fb Liberty®	PRE fb EPOST fb MPOST	160 fb 1,540 + 370/1,670 fb 1,540	Valent Agricultural Products fb Bayer Crop Science + Syngenta Crop Protection fb Bayer Crop Science	
Cotton	Fluometuron fb glyphosate + glufosinate + *S*-metolachlor fb glyphosate + glufosinate + *S*-metolachlor fb diuron fb flumioxazin	Cotoran® fb Roundup PowerMAX® + Liberty® + Dual II Magnum® fb Roundup PowerMAX® + Liberty® + Dual II Magnum® fb Direx® fb Valor®	PRE fb EPOST fb MPOST fb directed fb layby	1,120 fb 860 + 1,540 + 1,792 fb 860 + 1,540 + 1,792 fb 560 fb 90	Syngenta Crop Protection fb ADAMA fb Monsanto Company + Bayer Crop Science + Syngenta Crop Protection fb Monsanto Company + Bayer Crop Science + Syngenta Crop Protection fb ADAMA fb Valent Agricultural Products	NIS (directed) + COC (layby)

[a]Abbreviations: /, herbicide premix; +, herbicide tank mix; fb, followed by; COC, crop oil concentrate (1% v/v; Agridex®, Helena Chemical Co., Collierville, TN, USA); NIS, nonionic surfactant (0.25% v/v; Induce®, Helena Chemical Co.).
[b]Corn early postemergence (EPOST) treatments were 15 d after planting (DAP), and all mid-postemergence (MPOST) treatments were 30 DAP. Soybean EPOST treatments were applied at the V2 growth stage and MPOST at the V4/V5 growth stage. Cotton EPOST was applied at two- to three-leaf cotton, and MPOST was applied at six- to seven-leaf cotton.

Table 3. Planting date, seeding rate, application dates, and harvest dates for all crops from 2015 to 2017.[a,b]

Crop	Planting date	Seeding rate	Application date PRE	EPOST	MPOST	Layby[c]	Directed[d]	Harvest date
		seeds ha^{-1}						
Corn	30 Apr 2015	79,000	30 Apr 2015	21 May 2015	4 Jun 2015	NA	NA	14 Sep 2015
Corn	25 Apr 2016	79,000	25 Apr 2016	9 May 2016	—[e]	NA	NA	22 Sep 2016
Cotton	2 May 2016	136,000	2 May 2016	23 May 2016	8 Jun 2016	24 Jun 2016	11 Jul 2016	28 Oct 2016
Soybean	23 May 2016	321,000	23 May 2016	8 Jun 2017	6 Jul 2016	NA	NA	14 Oct 2016
Corn	19 Apr 2017	79,000	19 Apr 2017	11 May 2017	25 May 2017	NA	NA	21 Sep 2017
Cotton	25 Apr 2017	136,000	25 Apr 2017	18 May 2017	30 May 2017	16 Jun 2017	7 Jul 2017	16 Nov 2017
Soybean	18 May 2017	321,000	18 May 2017	30 May 2017	14 Jun 2017	NA	NA	26 Oct 2017

[a]Layby and directed applications were not applicable (NA) for corn and soybean crops.
[b]Abbreviations: NA, not applicable; PRE, preemergence; EPOST, early postemergence; MPOST, mid-postemergence.
[c]Applied and incorporated with or applied after the last cultivation of a crop.
[d]Precise application to a specific area or plant organ, such as to a row or bed or to the leaves or stems of plants.
[e]The MPOST application for corn in 2016 was not applied due to an accumulated 12 cm of rain over a 10-day period.

Table 4. Weed species recorded as percentage of the total weed population averaged across treatments and years of experimentation.

Species	Common name	Occurrence
		%
Acalypha ostryifolia Riddell	Hophornbeam copperleaf	7
Amaranthus palmeri S. Watson	Palmer amaranth	40
Cynanchum laeve (Michx.) Pers.	Honeyvine milkweed	<2
Urochloa platyphylla (Munro ex C. Wright) R.D. Webster	Broadleaf signalgrass	8
Digitaria sanguinalis (L.) Scop.	Large crabgrass	6
Echinochloa crus-galli (L.) P. Beauv.	Barnyardgrass	3
Ipomoea hederacea Jacq.	Ivyleaf morningglory	4
Ipomoea lacunosa L.	Pitted morningglory	12
Panicum dichotomiflorum Michx.	Fall panicum	<2
Setaria viridis (L.) P. Beauv.	Green foxtail	<2
Sida spinosa L.	Prickly sida	15
Solanum carolinense L.	Horsenettle	<2
Sorghum halepense (L.) Pers.	Johnsongrass	2

Statistical Analysis

A nested or hierarchical analysis of variance (ANOVA) was used for the analysis of emerged weeds, soil seedbank assessments, weed biomass, and crop yields. More particularly, herbicide programs were nested in the corresponding crop rotation sequences throughout the entire experimental period for each weed species separately that occurred for >2% of the weed population throughout the experimental period. Prior to data analysis, grassweed species (i.e., barnyardgrass, broadleaf signalgrass, johnsongrass, and large crabgrass) were pooled together to overcome the variability between species but also the absence of johnsongrass in 2015 and barnyardgrass in 2016 emergence counts. Similarly, emergence counts for morningglory species (i.e., pitted [*Ipomoea lacunosa* L.] and ivyleaf [*Ipomoea hederacea* Jacq.] morningglory) were also pooled together. Comparisons of weed emergence were made between weed counts in the covered and uncovered plots, which were crossed with herbicide program and rotation sequence. This approach enabled the conjoint analysis of herbicide program with its corresponding crop rotation sequence (henceforth treatment). Therefore evaluation of the dependent variable (e.g., weed density, total weed biomass, and soil seedbank) variability between the experimental treatments in time was possible. Nested ANOVA was used on both log-transformed (when assumptions of normality were not satisfied) and untransformed counts of weed emergence and soil seedbank. Results presented here are based on back-transformed values to facilitate a better understanding of the research outcome. JMP 16.0 Pro software (SAS Institute Inc., Cary, NC, USA) was used for data analysis.

Results and Discussion

Weed Occurrence

Fourteen weed species were recorded throughout the experimental period, but only those with occurrence > 2% of the total weed population averaged across treatments (crop rotation × herbicide program) and years of experimentation were analyzed and are presented here (Table 4). The dominant weed species, in descending order, were Palmer amaranth (40%), prickly sida (15%), and pitted morningglory (12%). Additional weed occurrence included broadleaf signalgrass (8%), hophornbeam copperleaf (*Acalypha ostryifolia* Riddell) (7%), large crabgrass (6%), ivyleaf morningglory (4%), barnyardgrass (3%), and johnsongrass (2%) (Table 4). Barnyardgrass was recorded in 2015 and 2017 only, whereas johnsongrass was recorded in 2016 and 2017 only.

Treatment Effects on the Emergence of Naturally Occurring Weeds

All herbicide programs associated with Treatments 1, 2, 3, and 4 were found relatively effective in controlling the emergence of naturally occurring weed species, whereas, in most cases, herbicide programs associated with Treatments 5 and 6 were less effective. HPPD-inhibiting herbicide-based programs applied as preemergence and mid-postemergence (i.e., mesotrione fb tembotrione or as premix, i.e., mesotrione with *S*-matolachlor and atrazine) and/or herbicides recommended for soybean or cotton in the subsequent years were effective on grassweed species. In general, treatments involving herbicides with six SOAs, such as Treatments 1 and 4 (i.e., inhibition of hydroxyphenyl pyruvate dioxygenase, inhibition of very-long-chain fatty-acid synthesis, inhibition of photosynthesis at photosystem II [PSll], inhibition of acetolactate synthase, inhibition of glutamine synthetase, inhibition of protoporphyrinogen oxidase), or herbicides with seven SOAs, such as Treatments 2 and 3 (i.e., inhibition of very-long-chain fatty-acid synthesis, inhibition of photosynthesis at PSll, inhibition of hydroxyphenyl pyruvate dioxygenase, inhibition of acetolactate synthase, inhibition of glutamine synthetase, inhibition of protoporphyrinogen oxidase, and inhibition of enolpyruvyl shikimate phosphate synthase), reduced weed emergence. On the contrary, treatments involving herbicides with fewer SOAs, such as Treatment 5 (five SOAs) and Treatment 6 (one SOA), were less effective. Only the top three emerged weeds are discussed in what follows.

Palmer Amaranth

Selected herbicide programs associated with corresponding crop rotation sequences across years affected the emergence (i.e., weed counts in uncovered vs. covered plots) of Palmer amaranth ($P < 0.0008$). Herbicides used in corn–soybean–cotton rotation (i.e., Treatment 2, involving herbicides with seven SOAs) or corn–soybean–corn rotation (i.e., Treatment 4, involving herbicides with six SOAs) (Table 2) reduced the emergence of Palmer amaranth by 89.8% and 88.5%, respectively. The herbicide program for Treatment 2 consisted of preemergence, early, and mid-postemergence herbicide applications fb directed and layby applications (in cotton), and that for Treatment 4 consisted of preemergence, early, and mid-postemergence applications.

The herbicide program associated with continuous corn, a combination of preemergence and mid-postemergence applications at the recommended dose (i.e., Treatment 5, which involved herbicides with five SOAs, namely, inhibition of very-long-chain fatty-acid synthesis, inhibition of photosynthesis at PSll, inhibition of hydroxyphenyl pyruvate dioxygenase, inhibition of acetolactate synthase, and inhibition of glutamine synthetase), reduced the emergence of Palmer amaranth by 76.2% between counts in uncovered compared to covered plots (Figure 1). Similarly, the herbicide program associated with corn–corn–soybean rotation, a combination of preemergence, early, and mid-postemergence herbicide applications (i.e., Treatment 1, which involved herbicides with

https://doi.org/10.1017/wet.2022.40 Published online by Cambridge University Press

Figure 1. Effects of herbicide program (i.e., herbicide program × crop rotation) and covered plots (i.e., covered vs. uncovered plot) on Palmer amaranth emergence throughout the experimental period. Vertical bars represent the standard error of the mean at significance level $\alpha = 0.1$. Treatments are as follows: 1, corn [PRE+MPOST] followed by (fb) corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST]; 2, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby]; 3, corn [PRE+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby] fb corn [PRE+EPOST]; 4, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb corn [PRE+MPOST]; 5, corn [PRE+MPOST] fb corn [PRE+MPOST] fb corn [PRE+MPOST]; 6, corn [EPOST+MPOST] fb corn [EPOST+MPOST] fb corn [EPOST+MPOST]. See Table 1 for a detailed description of the field treatments throughout the experimental period (from 2015 to 2017).

six SOAs), reduced Palmer amaranth emergence between uncovered and covered plots by 70.1% (Figure 1). Similar results were reported by Oliveira et al. (2017) when preemergence fb postemergence herbicide programs including glyphosate and glufosinate as pre- or tank mix provided 60% to 90% control of waterhemp under conventional corn. In addition, the preemergence application of mesotrione + *S*-metolachlor + atrazine provided 83% Palmer amaranth control in conventional corn (Chahal et al. 2018b). Herbicide programs associated with corn–cotton–corn rotation (i.e., Treatment 3, involving herbicides with seven SOAs) or those in continuous corn, that is, at half of the recommended dose of mesotrione fb tembotrione (i.e., Treatment 6, involving herbicides with one SOA, i.e., inhibition of hydroxyphenyl pyruvate dioxygenase), had a lesser effect on Palmer amaranth emergence (54.5% and 31.2%, respectively) (Figure 1).

Crop rotation leads to the diversification of individual cropping practices, thereby causing changes in weed population and species composition (Cardina et al. 2002; Norsworthy et al. 2012; Ross and Lembi 1985). On the basis of our results, the effective control of Palmer amaranth was achieved when corn was planted in a rotation with soybean and cotton, which enabled the use of preemergence fb early and mid-postemergence herbicide applications with distinct SOAs. The adoption of this approach, that is, crop rotation and vigorous HPPD-based herbicide programs applied preemergence and/or early to mid-postemergence, can also achieve long-term Palmer amaranth control in corn production systems. This is because the inclusion of the early and mid-postemergence herbicide applications in the weed control program enables the control of emerged weeds, including Palmer amaranth, at the time of application (Bollman et al. 2008; Chahal et al. 2017; Neve et al. 2011).

The long-term effects of treatment choice (herbicide program × crop rotation) were revealed when Palmer amaranth emergence counts were compared in uncovered plots only, in particular, when emergence counts in 2017 (final assessment) were compared to emergence counts in 2015 (initial assessment). Treatments 1, 2, 3, 4, and 5 (involving herbicides with six, seven, seven, six, and five SOAs, respectively), in that order, reduced Palmer amaranth emergence by 28-fold, 5.2-fold, 4.5-fold, 1.5-fold, and 1.1-fold, respectively. In contrast, Treatment 6 (i.e., weak HPPD herbicide program with one SOA in continuous corn) caused a 4-fold increase of Palmer amaranth emergence in 2017 compared to 2015 (Figure 1). Cultural practices for weed management that include crop rotations between soybean and corn accompanied with suitable herbicide rotations can be used to control weeds effectively (Liebman and Dyck 1993; Riar et al. 2013). On the basis of our results, this is true for Palmer amaranth emergence counts in corn–soybean rotation systems, as 88.7% control was obtained under Treatment 4 (a 3-yr corn–soybean–corn rotation) (Figure 1).

Prickly Sida

Herbicide programs, averaged across years, in uncovered (treated plots) compared to covered (untreated controls) reduced the emergence of prickly sida ($P < 0.0001$) (Figure 1). The most effective herbicide program was Treatment 2, which involved herbicides with seven SOAs (59% emergence reduction) fb, in descending

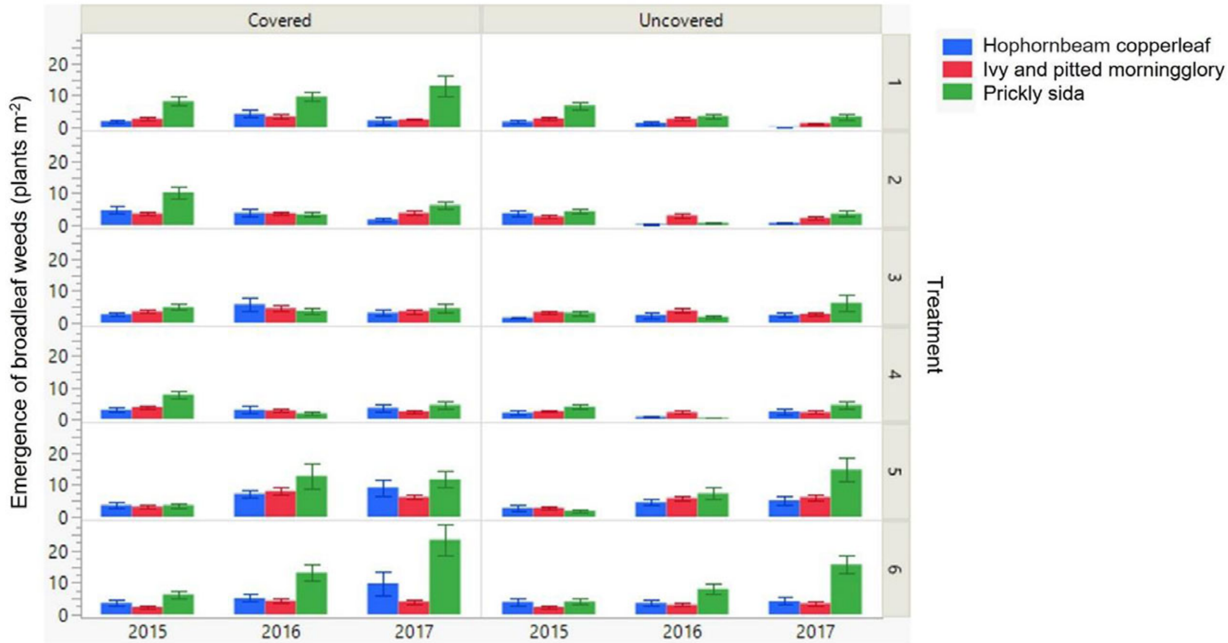

Figure 2. Effects of herbicide program (i.e., herbicide program × crop rotation) and covered plots (i.e., covered vs. uncovered plot) on broadleaf weeds emergence throughout the experimental period. Vertical bars represent the standard error of the mean at significance level $a = 0.1$, 0.1, and 5 for hophornbeam, morningglory, and prickly sida, respectively. Treatments are as follows: 1, corn [PRE+MPOST] followed by (fb) corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST]; 2, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby]; 3, corn [PRE+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby] fb corn [PRE+EPOST]; 4, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb corn [PRE+MPOST]; 5, corn [PRE+MPOST] fb corn [PRE+MPOST] fb corn [PRE+MPOST]; 6, corn [EPOST+MPOST] fb corn [EPOST+MPOST] fb corn [EPOST+MPOST]. See Table 1 for detailed description of the field treatments throughout the experimental period (from 2015 to 2017).

order, Treatment 1 (herbicides with six SOAs) (56% emergence decrease); Treatment 4 (herbicides with six SOAs) (38.3% decrease); Treatment 6 (herbicides with one SOA) (35% emergence decrease); Treatment 3 (herbicides with seven SOAs) (17.4% emergence decrease); and, finally, Treatment 5 (herbicides with five SOAs) (15% emergence decrease). Previous studies have reported high control of *S. spinosa* with residual herbicides applied prior to or at planting and followed by single or multiple POST herbicide applications (Beyers et al. 2002; Culpepper et al. 2000; Ellis and Griffin 2002), as in Treatments 1, 2, and 3. In another study, Burke et al. (2002) reported high prickly sida control when PRE application of flumioxazin was included in the herbicide program, as in Treatments 1, 2, and 4.

Morningglory Species

The two morningglory species evaluated have been grouped together owing to the similarity in their trends. Herbicide programs significantly reduced the emergence of both morningglory species in uncovered plots compared to covered plots ($P < 0.05$) and between years ($P < 0.001$). Treatment 5 was the least effective on the emergence of ivyleaf morningglory and pitted morningglory in relation to other treatments. More particularly, Treatment 1 (77% emergence reduction) fb Treatment 2 (70% emergence reduction) and Treatment 4 (64% emergence reduction) were the most effective in controlling the emergence of ivyelaf morningglory. In Treatments 3 and 6, the reduction of the weed was approximately 45% (Figure 2). Likewise, Treatment 5 was the least effective ($P < 0.001$) on pitted morningglory emergence reduction (12% reduction), followed by Treatments 3, 2 6, 1, and 4, which reduced morningglory emergence by 16%, 21%, 33%, 39%, and 43%, respectively (Figure 2).

The preemergence fb mid-postemergence application of mesotrione and tembotrione, respectively, in the first year, accompanied with premix applications of mesotrioane with atrazine and *S*-metolachlor and/or tank-mix applications of tembotrione + atrazine + glufosinate, as in Treatments 1, 2, and 4, along with treatments that contained flumioxazin and fluometuron in the following years as fitted to crop rotational system, improved the control of morningglory species compared to other treatments exclusively based on corn monoculture. The addition of atrazine to mesotrione applied postemergence improved *Ipomoea coccinea* L. control (Armel et al. 2007). Furthermore, the addition of atrazine to tembotrione resulted in a synergistic response in Palmer amaranth (Kohrt and Sprague 2017), whereas atrazine added to PRE applications of isoxaflutole also increased control of ivyelaf morningglory (Stephenson and Bond 2012). Johnson et al. (2002) and Breeden et al. (2001) reported increased control of ivyelaf morningglory and pitted morningglory by the addition of atrazine to mesotrione. Therefore the co-application of HPPD-inhibiting with PSII-inhibiting herbicides is well documented as a practice that can increase overall herbicidal activity and broaden the weed control spectrum.

Grass Species

Crop rotation allowed the use of different herbicides that improved the control of various grassweed species, such as broadleaf signalgrass, large crabgrass, and barnyardgrass ($P < 0.0001$) (Figure 3). Johnson and Coble (1986), for example, reported that broadleaf

Figure 3. Effects of herbicide program (i.e., herbicide program × crop rotation) and covered plots (i.e., covered vs. uncovered plot) on grassweed emergence throughout the experimental period. Vertical bars represent the standard error of the mean at significance level $\alpha = 0.1$. Grassweed species consist of large crabgrass, broadleaf signalgrass, barnyardgrass, and johnsongrass. Treatments are as follows: 1, corn [PRE+MPOST] followed by (fb) corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST]; 2, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby]; 3, corn [PRE+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby] fb corn [PRE+EPOST]; 4, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb corn [PRE+MPOST]; 5, corn [PRE+MPOST] fb corn [PRE+MPOST] fb corn [PRE+MPOST]; 6, corn [EPOST+MPOST] fb corn [EPOST+MPOST] fb corn [EPOST+MPOST]. See Table 1 for detailed description of the field treatments throughout the experimental period (from 2015 to 2017).

signalgrass has been observed in areas where corn, soybean, and peanut (*Arachis hypogaea* L.) are grown continually or in rotation. Additionally, Johnson and Coble found that broadleaf signalgrass density was highest in plots where corn dominated rotations. Our findings show a similar trend, where Treatment 6, that is, continuous corn monoculture associated with a weak HPPD herbicide program involving one herbicide SOA, had the highest grassy weed density, including broadleaf signalgrass, large crabgrass, and barnyardgrass (Figure 3; Supplementary Figure 1). Like broadleaf signalgrass, barnyardgrass emergence in Treatment 6, averaged across experimental years, was increased by 96.8% in the uncovered compared to covered plots, whereas little differences showed in the emergence of large crabgrass (Supplementary Figure 1). Differential response to herbicides could reflect differences in selection pressure caused by years of cropping system–related herbicide usage. De Cauwer et al. (2011) stated that one of the possible reasons for the increase of barnyardgrass emergence is the lack of crop rotation and the lower sensitivity of the weed to postemergence herbicides acting against panicoid grasses, such as HPPD-inhibiting herbicides, as in Treatment 6. Treatment 6 (involving herbicides with one SOA) was the least effective treatment for the emergence of johnsongrass compared to the most effective treatments, Treatments 2, 3, 4, and 5 (i.e., involving seven, seven, six, and five SOAs, respectively), with 95%, 95%, 90%, and 90% johnsongrass emergence reductions, respectively (Supplementary Figure 1). Findings for Treatment 6, a poor HPPD herbicide program in continuous corn, confirm reports by Frans et al. (1991), who stated that a high level of herbicide control is necessary to control johnsongrass in various crop rotation systems.

Treatment Effects on Total Weed Biomass

Treatment (herbicide program × crop rotation) significantly affected the total weed biomass ($P = 0.003$) between 2016 and 2017 (Figure 4). Biomass production in 2016 showed no significant decreases. However, comparisons between biomass in covered and uncovered plots for each herbicide × crop rotation treatment in 2017 revealed that Treatments 2, 1, 5, 4, and 6, in that order, were the most effective treatments in reducing weed total weight (Figure 4). Total weed dry weight between covered and uncovered plots increased by 1.2-fold under Treatment 2 in 2017.

Johnson et al. (2002) reported increased control of common cocklebur (*Xanthium strumarium* L.), ivyleaf morningglory, and yellow nutsedge (*Cyperus esculentus* L.) by the addition of atrazine to mesotrione. Mesotrione activity on common ragweed (*Ambrosia artemisiifolia* L.), horsenettle (*Solanum carolinense* L.), sicklepod (*Cassia obtusifolia* L.), and pitted morningglory has also been enhanced by adding atrazine.

https://doi.org/10.1017/wet.2022.40 Published online by Cambridge University Press

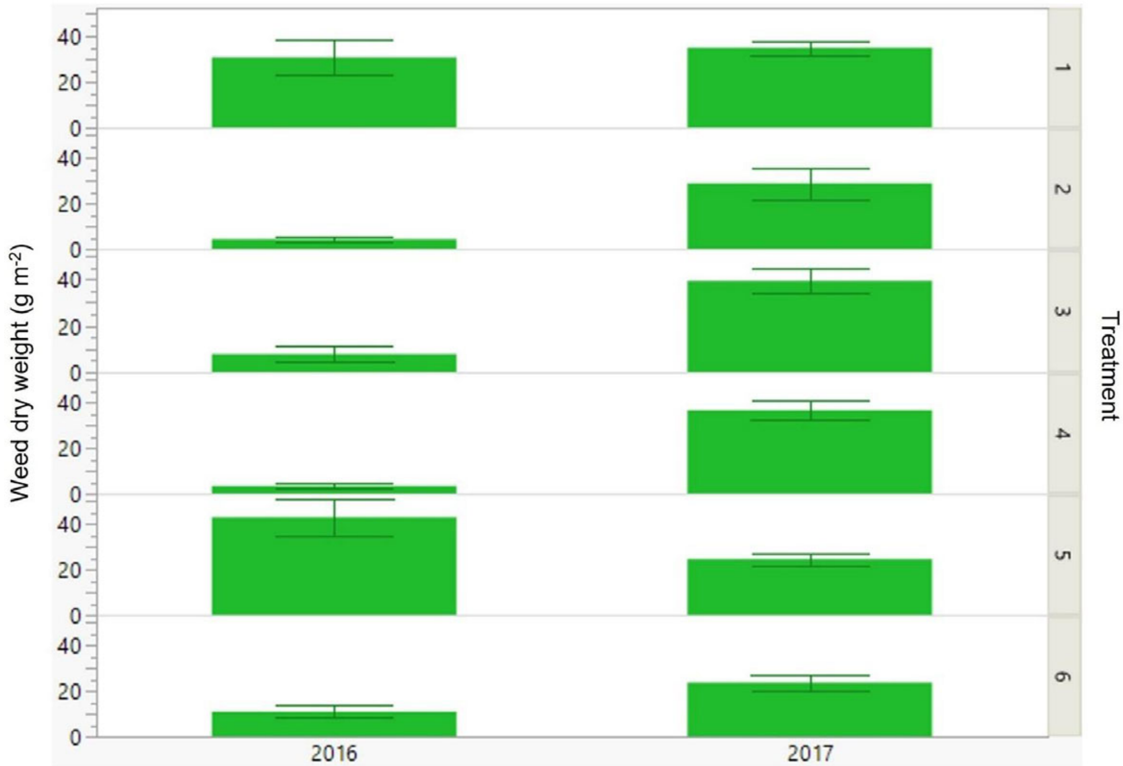

Figure 4. Effects of treatment (i.e., herbicide program × crop rotation) on total weed biomass in 2016 and 2017. Vertical bars represent the standard error of the mean at significance level $\alpha = 0.01$. Treatments are as follows: 1, corn [PRE+MPOST] followed by (fb) corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST]; 2, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby]; 3, corn [PRE+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby] fb corn [PRE+EPOST]; 4, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb corn [PRE+MPOST]; 5, corn [PRE+MPOST] fb corn [PRE+MPOST] fb corn [PRE+MPOST]; 6, corn [EPOST+MPOST] fb corn [EPOST+MPOST] fb corn [EPOST+MPOST]. See Table 1 for detailed description of the field treatments throughout the experimental period (from 2015 to 2017).

Treatment Effects on Soil Seedbank

Weed seedbanks may indicate the effects of crop management on weed population (Buhler et al. 2001), although the relationship between soil seedbank and weed emergence is not always direct (Sjursen 2001). However, Palmer amaranth seedbank under Treatments 2, 3 1, 4, and 5, in that order, was progressively reduced ($P < 0.001$) from 97% to 25% between 2015 and 2018 (Figure 5). These herbicide treatments, involving herbicides with seven, six, and five SOAs, were also more effective on Palmer amaranth emergence. Only under Treatment 6, Palmer amaranth seed counts increased ($P < 0.001$) 3-fold between 2015 and 2017 (Figure 5). Seed counts of weed species increased progressively toward the end of the experiment, particularly between 2017 and 2018. The soil seedbank of broadleaf weeds prickly sida and morningglory species increased between 2017 and 2018 in all treatments, especially under Treatments 3, 5, and 6. Seed counts of the broadleaf signalgrass and large crabgrass also increased independently of the treatment, whereas johnsongrass increased greatly under Treatment 6 (Figure 5). Increases in soil seedbank could increase the persistence of certain weed species, such as morningglory, which can remain viable for about 40 yr (Toole and Brown 1946). The prolonged period of weed germination, for example, Palmer amaranth (Monks et al. 2019), necessitates management systems that ensure long-term reductions of the soil seedbank. Wei et al. (2005) reported significant decreases, between 27% and 44%, of soil seedbank owing to crop rotation of wheat, corn, and soybean. The use of crop sequences reduces the selection pressure and prevents the proliferation of some weed species that have adapted well to a single cropping system, as in the case of Palmer amaranth. The soil seedbank of Palmer amaranth and morningglory increased under Treatment 6. With a continual increase in herbicide resistance, preservation of currently effective herbicide programs is paramount.

Practical Implications

HPPD-based herbicide programs augmented with crop rotation, especially when soybean and cotton are included in the sequence, reduced the emergence of naturally occurring weed flora and soil seedbank, especially Palmer amaranth. However, corn monocultures and weak HPPD-based herbicide programs with only one SOA resulted in Palmer amaranth and prickly sida emergence and soil seedbank increases. The latter approach cannot sustain a profitable crop production. Therefore integrated weed management that incorporates crop rotation of corn, soybean, and cotton with selected HPPD-based herbicide programs that involve six or seven SOAs can preserve herbicide efficacy in the long term and suppress the presence of weed species in corn fields, hence delaying the evolution of herbicide resistance.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2022.40

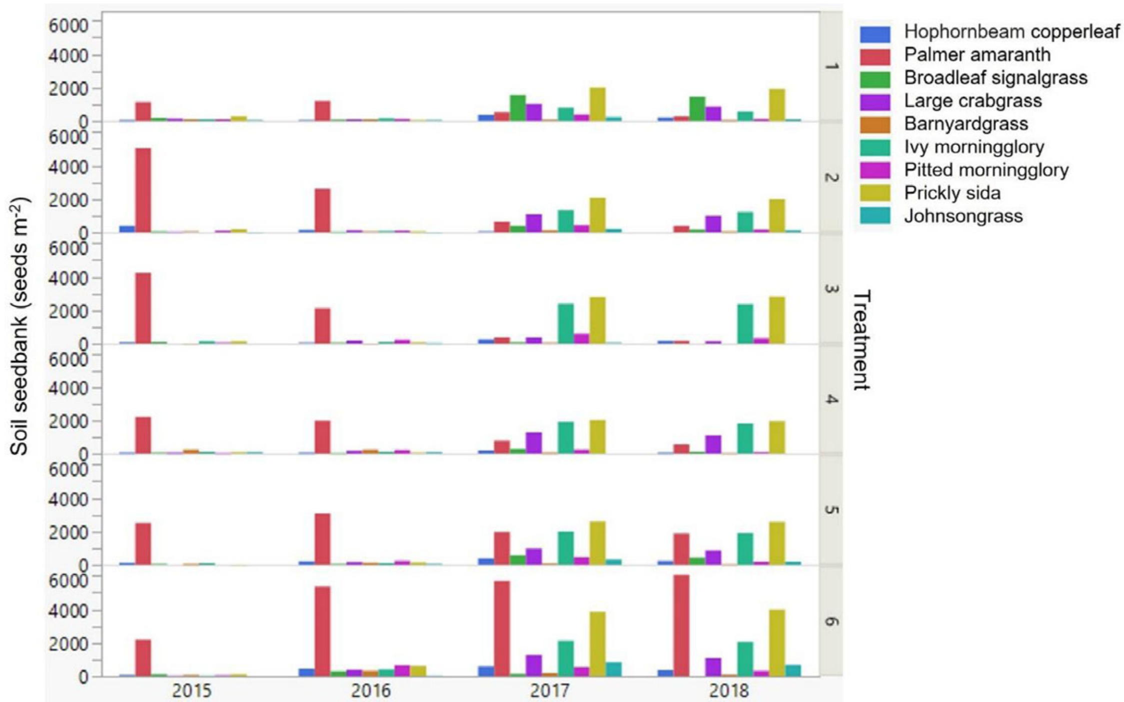

Figure 5. Effects of treatment (i.e., herbicide program × crop rotation) on weed soil seedbank throughout the experimental period at significance level $a = 0.1$. Treatments are as follows: 1, corn [PRE+MPOST] followed by (fb) corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST]; 2, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby]; 3, corn [PRE+MPOST] fb cotton [PRE+EPOST+MPOST+Directed+Layby] fb corn [PRE+EPOST]; 4, corn [PRE+MPOST] fb soybean [PRE+EPOST+MPOST] fb corn [PRE+MPOST]; 5, corn [PRE+MPOST] fb corn [PRE+MPOST] fb corn [PRE+MPOST]; 6, corn [EPOST+MPOST] fb corn [EPOST+MPOST] fb corn [EPOST+MPOST]. See Table 1 for detailed description of the field treatments throughout the experimental period (from 2015 to 2017).

Acknowledgments. The authors thank all the graduate students and research technicians and the Northeast Research and Extension Center farm crew for all their help with this research. No conflicts of interest have been declared. This research received no specific grant from any funding agency or the commercial or not-for-profit sectors.

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