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Management of pigweed (*Amaranthus* spp.) in grain sorghum with integrated strategies

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Research Article

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Abstract

Pigweed is difficult to manage in grain sorghum because of widespread herbicide resistance, a limited number of registered effective herbicides, and the synchronous emergence of pigweed with grain sorghum in Kansas. The combination of cultural and mechanical control tactics with an herbicide program are commonly recognized as best management strategies; however, limited information is available to adapt these strategies to dryland systems. Our objective for this research was to assess the influence of four components, including a winter wheat cover crop (CC), row-crop cultivation, three row widths, with and without a herbicide program, on pigweed control in a dryland system. Field trials were implemented during 2017 and 2018 at three locations for a total of 6 site-years. The herbicide program component resulted in excellent control (>97%) in all treatments at 3 and 8 weeks after planting (WAP). CC provided approximately 50% reductions in pigweed density and biomass for both timings in half of the site-years; however, mixed results were observed in the remaining site-years, ranging from no attributable difference to a 170% increase in weed density at 8 WAP in 1 site-year. Treatments including row-crop cultivation reduced pigweed biomass and density in most site-years 3 and 8 WAP. An herbicide program is required to achieve pigweed control and should be integrated with row-crop cultivation or narrow row widths to reduce the risk of herbicide resistance. Additional research is required to optimize the use of CC as an integrated pigweed management strategy in dryland grain sorghum.

Introduction

The challenge of weed management in grain sorghum has continued to increase in recent years with the occurrence of herbicide-resistant weed populations (Thompson et al. 2017). Pigweed species have been confirmed resistant to six herbicide sites of action in Kansas (Heap 2019). Yield reductions as high as 57% with 1.6 Palmer amaranth (*Amaranthus palmeri*) plants m^{-2} were observed when weeds were transplanted into grain sorghum at developmental stage 2 (Moore et al. 2004).

Best management practices indicate that grain sorghum should be planted by early June in Kansas (Ciampitti et al. 2019). Although planting at this timing can maximize grain yield, it also synchronizes emerging sorghum with the emergence of Palmer amaranth and waterhemp [*A. tuberculatus* (Moq.) J. D. Sauer], because soil surface (2.5-cm depth) temperatures can often approach and exceed 25 C during the optimal grain sorghum planting time (Guo and Al-Khatib 2003; Hartzler et al. 1999; Jha and Norsworthy 2009). Synchronous emergence of grain sorghum with pigweed may be more influential than pigweed density in determining grain yield loss (Knezevic et al. 1997) and may place grain sorghum at a competitive disadvantage in contrast to other crops.

Grain sorghum producers have few effective herbicide options for controlling pigweed (Hennigh et al. 2010). A systems approach of integrated weed management must be adopted when addressing tough-to-control weeds (e.g., Palmer amaranth and waterhemp) (Owen 2016; Thompson et al. 2017).

Because of herbicide resistance and a limited number of registered active ingredients, cultural weed management practices such as narrow row widths (NRWs) must be considered. NRWs generally result in faster canopy closure and increased evapotranspiration efficiency (Steiner 1986). Staggenborg et al. (1999) reported grain sorghum yields were increased 10% with NRWs compared with 76-cm row widths in favorable growing conditions. Best management recommendations for Kansas indicate that narrow row spacing should be selected over wide row spacing to increase yield (Ciampitti et al. 2019), which aligns with integrated weed management strategies to increase crop competitiveness with weeds (Norsworthy et al. 2012). The use of 38-cm and 19-cm row widths in grain sorghum increases control of Palmer amaranth, tumble pigweed (*A. albus* L.), redroot pigweed (*A. retroflexus* L.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and sicklepod [*Senna obtusifolia* (L.) H. S. Irwin & Barneby] when compared with wide row widths (≥76 cm) (Besancon et al. 2017; Grichar et al. 2004; Wiese et al. 1964).

Table 1. Winter wheat cover crop planting and termination dates, grain sorghum planting dates, herbicide application and row-crop application dates, and site characteristics for each site-year.

	2017			2018		
Site Characteristic[a]	Riley County	Reno County	Franklin County	Riley County	Reno County	Franklin County
Cover crop planting date		Early October, 2016			Late September, 2017	
Termination date		April 20			May 10	
Preplant application date	June 7	May 30	June 8	May 12	May 12	May 21
Sorghum planting PRE application date	June 21	June 13	June 22	May 22	May 22	June 4
Row-crop cultivation date	July 9	July 1	July 10	June 9	June 9	June 22
POST application date	July 12	July 5	July 13	June 12	June 12	June 25
Soil series[b]	Reading[c]	Ost[d]	Woodson[e]	Wymore[f]	Ost[d]	Woodson[e]
Soil texture	Silt loam	Loam	Silt loam	Silty clay loam	Loam	Silt loam
Soil organic matter, %[g]	3.5	2.5	3.5	2.9	2.5	3.3
Soil pH	6.0	6.1	6.6	6.5	5.7	6.4
Soil CEC, mEq/100g[h]	21.1	20.9	17.9	15.8	18.6	18.4

[a]Abbreviations: mEq, milliequivalents.
[b]All soil characteristics assessed from a 0- to 7.6-cm soil sampling depth.
[c]Fine-silty, mixed superactive, mesic Pachic Argiudolls.
[d]Fine-loamy, mixed, superactive, mesic Udic Argiustolls.
[e]Fine, smectic, thermic Abruptic Argiaquolls.
[f]Fine, smectitic, mesic Aquertic Argiudolls.
[g]Loss on ignition (Ball 1964).
[h]Adjusted to pH 7 (Rich 1969).

The use of row-crop cultivation has been a long-standing, effective tool for weed management in grain sorghum (Wiese et al. 1964); however, yield losses due to reduced soil moisture conservation and root pruning have been reported (Dickey et al. 2013). The use of row-crop cultivation can also increase the potential for soil erosion and must be weighed against integrated weed management benefits (Bates et al. 2012).

Cover crops (CCs) have provided economic benefit when used as part of a rotational system with grain sorghum (Mahama et al. 2016; Reinbott et al. 2004). Although CCs have suppressed Palmer amaranth and waterhemp (Cornelius and Bradley 2017; DeVore et al. 2013; Loux et al. 2017;), little to no research has investigated the role of CCs as an integrated pigweed management tool in grain sorghum. Maintaining adequate residue cover in a no-till dryland system can aid weed suppression in grain sorghum (Anderson 2000; Dhuyvetter et al. 1996; Thompson et al. 1998). An extension of this is to maintain ground cover with winter wheat residue in a double-crop grain sorghum production system (Crabtree et al. 1990).

Winter wheat as a CC offers similar suppression of Palmer amaranth and waterhemp in cotton (*Gossypium hirsutum* L.) and soybean [*Glycine max* (L.) Merr.] when compared with cereal rye (*Secale cereale* L.) (Wiggins et al. 2016). When planting a summer annual grass crop such as grain sorghum, a leguminous CC could be selected to avoid challenges of crop establishment and nitrogen immobilization (Mahama et al. 2016). However, leguminous CCs seldom produce the biomass and ground cover necessary to adequately suppress Palmer amaranth and waterhemp (Cornelius and Bradley 2017; Wiggins et al. 2015). Research has indicated that with appropriate agronomic practices (e.g., adequate nitrogen fertilization), establishment of summer annual grass crops such as corn (*Zea mays* L.) after cereal rye does not consistently reduce grain yields (Appelgate et al. 2017; Duiker and Curran 2005).

The repeated use of any one of these weed management tactics (herbicide, NRW, row-crop cultivation, or CCs) will eventually select for tactic-resistant biotypes (Shaner 2014). Thus, a combination of these practices in pursuit of an integrated weed management plan should be implemented as a system. In developing strategies, all farmers can be placed on a continuum ranging from the mindset of weed control (i.e., simplistic, short-term focus) to weed management (i.e., consideration of environmental, economic, and cultural aspects) to cropping systems–based decisions (i.e., complex, integrated decisions across many years), which is truly an integrated, sustainable approach (Cardina et al. 1999). By incorporating weed management decisions at the cropping systems level, the selection for resistance to a given practice will be delayed and create a more sustainable system overall (Gallandt et al. 1999). Unfortunately, limited research has investigated how to incorporate many of these best management practices into a dryland grain sorghum cropping system. The objective for this research was to assess the influence of a winter wheat CC, row-crop cultivation, three row widths, and herbicide program, each alone and in combination, on pigweed height, density, and biomass in dryland (limited rainfall, nonirrigated) grain sorghum in Kansas.

Materials and Methods

Field experiments were conducted in Riley (39.12567°N, 96.613488°W), Reno (37.931114°N, 98.029392°W), and Franklin (38.539265°N, 95.244301°W) counties on Kansas State University Department of Agronomy Experiment Fields during 2017 and 2018 for a total of 6 site-years. Riley and Reno counties contained an indigenous population of Palmer amaranth, whereas Franklin County contained an indigenous population of waterhemp. Sixteen treatments were established using a one-way treatment structure consisting of combinations of four components: the absence or presence of a herbicide program, three row widths (76, 38, and 19 cm), CCs, and row-crop cultivation of only the 76-cm row width. Cultivation of 19- and 38-cm row widths is not practical. The 76-cm row width with no cover crop (NCC) treatment is referred to as standard management (SM) in this article.

Winter Wheat CC Component Establishment and Termination

'Gallagher' winter wheat was no-till planted at 134 kg ha^{-1} in 19-cm row widths at all locations (Table 1). At spring green-up

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Table 2. Winter wheat cover crop aboveground dry biomass at grain sorghum planting and soil nitrogen concentration at grain sorghum planting and at grain sorghum maturity.[a]

Site-Year		Winter wheat biomass at planting (SE)	Soil nitrogen[b,c]			
			CC treatments		NCC treatments	
Year	County	Planting	Planting	Maturity	Planting	Maturity
		kg ha^{-1}	ppm			
	Riley	5,420 (777)	7.9	7.3	48.0	7.1
2017	Reno	4,120 (461)	17.1	22.4	19.2	39.3
	Franklin	4,468 (580)	27.6	2.9	30.5	2.8
	Riley	3,520 (702)	26.0	9.9	12.7	12.3
2018	Reno	2,580 (482)	20.3	10.2	22.9	11.7
	Franklin	3,144 (410)	86.5	9.6	78.7	10.1

[a]Soil sampled from 61-cm soil cores from CC and NCC plots.
[b]Abbreviations: CC, winter wheat cover crop; NCC, no winter wheat cover crop.
[c]PPM represents total concentration of nitrate plus ammoniacal nitrogen.

Table 3. Precipitation for each site-year during cover crop and grain sorghum growth and development.

		Precipitation from January through April[a,b]		Precipitation during grain sorghum growth and development[c]									
				WAP									
Site	Year	Accumulated	30-yr normal	1	2	3	4	5	6	7	8	Total	30-yr normal[d]
		mm											
Riley	2017	270	157	4	63	0	0	10	24	95	24	220	182
County	2018	81		0	38	16	3	18	5	2	43	125	231
Reno	2017	287	179	25	0	19	0	8	3	12	25	93	185
County	2018	94		0	9	37	0	84	50	0	67	247	218
Franklin	2017	246	179	4	103	0	26	2	22	19	69	245	172
County	2018	163		0	18	7	17	0	0	1	30	73	200

[a]Thirty-year normals referenced from 1980 to 2010 for each location as recorded by the National Oceanic and Atmospheric Administration (Arguez et al. 2010).
[b]Precipitation values reflect moisture that occurred during the growth and development of winter wheat cover crop.
[c]Abbreviation: WAP, weeks after sorghum planting.
[d]Values calculated from 30-yr normal precipitation from the planting date for each site-year through 8 WAP.

(i.e., Feekes 4), the CC was topdressed with 56 kg ha^{-1} urea fertilizer (46% nitrogen). The CC was terminated with 1,065 g ha^{-1} glyphosate (Roundup PowerMAX®; Monsanto Co., St. Louis, MO) at Feekes 10.5.1 "anthesis" (Table 1). Aboveground biomass of CC was harvested from one representative 0.25-m^2 area in each replication per site-year at grain sorghum planting, dried, and weighed (Table 2).

Grain Sorghum Establishment

Experiments were established in a randomized complete block design. Plots at all sites were 3-m wide and 9-m long, with four replications per site. Immediately before planting the grain sorghum, the entire experimental area received an application of 841 g ha^{-1} paraquat (Gramoxone® SL 2.0; Syngenta Crop Protection, LLC., Greensboro, NC) to control all emerged pigweed and a broadcast application of 112 kg ha^{-1} urea. Grain sorghum hybrid '7715' (Sorghum Partners®, New Deal, TX) was no-till planted at 148,200 seeds ha^{-1} using a no-till drill (Model 1590; Deere and Co., Moline, IL) at all locations. The same seeding rate was used across all row widths, with drill slots being closed to accommodate the various row widths. Key operation dates and site characteristics are listed in Table 1. At grain sorghum planting and maturity, soil cores were collected from a 61-cm depth to assess nitrogen content in CC and NCC plots (Table 2). Daily rainfall events were recorded at weather stations located no more than 2.5 km from each site (Table 3). All locations received a broadcast application of 75 g ha^{-1} chlorantraniliprole (Prevathon®; E.I. du Pont e Nemours and Co., Wilmington, DE) during grain sorghum fill to control unwanted insects.

Herbicide Program and Row-Crop Cultivation Components

The herbicide program component consisted of the absence or presence of preplant, PRE, and 3 weeks after planting (WAP) POST applications to facilitate overlapping residual herbicides. The split preplant and PRE application consisted of a premix of 1,884 g ha^{-1} *S*-metolachlor, 707 g ha^{-1} atrazine, and 188 g ha^{-1} mesotrione (Lumax® EZ; Syngenta Crop Protection, LLC.); two-thirds of the total herbicide was applied 2 weeks before planting and the remainder applied immediately after planting. The POST application consisted of a tank mix of 43 g ha^{-1} pyrasulfotole and 245 g ha^{-1} bromoxynil (Huskie®; Bayer Crop Science, Research Triangle Park, NC), 280 g ha^{-1} dicamba (Clarity®; BASF Corp., Research Triangle Park, NC), 2,800 g ha^{-1} acetochlor and 1,389 g ha^{-1} atrazine (Degree Xtra®; Monsanto Co.), 2.5% vol/vol urea ammonium nitrate, plus 0.25% vol/vol nonionic surfactant (Activate Plus™, Winfield United, Bloomberg, MN).

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Table 4. Influence of grain sorghum row width, winter wheat cover crop, and row-crop cultivation on Palmer amaranth density and biomass averaged across site-years in Riley County during 2017 and 2018 and Reno County during 2017 in the absence of the herbicide program component.

Treatment[a]		3 WAP[b,c]		8 WAP	
Row width[d]	Component(s)	Density	Biomass	Density	Biomass
cm		plants m^{-2}	g m^{-2}	plants m^{-2}	g m^{-2}
76	CC + RC	20 d	0.7 e	48 c	31 e
	CC	320 bc	19 b-d	343 ab	190 bc
	RC	120 cd	10.2 de	205 bc	83 de
	–	710 a	38 a	431 a	303 a
38	CC	310 bc	11 de	208 bc	108 c-e
	–	600 a	29 ab	524 a	178 bc
19	CC	300 b-d	15 cd	181 bc	140 b-d
	–	550 ab	26 bc	496 a	218 ab
P value		<0.0001	<0.0001	<0.0001	<0.0001
Treatment contrast[e]					
Row width, cm					
76 vs. 38		515 vs. 455 NS	28.5 vs. 20[f]	387 vs. 366 NS	246 vs. 143[g]
76 vs. 19		515 vs. 425 NS	28.5 vs. 20.5[h]	387 vs. 339 NS	246 vs. 179f
38 vs. 19		455 vs. 425 NS	20 vs. 20.5 NS	366 vs. 339 NS	143 vs. 179 NS
CC vs. NCC		310 vs. 620[i]	15 vs. 31	244 vs. 484[i]	146 vs. 233[g]

[a]Abbreviations: –, no CC or RC was present in the treatment; CC, winter wheat cover crop; NCC, no cover crop; NS, not significant; RC, row-crop cultivation; WAP, weeks after planting.
[b]Means followed by the same letter within a column are not statistically different according to Fisher Protected LSD ($\alpha = 0.05$).
[c]Height data for means and contrasts were NS and are not shown.
[d]The76-cm row width without CC or RC is described as standard management in the text.
[e]All contrasts were conducted in the absence of RC-containing treatments.
[f]$P = 0.05$ to 0.01.
[g]$P = 0.01$ to 0.0001.
[h]$P = 0.1$ to 0.05.
[i]$P < 0.0001$.

The herbicide applications were made using a four-nozzle CO_2-pressurized backpack sprayer calibrated to deliver 144 L ha^{-1} at 241 kPa using Turbo TeeJet® Induction 110015 nozzles (TeeJet Technologies, Springfield, IL) for the preplant and PRE applications and Air Induction Extended Range 110015 nozzles for the POST application. A three-shank row-crop cultivator (Buffalo Model 6200; Bison Industries Inc., Norfolk, NE) with 46-cm–wide sweeps was operated 5-cm deep at 6.4 km hr^{-1} approximately 2.5 WAP for the row-crop cultivation component.

Pigweed Height, Density, and Biomass Data Collection and Analysis

The average height of 10 plants per plot as well as density were recorded, and biomass harvested from representative 0.25-m^2 areas between the center rows in each plot at 3 and 8 WAP. Biomass was oven dried at 65 C for 10 d and weighed. Data were analyzed using the Mixed Procedure in JMP Pro 14 (SAS Institute, Cary, NC), and means were separated using Fisher Protected LSD at $\alpha = 0.05$. Pigweed height, density, and biomass data were assessed for basic assumptions of ANOVA. To meet these assumptions of ANOVA, Franklin County waterhemp density data collected 3 and 8 WAP in 2017 and 8 WAP in 2018 required natural log transformation, whereas waterhemp biomass data at 3 WAP in 2017 from Franklin County required square root transformation. All values were back transformed for discussion. When no site-by-year-by-treatment interactions were detected, site-year was considered a random effect with replication nested within the site-year (within a species). Contrasts of a single degree of freedom were applied to compare groups of treatments that excluded treatments with row-crop cultivation to assess the effects of NRW (i.e., 38 cm and 19 cm) and CC.

Results and Discussion

All treatments that included the herbicide program component resulted in excellent pigweed control (>97%; data not shown); therefore, data not containing this component were extracted and analyzed separately. No interactions were detected for Palmer amaranth height, density, or biomass for effects of site-year by treatment for Riley County in 2017 and 2018 and Reno County in 2017; therefore, data were pooled. Data for Reno County plots in 2018 were analyzed separately because there was a significant year-by-treatment interaction with all other site-years containing Palmer amaranth. Franklin County waterhemp data were analyzed separately for each site-year because significant year-by-treatment interactions were detected.

Palmer Amaranth Density and Biomass Across 3 Site-Years (Riley and Reno Counties)

Palmer amaranth densities were similar (550 to 710 plants m^{-2}) across all row widths with NCC at 3 WAP (Table 4). When a CC was added to the 76-cm row width, a 55% reduction in Palmer amaranth density was observed. Treatments with row-crop cultivation reduced density by 97% compared with SM. Row-crop cultivation and CC were effective components to integrate in terms of reducing the selection pressure on Palmer amaranth with POST herbicide applications; this demonstrated the importance of considering cultural and mechanical tactics when developing pigweed management strategies (Buhler 2002; Loux et al. 2017). When NRW was combined with CC, density was reduced compared with SM. Contrasts revealed that differences in Palmer amaranth density could not be attributed to NRW at 3 WAP. Treatments containing CC resulted in a 50% reduction in Palmer amaranth density across all row widths (Table 4). It is important to note that

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the control offered by CC was achieved with a dual-purpose winter wheat, which is commonly used for forage (i.e., biomass producing) qualities; it is unclear if results would have differed if a single-purpose wheat cultivar had been selected.

Biomass was reduced only with the 19-cm row width compared with the 76- and 38-cm row widths and NCC treatments at 3 WAP (Table 4). Compared with SM, combining CC with row-crop cultivation reduced biomass by 97%, whereas row-crop cultivation alone reduced weed biomass by 83%. The combination of NRW plus CC reduced Palmer amaranth biomass compared with SM, but NRW alone did not. When pooled across all combinations, contrasts found that NRW reduced biomass compared with the 76-cm row width. The use of a CC resulted in a 52% biomass reduction compared with NCC across all row widths by 3 WAP in these 3 site-years (Table 4).

Palmer amaranth densities were similar by 8 WAP in all NRW plus NCC and all 76-cm row width treatments (excluding row-crop cultivation-containing treatments) (Table 4). This indicated that CC or NRW as stand-alone tactics did not reduce late-season densities. Densities after row-crop cultivation or NRW plus CC treatments (≤208 plants m^{-2}) were reduced from SM (431 plants m^{-2}) by 8 WAP. That each component on its own was not enough to provide suppression illustrated the importance of applying a systems approach that uses cultural and mechanical strategies in addition to an herbicide program (Beckie 2006; Norsworthy et al. 2012; Owen 2016; Owen et al. 2014). Generally, row-crop cultivation has been associated with increasing late-season weed emergence because of soil disturbance (Forcella and Lindstrom 1988). In some environments, as in this study, increased emergence did not occur; therefore, timely row-crop cultivation could be used to control early-season weeds without causing additional emergence, especially in dryland cropping systems. Contrasts indicated that no reduction in density could be attributed to NRW, but the addition of CC across all row widths reduced density by 50% (Table 4).

Palmer amaranth biomass was reduced with the CC plus 76-cm row width or 38-cm NCC treatments compared with SM by 8 WAP. Both 19-cm row width treatments (CC or NCC) produced a similar level of biomass to SM (Table 4). Treatments including CC or row-crop cultivation reduced Palmer amaranth biomass compared with SM. Contrasts revealed that NRW provided 27% and 46% reductions in late-season biomass with 38- and 19-cm row widths, respectively, compared with the 76-cm row width, and the addition of CC provided a 37% reduction in late-season biomass compared with NCC treatments across all row widths (Table 4). Butts et al. (2016) found similar results in soybean in terms of a benefit from NRW for Palmer amaranth late-season biomass suppression.

Table 5. Influence of grain sorghum row width, winter wheat cover crop, and row-crop cultivation on Palmer amaranth height, density, and biomass at 8 WAP in Reno County in 2018 in the absence of the herbicide program component.

Treatment[a]		8 WAP[b,c]		
Row width[d]	Component(s)	Height	Density	Biomass
cm		cm	plants m^{-2}	g m^{-2}
76	CC + RC	30 c	382 a	266 b
	CC	45 ab	336 a	388 ab
	RC	40 a–c	119 bc	191 b
	–	47 a	175 bc	600 a
38	CC	44 ab	114 bc	353 ab
	–	45 ab	50 c	588 a
19	CC	36 bc	241 ab	216 b
	–	50 a	31 c	403 ab
P value		0.0115	0.0009	0.0281
Contrasts[e]				
Row width, cm				
76 vs. 38		46 vs. 44.5 NS	256 vs. 82[f]	494 vs. 471 NS
76 vs. 19		46 vs. 43 NS	256 vs. 136[g]	494 vs. 310[h]
38 vs. 19		44.5 vs. 43 NS	82 vs. 136 NS	471 vs. 310[h]
CC vs. NCC		42 vs. 47[g]	230 vs. 85[f]	319 vs. 530[f]

[a]Abbreviations: –, no CC or RC was present in the treatment; CC, winter wheat cover crop; NCC, no cover crop; NS, not significant; RC, row-crop cultivation; WAP, weeks after planting.
[b]3 WAP data are not included as Palmer amaranth was not emerged.
[c]Means followed by the same letter within a column are not statistically different according to Fisher Protected LSD ($\alpha = 0.05$).
[d]76-cm row width without CC or RC is described as standard management in the text.
[e]All contrasts were conducted in the absence of RC-containing treatments.
[f]$P = 0.01$ to 0.0001.
[g]$P = 0.05$ to 0.01.
[h]$P = 0.1$ to 0.05.

Palmer Amaranth Height, Density, and Biomass in Reno County, 2018

Palmer amaranth was not present at 3 WAP because of the lack of moisture to stimulate emergence (Table 3), but all treatments were still implemented per protocol (i.e., row-crop cultivation at 2.5 WAP). Palmer amaranth height was only reduced in the 19-cm row width plus CC and row-crop cultivation plus CC treatments, compared with SM, by 8 WAP (Table 5). Contrasts indicated that NRW had no effect on height at 8 WAP; however, CC treatment reduced height compared with NCC over all row widths.

Palmer amaranth densities were greater in the 76-cm row width plus CC and row-crop cultivation plus CC treatments than the SM 8 WAP (Table 5). Typically, CC is expected to decrease weed density; it is possible that the density increase for CC-containing treatments was caused by moisture retained at the soil surface, along with other abiotic conditions occurring in this site-year (Wells et al. 2014). The CC at Reno County in 2018 also could have been disadvantaged because of dry conditions; 94 mm of precipitation fell during CC growth as compared with the 179 mm normally received during this time (Table 3). Subsequently, less CC aboveground biomass was produced at grain sorghum planting (2,580 kg ha^{-1}) compared with all other site-years (Table 2). The condition of the CC was also likely further degraded by the 134 mm of precipitation that occurred during 5 to 6 WAP (Table 3). The row-crop cultivation treatment did not change Palmer amaranth density compared with SM, which corresponded to observations in other site-years, indicating the soil disturbance from row-crop cultivation did not stimulate more weed emergence. Densities in NRW or CC plus NRW treatments did not differ from SM. Although the 38-cm row width and 19-cm row width plus CC treatments did not differ from SM, the 19-cm row width with NCC treatment reduced density, compared with the 19-cm row width plus CC treatment. This indicated the addition of CC to this row width was counterproductive. Contrasts indicated the 38- and 19-cm row widths reduced weed density by 47% and 68%, respectively, compared with the 76-cm row width. When CC and NCC treatments across all row widths were compared, use of a CC resulted in a 170% increase in weed density compared with the NCC treatments. Thus, the use of a CC may not consistently result in lower weed densities (Table 5).

Palmer amaranth biomass was less in the CC plus 19-cm row width treatment and in response to row-crop cultivation compared with SM 8 at WAP in Reno County in 2018 (Table 5). Similar levels of biomass were observed for the row-crop cultivation and 19-cm row width plus CC treatments, whereas all other treatments did not differ from SM. Contrasts revealed no differences in biomass between the 76- and 38-cm row widths, whereas the 19-cm row

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Table 6. Influence of grain sorghum row width, winter wheat cover crop, and row-crop cultivation on waterhemp height, density, and biomass at 3 and 8 WAP in Franklin County during 2017 in the absence of the herbicide program component.

Treatment[a]		3 WAP[b]			8 WAP		
Row width[c]	Component(s)	Height	Density	Biomass	Height	Density	Biomass
cm		cm	plants m^{-2}	g m^{-2}	cm	plants m^{-2}	g m^{-2}
76	CC + RC	18 b	111 b-d	7.8 b	99 c	45 b	81 bc
	CC	18 b	304 a	20 ab	101 c	205 a	110 bc
	RC	22 b	61 d	10 b	131 ab	7 c	63 bc
	-[d]	32 a	165 a-d	36 a	146 a	93 ab	230 a
38	CC	21 b	220 a-d	16 ab	101 c	71 ab	49 bc
	-	33 a	234 a-c	37 a	133 a	84 ab	123 a-c
19	CC	16 b	88 cd	8 b	105 bc	62 ab	26 c
	-	33 a	261 ab	24 ab	149 a	95 ab	156 ab
P value		0.0033	0.0463	0.0432	0.0012	0.0026	0.0322
Contrasts[d]							
Row width, cm							
76 vs. 38		25 vs. 27 NS	235 vs. 227 NS	28 vs. 27 NS	124 vs. 117 NS	149 vs. 78 NS	170 vs. 86[e]
76 vs. 19		25 vs. 25 NS	235 vs. 175 NS	28 vs. 16 NS	124 vs. 127 NS	149 vs. 79 NS	170 vs. 91[f]
38 vs. 19		27 vs. 25 NS	227 vs. 175 NS	27 vs. 16 NS	117 vs. 127 NS	78 vs. 79 NS	86 vs. 91 NS
CC vs. NCC		18 vs. 33[g]	204 vs. 220 NS	15 vs. 32[e]	102 vs. 143[g]	113 vs. 91 NS	62 vs. 170[h]

[a]Abbreviations: –, no CC or RC was present in the treatment; CC, winter wheat cover crop; NCC, no cover crop; NS, not significant; RC, row-crop cultivation; WAP, weeks after planting.
[b]Means followed by the same letter within a column are not statistically different according to Fisher Protected LSD ($\alpha = 0.05$).
[c]76-cm row width without CC or RC is described as standard management in the text.
[d]All contrasts were conducted in the absence of RC-containing treatments.
[e]$P = 0.05$ to 0.01.
[f]$P = 0.1$ to 0.05.
[g]$P < 0.0001$.
[h]$P = 0.01$ to 0.0001.

width provided greater suppression compared with the 76- and 38-cm row widths. CC also provided a 40% reduction in late-season biomass compared with the NCC treatments across all row widths. This could be due to increased crop-weed competitiveness, which has been associated with the use of CCs (Teasdale 1996). The weed biomass data conflict with the density data in this site-year: CC reduced biomass but increased density, likely as a function of the plasticity of Palmer amaranth (Horak and Loughin 2000) (i.e., fewer but larger weeds) in this dryland environment (Table 5).

Waterhemp Height, Density, and Biomass in Franklin County, 2017

Waterhemp was shorter in treatments containing row-crop cultivation, CC, or NRW plus CC, compared with SM at 3 WAP (Table 6). No differences in waterhemp height were observed with NRW in the absence of CC, as compared with SM. Waterhemp density in all treatments did not differ from SM at 3 WAP. Contrasts indicated no overall effects on waterhemp density as a result of NRW or CC (Table 6).

Waterhemp biomass was less with row-crop cultivation and with CC plus 19-cm row width treatments than SM at 3 WAP (Table 6). For this site-year, a combination of cultural tactics or mechanical control was required to reduce waterhemp biomass, albeit when data were pooled across row widths, CC provided a 53% reduction in biomass compared with NCC treatments (Table 6).

Late-season waterhemp was shorter compared with SM for all CC-containing treatments at 8 WAP (Table 6). Row-crop cultivation plus CC reduced waterhemp height compared with row-crop cultivation alone, indicating that some level of suppression was achieved with the addition of CC. When row-crop cultivation is used, producers should consider the use of a CC or retain previous crop residues for benefits outside of weed management (e.g., soil conservation, soil moisture retention) (Hartzler et al. 1993; Keene and Curran 2016). Waterhemp was not shorter with NRW in the absence of CC compared with SM 8 WAP. Furthermore, contrasts revealed a 29% reduction in height with CC compared with the NCC treatments (Table 6).

At 8 WAP, reductions in waterhemp density from SM were only observed in row-crop cultivation treatments (Table 6). The general lack of difference between treatments was likely due to the waterhemp emergence pattern in this specific environment. For example, the majority of waterhemp may have emerged earlier in the season, prior to the row-crop cultivation 2.5 WAP, and thus a significant proportion of emerged waterhemp was controlled. Fewer waterhemp emerged late, thereby having a reduced density at 8 WAP, and CC likely provided the grain sorghum crop other competitive advantages.

Reductions in waterhemp biomass were observed for all CC or row-crop cultivation treatments as compared with SM at 8 WAP (Table 6). Biomass in treatments containing NRW in the absence of CC did not differ from SM, though contrasts indicated that 38- and 19-cm row widths contributed 49% and 46% reductions in biomass by 8 WAP, compared with the 76-cm row widths. The use of NRW provided a similar benefit in soybean in terms of suppressing late-season waterhemp biomass (Butts et al. 2016). CC also provided waterhemp suppression, with a 64% reduction in biomass compared with NCC-containing treatments (Table 6).

Waterhemp Density in Franklin County, 2018

No differences in waterhemp height or biomass were detected at either observation time in Franklin County in 2018 (data not shown). At 3 and 8 WAP, waterhemp density was less than with SM in those treatments that contained row-crop cultivation (Table 7). All treatments, regardless of the presence of CC or NRW, resulted in similar densities. This could have been due to the lack of moisture from planting through 8 WAP (73 mm, compared with the 200 mm normally received during this period) (Table 3). In the absence of a CC, the 19-cm row width reduced

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Table 7. Influence of grain sorghum row width, winter wheat cover crop, and row-crop cultivation on waterhemp density at 3 and 8 WAP in Franklin County in 2018 in the absence of the herbicide program component.

Treatment[a]		Density	
Row width[d]	Component(s)	3 WAP[b,c]	8 WAP
cm		plants m^{-2}	
76	CC + row-crop cultivation	16 b	10 c
	CC	76 a	34 ab
	row-crop cultivation	18 b	11 c
	–	73 a	51 ab
38	CC	77 a	45 ab
	–	84 a	61 a
19	CC	95 a	39 ab
	–	93 a	20 bc
P value		0.0093	0.0237
Contrasts[e]			
Row width, cm			
76 vs. 38		73 vs. 81 NS	43 vs. 53 NS
76 vs. 19		73 vs. 94 NS	43 vs. 30 NS
38 vs. 19		81 vs. 94 NS	53 vs. 30[f]
CC vs. NCC		83 vs. 83 NS	39 vs. 44 NS

[a]Abbreviations: –, no CC or row-crop cultivation was present in the treatment; CC, winter wheat cover crop; NCC, no cover crop; NS, not significant; row-crop cultivation, row-crop cultivation; WAP, weeks after planting.
[b]Means followed by the same letter within a column are not statistically different according to Fisher Protected LSD ($\alpha = 0.05$).
[c]3 WAP height and biomass and 8 WAP height and biomass means and contrasts were found to be NS and are not shown.
[d]76-cm row width without CC or row-crop cultivation is described as standard management in the text.
[e]All contrasts were conducted in the absence of row-crop cultivation-containing treatments.
[f]$P = 0.1$ to 0.05.

density at 8 WAP, compared with the 38-cm row width. The general lack of difference between NRW and CC indicate both components were ineffective at providing waterhemp suppression in this site-year. Although reduced CC biomass or soil nitrogen availability could have contributed to the lack of differences in this site-year, similar biomass and soil nitrogen levels were found (Table 2), which indicated that environmental factors (e.g., rainfall, soil moisture, thermal amplitude at the soil surface) contributed to the lack of differences.

Practical Implications for Management

The herbicide program component provided the most effective pigweed control in contrast to the cultural and mechanical components considered. The success of this program was likely due to the use of overlapping residuals, multiple effective sites of action in each application, and the timeliness of all applications. This herbicide program achieved excellent pigweed control (>97%) across all systems, and this type of approach would slow the development of herbicide resistance (Godar and Stahlman 2015; Meyer et al. 2015; Norsworthy et al. 2012; Reddy et al. 2013; Sarangi and Jhala 2018; Steckel et al. 2002), albeit herbicide resistance will eventually develop in the absence of integrated strategies, even with a robust herbicide program (Shaner 2014).

The integration of other mechanical and cultural tactics must be considered to extend the life of the limited, effective herbicide options currently available in grain sorghum (Stahlman and Wicks 2000; Thompson et al. 2017). Row-crop cultivation was the most effective component outside of the herbicide program and provided 79% reduction in pigweed density by 3 WAP when implemented at 2.5 WAP. Greater success of the row-crop cultivation component would be possible when implemented in fields with lower pigweed densities than those in this study (Buhler et al. 1992; Dieleman et al. 1999). This mechanical tactic could substantially reduce the selection pressure on pigweed imposed by POST herbicides and should be used when row widths are wide enough to accommodate row-crop cultivation equipment and soil conservation plans allow (Buhler 2002). Even though the integration of CC with row-crop cultivation did not consistently improve weed control, it may facilitate soil conservation (Buhler 1995; Keene and Curran 2016). Ultimately, more consideration must be given to integrate row-crop cultivation with herbicides to improve the long-term control offered by the system and to control weeds within the row (Buhler 1995; VanGessel et al. 1998).

Pigweed control with the CC component had mixed results. Although the treatment in half the site-years (specifically, Riley County and Reno County during 2017) (Table 4) resulted in approximately 50% reductions in Palmer amaranth density and biomass in both early- and late-season observations, there was no change in or greater densities of Palmer amaranth and waterhemp in the other site-years. Although this demonstrates the potential benefit of CC as a strategy to reduce the selection pressure on pigweed by herbicides and to limit seedbank replenishment, more research is needed to understand other agronomic practices (e.g., termination timing, species selection) to improve the consistency of CC performance in dryland cropping systems featuring grain sorghum.

Pigweed control 3 WAP was not influenced by NRW, and NRW would not reduce the selection pressure on pigweed from POST herbicide applications. Limited early-season benefit from NRW has been reported in grain sorghum (Besancon et al. 2017) and other crops (Bradley 2006; Butts et al. 2016; Norsworthy and Oliveira 2004). Our research demonstrated NRW could result in reduced pigweed biomass at 8 WAP, which would limit pigweed seed production. As result of this research, integrating the use of NRW or row-crop cultivation together with an herbicide program will achieve consistent control of pigweed and reduce the risk of evolving herbicide resistance.

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