Weed Science

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Research Article

Cite this article: Dhanda S, Kumar V, Dille JA, Obour A, Yeager EA, Holman J (2025). Effect of fall-planted cover crops on weed suppression, grain sorghum yield, and profitability in the semiarid Central Great Plains. Weed Sci. **73**(e24), 1–11. doi: 10.1017/wsc.2024.100

Received: 22 September 2024
Revised: 2 December 2024
Accepted: 9 December 2024

Associate Editor:
John M. Wallace, Penn State University

Keywords:
Dryland; kochia; Palmer amaranth; residual herbicide

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Effect of fall-planted cover crops on weed suppression, grain sorghum yield, and profitability in the semiarid Central Great Plains

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Abstract

Integrating cover crops (CCs) in dryland crop rotations could help in controlling herbicide-resistant weeds. Field experiments were conducted at Kansas State University Agricultural Research Center near Hays, KS, from 2020 to 2023 to determine the effect of fall-planted CCs on weed suppression in grain sorghum [*Sorghum bicolor* (L.) Moench], crop yield, and net returns in no-till dryland winter wheat (*Triticum aestivum* L.)–grain sorghum–fallow (W-S-F) rotation. The field site had a natural seedbank of glyphosate-resistant (GR) kochia [*Bassia scoparia* (L.) A. J. Scott] and Palmer amaranth (*Amaranthus palmeri* S. Watson). A CC mixture [winter triticale (×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*])–winter peas (*Pisum sativum* L.)–canola (*Brassica napus* L.)–radish (*Raphanus sativus* L.)] was planted after wheat harvest and terminated at triticale heading stage before sorghum planting. Treatments included nontreated control, chemical fallow, CC terminated with glyphosate (GLY), and CC terminated with GLY+ acetochlor/atrazine (ACR/ATZ). Across 3 yr, CC terminated with GLY+ACR/ATZ reduced total weed density by 34% to 81% and total weed biomass by 45% to 73% compared with chemical fallow during the sorghum growing season. Average grain sorghum yield was 786 to 1,432 kg ha^{-1} and did not differ between chemical fallow and CC terminated with GLY+ ACR/ATZ. However, net returns were lower with both CC treatments (−US$275 to US$66) in all 3 yr compared with chemical fallow (−US$111 to US$120). These results suggest that fallow replacement with fall-planted CCs in the W-S-F rotation can help suppress GR *B. scoparia* and *A. palmeri* in the subsequent grain sorghum. However, the cost of integrating CCs exceeded the benefits of improved weed control, and lower net returns were recorded in all 3 yr compared with chemical fallow.

Introduction

The Central Great Plains (CGP) is characterized by a semiarid climate with relatively low annual precipitation (~300 to ~1,200 mm) (Lenssen et al. 2007; NOAA 2024). To conserve soil moisture and prevent soil erosion by wind, no-tillage (NT)- and fallow-based cropping systems are widely adopted in the region. Successful adoption of these soil conservation practices was achieved utilizing chemical-based weed control (Hansen et al. 2012; Kumar et al. 2020). However, the adoption of NT-based production systems has resulted in weed species representing smaller-seeded weeds like kochia [*Bassia scoparia* (L.) A.J. Scott], Palmer amaranth (*Amaranthus palmeri* S. Watson), horseweed [*Conyza canadensis* (L.) Cronquist; syn.: *Erigeron canadensis* (L.) Cronquist], common lambsquarters (*Chenopodium album* L.), Russian thistle (*Salsola tragus* L.), downy brome (*Bromus tectorum* L.), wild oat (*Avena fatua* L.), foxtail species (*Setaria* spp.), and tumble windmill grass (*Chloris verticillata* Nutt.) (Jha et al. 2016; Nichols et al. 2015).

Winter wheat (*Triticum aestivum* L.)–grain sorghum [*Sorghum bicolor* (L.) Moench]–fallow (W-S-F) is a dominant crop rotation in the CGP region (Holman et al. 2022). This 3-yr crop rotation includes a fallow period of approximately 10 mo between winter wheat harvest and sorghum planting as well as 10 mo of fallow period between sorghum harvest and the next winter wheat planting (Kumar et al. 2020). Continuous reliance on herbicides with the same site(s) of action for weed control has resulted in the evolution of herbicide-resistant weeds, including *B. scoparia*, *A. palmeri*, and *C. canadensis* (Heap 2024). For instance, glyphosate resistance is widespread among *B. scoparia* and *A. palmeri* populations in Kansas and other neighboring states in the CGP region (Heap 2024; Kumar et al. 2019a, 2019b, 2020; Westra et al. 2019). Evolution of glyphosate-resistant (GR) weed populations and limited availability of alternative effective herbicide options pose a serious production challenge for grain sorghum producers in the region. Previous researchers have reported that season-long weed interference can result in an average grain yield loss of 47% in sorghum, which is an estimated loss of around US$953 million annually (Dille et al. 2020). Therefore, alternative integrated weed management strategies are needed to achieve effective control of herbicide-resistant weed populations in grain sorghum.

Integration of cover crops (CCs) in crop rotations has been proven as one of the effective tools to suppress herbicide-resistant weeds in the CGP region (Kumar et al. 2020; Mesbah et al. 2019; Obour et al. 2022a; Petrosino et al. 2015). Growing CCs in the semiarid CGP also provides several other benefits, including reduced soil erosion, enhanced nutrient cycling, increased microbial activity, improved soil health, and increased plant diversity and pollinator resources (Blanco-Canqui et al. 2011, 2013; Simon et al. 2022). Additionally, CC residue left on the soil surface after termination reduces soil temperature and soil moisture evaporation, thereby contributing to increased soil water storage (Holman et al. 2020, 2021). However, replacing the fallow period with CCs in the semiarid cropping systems sometimes reduces the yield of successive crops because of the reduced plant-available water (Holman et al. 2018; Nielsen et al. 2016). However, the U.S. Department of Agriculture–Natural Resources Conservation Service (USDA-NRCS) provides some financial support to growers under the Environmental Quality Incentives Program (EQIP) to pay some of the cost of growing CCs and improve net returns (USDA-NRCS 2024). Previous studies have evaluated the effect of spring-planted CCs on weed suppression and winter wheat yields when CCs replaced the fallow phase of W-S-F rotation in this region (Holman et al. 2022; Mesbah et al. 2019; Obour et al. 2022a). For instance, Obour et al. (2022a) reported that spring-planted CCs (oats [*Avena sativa* L.]−triticale [×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*]]–spring peas [*Pisum sativum* L.]) in W-S-F rotation can reduce weed biomass by 86% to 99% compared with weedy fallow. Holman et al. (2022) reported that spring-planted CCs had no significant effect on wheat and grain sorghum yields when conditions were either extremely dry with poor yields or very wet with above-average yields; however, replacing fallow with CCs increased the cost of production by 16% to 97% compared with fallow.

Farmers are currently relying on residual herbicides to manage GR weeds in the dryland W-S-F rotation (Kumar et al. 2020). Several researchers have previously documented the importance of residual herbicides in combination with CCs to achieve season-long weed control (Perkins et al. 2021; Teasdale et al. 2005; Whalen et al. 2020). For instance, Whalen et al. (2020) reported that CCs terminated with glyphosate plus 2,4-D in combination with residual herbicides (sulfentrazone plus chlorimuron) resulted in greater waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer.] control (73% to 84%) compared with no residual herbicide (44% to 65%). Most CC weed suppression research studies were conducted in cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), or soybean [*Glycine max* (L.) Merr.] in greater-precipitation environments (Weisberger et al. 2023; Whalen et al. 2020). However, limited information exists regarding the integration of fall-planted CCs in combination with soil-residual herbicides at the termination of CCs on weed suppression in subsequent grain sorghum in the semiarid CGP region. The main objectives of this study were to determine the effect of fall-planted CCs in combination with soil-residual herbicides on (1) weed suppression (density and biomass) in subsequent grain sorghum and grain yield and (2) net returns with integrating CCs in the no-till dryland W-S-F cropping system. We hypothesized that fall-planted CCs combined with residual herbicides would provide adequate weed suppression in grain sorghum with minimal or no impact on sorghum yield, resulting in higher net returns.

Materials and Methods

Experimental Design and Treatments

A field experiment was conducted at Kansas State University Agricultural Research Center (KSU-ARCH) near Hays, KS (38.85196°N, 99.34279°W) during the 2020 to 2021, 2021 to 2022, and 2022 to 2023 growing seasons. The experiment was initiated in the fall of 2020. The soil type at the experimental site was a Roxbury silt loam with a pH of 6.9 and organic matter of 1.6% (USDA Soil Series lists: fine-silty, mixed, superactive, mesic Cumulic Haplustolls). The study site was under no-till W-S-F rotation for >10 yr before study initiation and had a natural uniform seedbank of GR *B. scoparia* and *A. palmeri* (VK, personal observations). All three phases of the W-S-F crop rotation were present each year. After wheat harvest, all plots were sprayed in late July with glyphosate (GLY) (Roundup PowerMax®, Bayer Crop Science, St Louis, MO, USA) at 1,260 g ae ha^{-1} plus dicamba (Clarity®, BASF, Research Triangle Park, NC, USA) at 560 g ae ha^{-1}. A CC mixture of winter triticale (60%)–winter peas (30%)–canola (*Brassica napus* L.) (5%)–radish (*Raphanus sativus* L.) (5%) was drill seeded into wheat stubble at a rate of 67 kg ha^{-1} during each fall and terminated in the following spring at the triticale heading stage. The CC planting dates were September 28, October 7, and September 30 in 2020, 2021, and 2022, respectively. The CC was terminated on May 13, May 11, and May 22 in 2021, 2022, and 2023, respectively. During each spring, four treatments were established: (1) weedy fallow, (2) chemical fallow, (3) CC terminated with GLY alone, and (4) CC terminated with GLY + residual herbicide. In the weedy fallow treatment, no CC was planted and no herbicides were applied to control weeds. In the chemical fallow treatment, no CC was planted but the plot area was treated with GLY at 1,260 g ae ha^{-1} plus a premix of acetochlor/atrazine (ACR/ATZ) (Degree Xtra®, Bayer Crop Science) at 1,665/826 g ai ha^{-1} plus dicamba at 560 g ae ha^{-1} at the same time as CC termination. For CC termination, GLY at 1,260 g ae ha^{-1} was used, and the residual herbicide was a premix of ACR/ATZ at 1,665/826 g ai ha^{-1}. All treatments were established in a randomized complete block design with four replications. During 2020 to 2021, weedy fallow treatment was not present and there were only three treatments. The individual plot size was 45-m long and 13-m wide each year. During 2021 to 2022 and 2022 to 2023 experimental years, the initial chemical fallow plot was subdivided into two plots (each 45-m long and 6.5-m wide) to have both weedy fallow and chemical fallow treatments for comparison of weed suppression. A sorghum hybrid 'DKS 38-16' was planted at a seeding rate of 114,855 seeds ha^{-1} in rows spaced 76-cm apart on June 9, June 2, and June 15 during 2021, 2022, and 2023, respectively. All local agronomic practices for grain sorghum production as recommended by Kansas State University were followed (Ciampitti et al. 2022). No herbicides were applied in the grain sorghum growing season. Grain sorghum was harvested on November 4, October 26, and October 19 in 2021, 2022, and 2023, respectively. Data on

https://doi.org/10.1017/wsc.2024.100

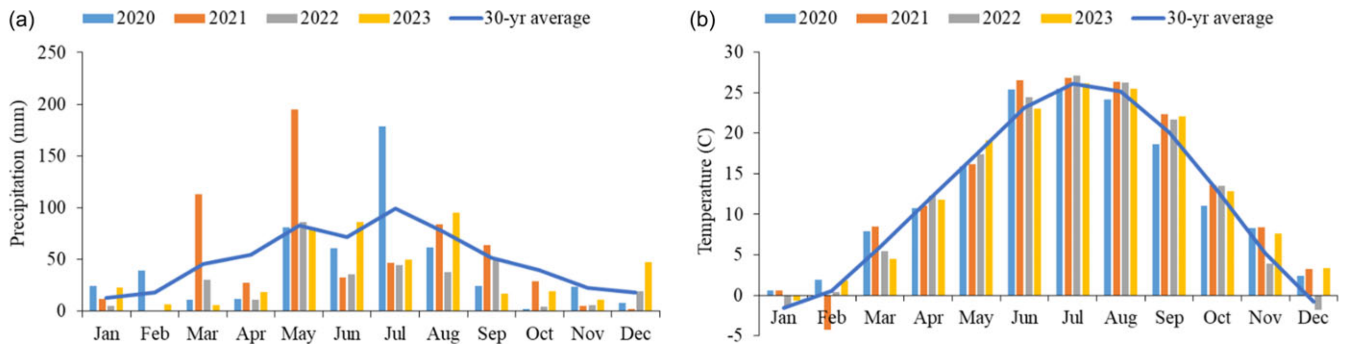

Figure 1. Total monthly precipitation (mm) and average monthly air temperature (C) from 2020 to 2023 growing seasons at Kansas State University Agricultural Research Center near Hays, KS.

monthly precipitation and air temperature over the 3-yr study period were obtained from the Kansas State University Mesonet weather station (https://mesonet.k-state.edu) located approximately 400 m from the study site (38.8495°N, 99.3446°W) (Figure 1).

Cover Crop Biomass, Weed Density, and Weed Biomass

Each year, the aboveground CC shoot biomass was manually harvested from two 1-m^2 quadrats from each plot just before CC termination and oven-dried at 72 C for 4 d to obtain dry biomass. Weed density by species (number of emerged seedlings for each species) was recorded from two randomly placed 1-m^2 quadrats from each plot at CC termination and at monthly intervals until sorghum harvest (except 2021, where data at 90 d after CC termination were not collected) and aboveground weed biomass was manually harvested and oven-dried at 72 C for 4 d to obtain total weed dry biomass. The averages of CC biomass, total weed density, and total weed dry biomass from the two quadrats in each plot at each time were used in the data analysis. The weed species composition was characterized by calculating the relative abundance of each species in each plot using the method described by Thomas (1985) and used by Obour et al. (2022a). Relative abundance was determined using Equation 1. Relative density and relative frequency were calculated using Equations 2 and 3, respectively.

$$\text{Relative abundance} = \frac{\text{Relative density} + \text{relative frequency}}{2} \quad (1)$$

$$\text{Relative density} = \left[\frac{\text{Number of plants for each species within the quadrat per plot}}{\text{Total number of plants in that sampled quadrat}}\right] \times 100 \quad (2)$$

$$\text{Relative frequency} = \left[\frac{\text{Proportion of quadrats in which the species was present in a plot}}{\text{Frequency of all species in that sampled quadrat}}\right] \times 100 \quad (3)$$

Volumetric Water Content and Grain Sorghum Yield

The CC effect on soil water content at grain sorghum planting was determined gravimetrically in 30-cm increments up to 150-cm depth. Two soil cores were taken from each plot using a hydraulic probe (Giddings Machine Company, Windsor, CO, USA) in June 2021 and 2023 before sorghum planting. During 2022, the soil samples were not collected. Soil sample portions from each 30-cm depth were weighed fresh and then dried at 105 C for 4 d to calculate bulk density by dividing the mass of oven-dried soil by the volume of the core. Gravimetric water content was calculated using Equation 4.

$$\text{Gravimetric water content} = \left[\frac{\text{Wet soil weight} - \text{dry soil weight}}{\text{Dry soil weight}}\right] \quad (4)$$

Data from both soil cores were averaged to obtain a single soil water measurement that was converted to volumetric water content by multiplying it with measured bulk density at each sampling depth. Data for volumetric water content were averaged for both CC treatments, as both treatments were the same before termination. Grain sorghum yield was recorded by harvesting each whole plot using a Massey Ferguson 8XP small-plot combine harvester (Massey Ferguson, Duluth, GA, USA) and was adjusted to 13.5% moisture content.

Economic Analyses

Gross returns were calculated by multiplying the grain sorghum yield and the price of sorghum grain. Net returns were calculated as gross returns minus total variable costs for each treatment for each year. Fixed costs were ignored in this analysis, as they were assumed to be consistent across treatments. Four-year average custom rate values published by Kansas State University Land Use Survey Program and the Kansas Department of Agriculture (AgManager 2022) were used for current field operations and input costs. Total variable cost was calculated by adding all the expenses for planting (CC and sorghum), inputs (fertilizer, herbicides, etc., and their application costs), and harvesting. Grain sorghum price for each experimental year was taken from the U.S. Department of Agriculture–Economic Research Service market reports (USDA-ERS 2023). Prices for grain sorghum were calculated on a per kilogram basis and ranged from US$0.20 to US $0.24. All costs and revenue were calculated in U.S. dollars per hectare.

Statistical Analyses

Data were tested for homogeneity of variance and normality of the residuals using the PROC UNIVARIATE procedure in SAS v. 9.3 (SAS Institute, Cary, NC, USA). Data for total weed density and total dry biomass were log transformed to improve the normality of the residuals and homogeneity of variance; however, back-

https://doi.org/10.1017/wsc.2024.100

Table 1. Total weed density and mean relative abundance of weed species observed in the cover crop (CC) treatments at 0 to 120 d after CC termination (DATe) in 2021 at Kansas State University Agricultural Research Center near Hays, KS[a].

		Mean relative abundance			
Treatments[b]	Total weed density	*Bassia scoparia*	*Amaranthus palmeri*	*Hibiscus trionum*	*Tribulus terrestris*
	plants m^{-2}	%			
At 0 DATe					
Chemical fallow	43 a	43	41	16	0
CC + GLY	6 b	0	100	0	0
CC + GLY + ACR/ATZ	4 b	0	100	0	0
At 30 DATe					
Chemical fallow	10 a	38	50	4	8
CC + GLY	10 a	12	69	0	19
CC + GLY + ACR/ATZ	6 a	11	53	8	28
At 60 DATe					
Chemical fallow	9 a	24	70	0	6
CC + GLY	12 a	10	90	0	0
CC + GLY + ACR/ATZ	3 b	10	90	0	0
At 120 DATe					
Chemical fallow	4 a	50	50	0	0
CC + GLY	5 a	29	71	0	0
CC + GLY + ACR/ATZ	2 b	39	61	0	0

[a]Means followed by the same letter within a column at each timing are not different according to Fisher's protected LSD at P < 0.05.
[b]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Cover crop was terminated on May 13, 2021.

transformed data were presented with mean separation based on the transformed data, whereas the rest of the data met both ANOVA assumptions. All data for CC biomass, total weed density, and total weed dry biomass at each time, volumetric water content, grain yield, and net returns were subjected to ANOVA using the PROC MIXED procedure. For CC biomass data, year was considered as fixed effect and replication was considered as random effect. For total weed density and total weed dry biomass data, CC treatment, year, monthly timing, and their interactions were considered as fixed effects, whereas replication and their interactions were considered as random effects. Repeated measures accounted for monthly timing. For volumetric water content, the CC treatment, year, soil depth, and their interactions were considered as fixed effects, whereas replications and their interactions were considered as random effects. For data on grain sorghum yield and net returns, the CC treatment, year, and their interactions were considered as fixed effects, whereas replication and their interactions were considered as random effects. Data for total weed density, total weed dry biomass, volumetric water content, grain sorghum yield, and net returns were analyzed separately for each year because of significant year by treatment interaction ($P < 0.01$). Treatment by monthly evaluation interaction for total weed density and total weed dry biomass was significant ($P < 0.001$); therefore, data were sorted by monthly evaluation timings using PROC SORT, with monthly evaluations treated as a repeated measure. Treatment means were separated using Fisher's protected LSD test ($P < 0.05$). The grain sorghum yields were low because of drought conditions during the study period; therefore, a sensitivity analysis was conducted to obtain net returns to possible grain sorghum yield (700 to 7,400 kg ha^{-1}) and prices (US$0.09 kg^{-1} to US$0.24 kg^{-1}) in the region.

Results and Discussion

Variable precipitation amount and frequency were observed at KSU-ARCH during the experimental periods 2020 to 2021, 2021 to 2022, and 2022 to 2023 (Figure 1). The total amount of precipitation received during the CC growing season (September to May) in 2020 to 2021, 2021 to 2022 and 2022 to 2023 was 217, 99, and 130 mm, respectively (Figure 1). The 30-yr average precipitation from September to May in the region is 347 mm (Figure 1). No difference was recorded in aboveground CC dry biomass at the time of termination across the years, which was 1,520, 1,130, and 1,470 kg ha^{-1} in 2021, 2022, and 2023, respectively, with an average of 1,370 ± 123 kg ha^{-1}. During the sorghum growing season (June through October), the total precipitation amount was 256, 171, and 237 mm in 2021, 2022, and 2023, respectively (Figure 1). The 30-yr average precipitation from June to October in the region is 341 mm (Figure 1).

Total Weed Density and Weed Dry Biomass

Across 3 yr, four summer annual broadleaf weed species were observed at the study site, including *B. scoparia*, *A. palmeri*, Venice mallow (*Hibiscus trionum* L.), and puncturevine (*Tribulus terrestris* L.). Based on the relative abundance, *B. scoparia* and *A. palmeri* were the dominant weed species across 3 yr.

The 2021 Growing Season

Amaranthus palmeri was the most dominant weed species, with a mean relative abundance of >40% across treatments at all monthly evaluation timings (Table 1). Before termination (0 d after termination [DATe]), CCs reduced the total weed density by 86% to 95% compared with chemical fallow (no herbicide was applied in chemical fallow at this time) (Table 1). However, an application of GLY plus ACR/ATZ plus dicamba in chemical fallow at the time of CC termination reduced weed density at later evaluation timings. Total weed density at 60 DATe was dominated by *A. palmeri* (relative abundance = 90%) and was significantly greater (approximately 4 times) following the CC terminated with GLY only compared with the CC terminated with GLY plus ACR/ATZ (Table 1). This would be due to a lack of residual herbicide and not enough CC residue to suppress the emerging *A. palmeri* seedlings. At the time of grain sorghum harvest (120 DATe), CC terminated with GLY plus ACR/ATZ reduced the total weed density by 50%

https://doi.org/10.1017/wsc.2024.100

Table 2. Total weed dry biomass in the cover crop (CC) treatments at 0, 30, 60, 90, and 120 d after CC termination during 2021 to 2023 growing seasons at Kansas State University Agricultural Research Center near Hays, KS.

Treatments[a]	Total weed dry biomass[b]													
	2021				2022					2023				
	0	30	60	120	0	30	60	90	120	0	30	60	90	120
	$g\ m^{-2}$													
Weedy fallow	–	–	–	–	34 a	107 a	118 a	193 a	263 a	12 a	115 a	388 a	1430 a	1624 a
Chemical fallow	15 a	72 a	139 a	147 a	30 a	2 c	3 bc	6 c	12 c	9 a	5 c	13 c	345 bc	560 bc
CC + GLY	1 b	41 a	69 b	85 b	1 b	6 b	15 b	41 b	97 b	0 b	44 b	167 b	513 b	1258 ab
CC + GLY + ACR/ATZ	1 b	24 a	48 b	47 b	1 b	1 c	1 c	3 c	10 c	0 b	0 d	7 d	236 c	278 c

[a]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine.
[b]Means followed by the same letter within a column are not different according to Fisher's protected LSD at $P < 0.05$.

compared with chemical fallow (Table 1). Consistent with total weed density, CC at termination reduced the total weed dry biomass by 93% compared with chemical fallow (Table 2). The CC terminated with GLY only and with GLY plus ACR/ATZ reduced the total weed dry biomass by 50% to 65% and 42% to 68% at 60 to 120 DATe, respectively, compared with chemical fallow. It is interesting to note that no differences were observed in total weed density between chemical fallow and CC terminated with GLY only at 120 DATe; however, the same CC treatment significantly reduced the total weed dry biomass by 42% compared with chemical fallow, indicating the suppressive effect of CCs on weed growth that would ultimately reduce the weed seed production (Baraibar et al. 2018).

The 2022 Growing Season

Mean relative abundance was 46% to 56% for *B. scoparia*, 0% to 21% for *A. palmeri*, and 29% to 49% for *H. trionum* before CC termination (Table 3). Similar to 2021, the CC at termination reduced the total weed density by 90% to 93% compared with weedy fallow. At 30 DATe, the CC terminated with GLY plus ACR/ATZ reduced the total weed density by 92% compared with chemical fallow and 96% compared with weedy fallow. At 60 DATe, the mean relative abundance was 41% to 75% for *B. scoparia*, 11% to 53% for *A. palmeri*, and 12% to 31% for *H. trionum* among all treatments. The CC termination with GLY only treatment did not produce enough CC biomass to suppress emerging weed seedlings and resulted in 21 more weed seedlings m^{-2} than the CC terminated with GLY plus ACR/ATZ at 60 DATe (Table 3). These results indicate the importance of residual herbicide with CCs to achieve effective weed suppression. Our findings are consistent with those of Wiggins et al. (2016), who also concluded that CC alone was not enough for season-long control of GR *A. palmeri* and suggested integrating residual herbicides to complement the suppressive effect of CCs. In the current study, total weed density did not differ between chemical fallow and CC terminated with GLY plus ACR/ATZ treatments at 120 DATe; however, weed density was nearly 95% lower in CC terminated with GLY plus ACR/ATZ compared with weedy fallow and CC terminated with GLY only (Table 3). These results are consistent with those of Obour et al. (2022a), who previously reported 82% reduction in total weed density with spring-planted CC mixture (oat–triticale–pea) compared with weedy fallow. Petrosino et al. (2015) also reported a 78% to 94% reduction in *B. scoparia* density with fall-planted CCs (triticale/triticale–hairy vetch [*Vicia villosa* Roth] mixture) compared with chemical fallow in winter wheat–fallow rotation. Similar to weed density reduction, CCs at the time of termination provided >95% total weed dry biomass reduction compared with weedy fallow (Table 2). The presence of CCs reduces the sunlight penetration to the ground for weed seed germination and also reduces weeds' competitive ability for other resources, thereby resulting in lower weed biomass (Silva and Bagavathiannan 2023; Webster et al. 2016). The CC terminated with GLY only reduced total weed dry biomass by 94% at 30 DATe and 63% at 120 DATe compared with weedy fallow. In contrast, the CC terminated with GLY plus ACR/ATZ reduced total weed dry biomass by >95% compared with weedy fallow throughout the sorghum growing season (Table 2). These results indicate the need of residual herbicide in combination with CCs for a season-long weed control in grain sorghum. These results are consistent with those of Whalen et al. (2020), who previously reported that fall-planted CCs, including Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.)

https://doi.org/10.1017/wsc.2024.100

Table 3. Total weed density and mean relative abundance of weed species observed in the cover crop (CC) treatments at 0 to 120 d after CC termination (DATe) in 2022 at Kansas State University Agricultural Research Center near Hays, KS.[a]

Treatments[b]	Total weed density	Mean relative abundance			
		Bassia scoparia	*Amaranthus palmeri*	*Hibiscus trionum*	*Tribulus terrestris*
	plants m^{-2}	%			
At 0 DATe					
Weedy fallow	58 a	46	21	33	0
Chemical fallow	47 a	53	18	29	0
CC + GLY	4 b	51	0	49	0
CC + GLY + ACR/ATZ	6 b	56	6	38	0
At 30 DATe					
Weedy fallow	27 ab	56	36	6	2
Chemical fallow	13 b	62	32	6	0
CC + GLY	37 a	41	54	5	0
CC + GLY + ACR/ATZ	1 c	62	38	0	0
At 60 DATe					
Weedy fallow	28 a	58	11	31	0
Chemical fallow	6 bc	47	53	0	0
CC + GLY	22 ab	41	47	12	0
CC + GLY + ACR/ATZ	1 c	75	25	0	0
At 90 DATe					
Weedy fallow	27 a	80	20	0	0
Chemical fallow	1 b	100	0	0	0
CC + GLY	13 a	43	57	0	0
CC + GLY + ACR/ATZ	1 b	87	13	0	0
At 120 DATe					
Weedy fallow	19 a	93	7	0	0
Chemical fallow	2 b	91	9	0	0
CC + GLY	21 a	46	54	0	0
CC + GLY + ACR/ATZ	1 b	89	11	0	0

[a]Means followed by the same letter within a column at each timing are not different according to Fisher's protected LSD at $P < 0.05$.
[b]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Cover crop was terminated on May 11, 2022.

Husnot], oat, and winter wheat provided 38% to 48% weed control without a residual herbicide; however, the control ranged from 72% to 85% under CCs with a residual herbicide (sulfentrazone plus chlorimuron) application.

The 2023 Growing Season

No weed emergence was observed under both CC treatments at the time of termination (Table 4). In addition, no weed emergence was observed in the CC terminated with GLY plus ACR/ATZ treatment at 30 DATe. In contrast, a greater weed density of 91 plants m^{-2} with a relative abundance of 70% for *A. palmeri* and 30% for *B. scoparia* was recorded in the CC terminated with GLY only treatment at 30 DATe (Table 4). This increase in *A. palmeri* and *B. scoparia* densities under CC terminated with GLY only was probably due to more precipitation within 30 DATe (78 mm, 33% of total precipitation received during the entire sorghum growing season), and lack of any residual herbicide applied at CC termination. Treatments including the CC terminated with GLY plus ACR/ATZ and chemical fallow, reduced the total weed density by 70% compared with weedy fallow at 90 DATe. Chemical fallow and CC terminated with GLY plus ACR/ATZ had far fewer weeds (7 to 8 plants m^{-2}) compared with weedy fallow (54 plants m^{-2} with 73% relative abundance of *A. palmeri*) at 120 DATe (Table 4). Similar to weed density reduction, CC terminated with GLY plus ACR/ATZ resulted in 98%, 46%, and 57% total weed dry biomass reduction compared with weedy fallow, chemical fallow, and CC terminated with GLY only, respectively, at 60 DATe (Table 2). At 120 DATe, the CC terminated with GLY plus ACR/ATZ and chemical fallow reduced the total weed dry biomass by 83% and 65% compared with weedy fallow. Our results are consistent with those of Petrosino et al. (2015), who also reported that fall-planted triticale and a triticale–hairy vetch mixture reduced *B. scoparia* density by 78% and 94%, respectively, and biomass up to 98% compared with chemical fallow. Compared with chemical fallow, the CC terminated with GLY plus ACR/ATZ provided 5% to 18% greater reduction in total weed dry biomass during the entire grain sorghum growing season (Table 2). Wiggins et al. (2016) reported that CCs including cereal rye (*Secale cereale* L.), hairy vetch, crimson clover (*Trifolium incarnatum* L.), or winter wheat had less than 65% control of *A. palmeri*, whereas the same CCs in combination with preemergence-applied acetochlor or fluometuron resulted in >87% control of *A. palmeri*.

Volumetric Water Content and Grain Sorghum Yield

The soil water content at sorghum planting is directly related to grain yields in the dryland region (Holman et al. 2023; Obour et al. 2022b). In 2021, fall-planted CCs did not affect volumetric water content at grain sorghum planting compared with chemical fallow across all soil depths (Figure 2). This is likely due to greater precipitation at pre- and post-CC termination time (Figure 1). The precipitation received closer to termination or posttermination of CCs likely recharged the soil profile, thereby diminishing the effects of the growing CCs on water availability. Furthermore, the CC residue likely decreased soil water evaporation, increasing moisture storage (Holman et al. 2020, 2021). In contrast, fall-planted CCs did reduce the volumetric water content at grain sorghum planting compared with chemical fallow at 0- to 30-cm and 30- to 60-cm depths in the 2023 growing season (Figure 2). No differences in the water content were observed between CC and

https://doi.org/10.1017/wsc.2024.100

Table 4. Total weed density and mean relative abundance of weed species observed in the cover crop (CC) treatments at 0 to 120 d after CC termination (DATe) in 2023 at Kansas State University Agricultural Research Center near Hays, KS.[a]

Treatments[b]	Total weed density	Mean relative abundance			
		Bassia scoparia	*Amaranthus palmeri*	*Hibiscus trionum*	*Tribulus terrestris*
	plants m^{-2}	%			
At 0 DATe					
Weedy fallow	32 a	100	0	0	0
Chemical fallow	28 a	100	0	0	0
CC + GLY	0 b	0	0	0	0
CC + GLY + ACR/ATZ	0 b	0	0	0	0
At 30 DATe					
Weedy fallow	142 a	37	61	2	1
Chemical fallow	12 b	0	100	0	0
CC + GLY	91 a	30	70	0	0
CC + GLY + ACR/ATZ	0 b	0	0	0	0
At 60 DATe					
Weedy fallow	22 a	13	87	0	0
Chemical fallow	7 b	0	100	0	0
CC + GLY	15 ab	25	75	0	0
CC + GLY + ACR/ATZ	1 b	0	100	0	0
At 90 DATe					
Weedy fallow	30 a	16	84	0	0
Chemical fallow	9 b	10	90	0	0
CC + GLY	20 ab	15	85	0	0
CC + GLY + ACR/ATZ	9 b	0	100	0	0
At 120 DATe					
Weedy fallow	54 a	27	73	0	0
Chemical fallow	8 b	19	81	0	0
CC + GLY	22 ab	27	73	0	0
CC + GLY + ACR/ATZ	7 b	0	100	0	0

[a]Means followed by the same letter within a column at each timing are not different according to Fisher's protected LSD at $P < 0.05$.
[b]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Cover crop was terminated on May 22, 2023.

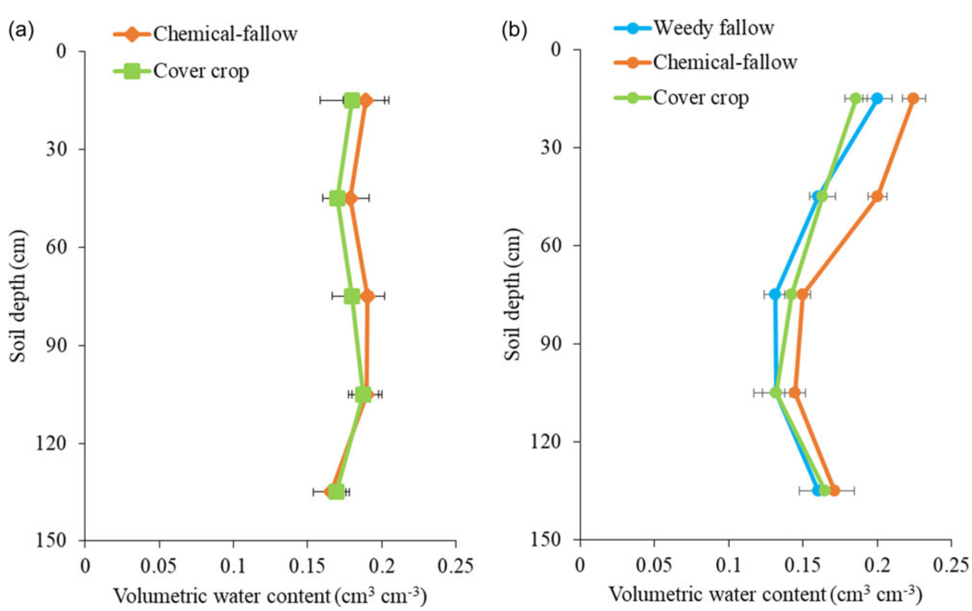

Figure 2. Fall-planted cover crop effect on volumetric water content at grain sorghum planting in 2021 (A) and 2023 (B) growing seasons at Kansas State University Agricultural Research Center near Hays, KS. Error bars represent standard error of the mean.

chemical fallow treatments at greater soil depths. Similar to CC, the weedy fallow treatment also resulted in relatively low volumetric water content (0.16 to 0.20 $cm^3\ cm^{-3}$) up to 60-cm soil depth compared with chemical fallow (0.20 to 0.22 $cm^3\ cm^{-3}$), indicating soil water depletion by weeds. Holman et al. (2021) reported no difference in the available soil moisture at time of wheat planting between fallow and spring-planted CCs left standing during the fallow phase of W-S-F rotation.

No differences in grain sorghum yields were observed between chemical fallow (1,876 kg ha^{-1}) and CC terminated with GLY plus ACR/ATZ (2,072 kg ha^{-1}) in 2021, and the lowest grain yield (1,456 kg ha^{-1}) was recorded under CC terminated with GLY only

https://doi.org/10.1017/wsc.2024.100

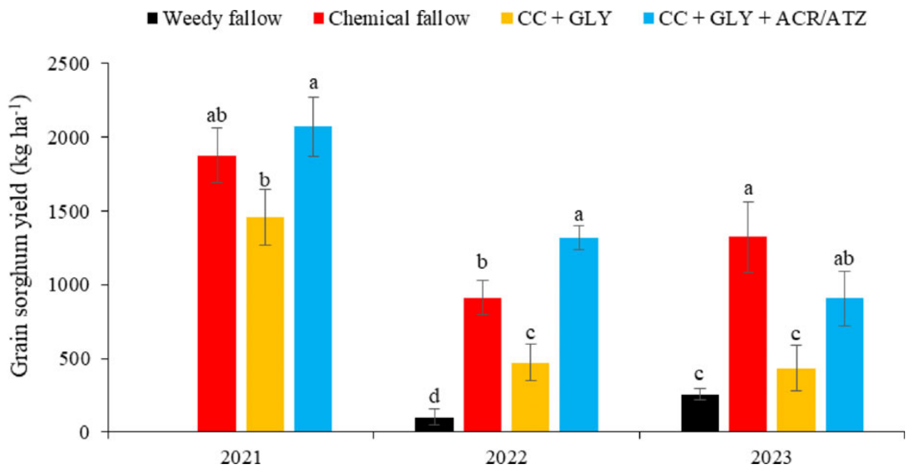

Figure 3. Fall-planted cover crop (CC) effect on grain sorghum yield over three growing seasons at Kansas State University Agricultural Research Center near Hays, KS. CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Bars followed by the same letter within the year are not significantly different according to Fisher's protected LSD test at $P < 0.05$. Error bars represent standard error of the mean.

(Figure 3). During the 2022 growing season, the overall grain sorghum yield was low due to lower season precipitation (171 mm) compared with 2021 (256 mm). Effective weed suppression (both density and total weed dry biomass) achieved with the CC terminated with GLY plus ACR/ATZ resulted in a greater grain sorghum yield (1,319 kg ha^{-1}) compared with chemical fallow (912 kg ha^{-1}). The CC termination with GLY only suppressed weeds up to 30 DATe (Table 3), and *A. palmeri* emerging after 30 DATe reduced the grain sorghum yield (472 kg ha^{-1}) (Figure 3). The total precipitation during the 2023 sorghum growing season was 237 mm, but the majority of this precipitation occurred in May and June. There was moisture stress at the boot stage of grain sorghum in September (only 17 mm of rainfall) that resulted in reduced grain yield (432 to 1,323 kg ha^{-1}) (Figures 1 and 3). No difference in grain sorghum yield was observed between chemical fallow and CC terminated with GLY plus ACR/ATZ. The precipitation events in May and June resulted in the emergence of several cohorts of *A. palmeri* following the CC terminated with GLY only that resulted in competition with grain sorghum and reduced yield (432 kg ha^{-1}) compared with chemical fallow and CC terminated with GLY plus ACR/ATZ (Figure 3). Based on the precipitation amount and frequency, fall-planted CC had a variable impact on grain sorghum yield. Nielsen et al. (2016) reported a 10% reduction in winter wheat yield following a CC compared with fallow in the W-S-F rotation in the semiarid CGP. Holman et al. (2022) reported that spring-planted CC (oat grain) after sorghum harvesting in the fallow phase of W-S-F rotation resulted in 29% less available soil moisture at sorghum planting and did not affect the wheat and sorghum yield compared with fallow. In south-central Kansas, Janke et al. (2002) reported no differences in grain sorghum yield following CCs (hairy vetch–winter pea) in winter wheat–grain sorghum rotation compared with no CC in years with good rainfall; however, during years with low rainfall, CC establishment was poor, and grain sorghum yield was reduced because of water use by the CC compared with no CC treatment. Eash et al. (2021) also reported that CCs had no impact on subsequent crop yields in a very-low-yielding environment in Colorado, mainly due to low CC biomass. In this study, the chemical fallow treatment provided more available soil water in 1 of 2 yr compared with CC treatments before sorghum planting. However, this did not translate into a higher grain yield as long as the residual herbicide ACR/ATZ was applied with GLY at CC termination.

Economic Analyses

During 2021, the CC terminated with GLY plus ACR/ATZ resulted in greater gross returns of US$497 ha^{-1} compared with US$450 ha^{-1} following chemical fallow (Table 5). This was because of better weed control and greater sorghum yield under CC terminated with GLY plus ACR/ATZ compared with chemical fallow. However, CC seed and planting costs decreased net returns. Chemical fallow had the highest net returns by US$55 ha^{-1} compared with CC terminated with GLY plus ACR/ATZ. Net returns were negative under CC terminated with GLY only because of lower grain sorghum yield than chemical fallow and CC terminated with GLY plus ACR/ATZ.

Similar to 2021, CC terminated with GLY plus ACR/ATZ had greater gross returns (US$317 ha^{-1}), followed by chemical fallow (US$219 ha^{-1}) and CC terminated with GLY only (US$113 ha^{-1}) in 2022 (Table 6). Weedy fallow had the lowest gross returns of US $24 ha^{-1}. The net returns for 2022 were negative for all treatments because of low grain sorghum yield, which suggests that gross return from grain sorghum was not enough to cover the variable input costs. However, net returns for CC terminated with GLY plus ACR/ATZ and chemical fallow were not significantly different (Table 6).

In 2023, the lower grain sorghum yield in CC terminated with GLY plus ACR/ATZ resulted in a lower gross return of US$181 ha^{-1} compared with US$265 ha^{-1} in chemical fallow (Table 7). Similar to 2022, the net returns in 2023 were also negative for all treatments. Chemical fallow had less negative net returns (−US$65 ha^{-1}) compared with other treatments (−US$138 to −US$275 ha^{-1}). The cost of CC seed and planting increased the variable cost for both CC treatments and thus resulted in greater negative net returns. Janke et al. (2002) also reported lower net returns with fall-planted CCs (hairy vetch–winter pea) before grain sorghum because of lower grain sorghum yield in the years with low rainfall. Obour et al. (2022a) also reported that integrating CCs in the dryland cropping system resulted in negative net returns compared with fallow. These results indicate that growing CCs only for weed suppression was not profitable compared with chemical fallow.

Based on the sensitivity analysis, a minimum grain sorghum yield of 2,000 kg ha^{-1} was needed to obtain a positive net return (US$8 ha^{-1}) following CC terminated with GLY plus ACR/ATZ at the average grain sorghum price (US$0.22 kg^{-1}) during the

https://doi.org/10.1017/wsc.2024.100

Table 5. Economic analyses of grain sorghum after fall-planted cover crop in 2021 growing season at Kansas State University Agricultural Research Center near Hays, KS

Variables	Treatments[a]		
	Chemical fallow	CC + GLY	CC + GLY + ACR/ATZ
	US$ ha^{-1}		
Grain sorghum yield[b]	1,877.00	1,456.00	2,072.00
Grain sorghum price[c]	0.24	0.24	0.24
Revenue from grain sorghum	450.48	349.44	497.28
Gross returns	450.48	349.44	497.28
Variable input costs			
Cover crop seed	0.00	95.70	95.70
Cover crop planting	0.00	37.10	37.10
Grain sorghum seed	30.38	30.38	30.38
Grain sorghum planting	32.10	32.10	32.10
Fertilizer with application cost	66.69	66.69	66.69
Herbicide	126.91	25.61	95.72
Herbicide application cost	13.61	13.61	13.61
Grain sorghum harvesting	60.32	60.32	60.32
Total variable cost	330.01	361.51	431.62
Net returns	120.47 a	−12.07 b	65.66 b

[a]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Means followed by the same letter among treatments are not different according to Fisher's protected LSD at $P < 0.05$.
[b]Grain sorghum yield is in kg ha^{-1}.
[c]Grain sorghum price is in US$ kg^{-1}.

Table 6. Economic analyses of grain sorghum after fall-planted cover crop in 2022 growing season at Kansas State University Agricultural Research Center near Hays, KS

Variables	Treatments[a]			
	Weedy fallow	Chemical fallow	CC + GLY	CC + GLY + ACR/ATZ
	US$ ha^{-1}			
Grain sorghum yield[b]	101.00	912.00	472.00	1,319.00
Grain sorghum price[c]	0.24	0.24	0.24	0.24
Revenue from grain sorghum	24.24	218.88	113.28	316.56
Gross returns	24.24	218.88	113.28	316.56
Variable input costs				
Cover crop seed	0.00	0.00	95.70	95.70
Cover crop planting	0.00	0.00	37.10	37.10
Grain sorghum seed	30.38	30.38	30.38	30.38
Grain sorghum planting	32.10	32.10	32.10	32.10
Fertilizer with application cost	66.69	66.69	66.69	66.69
Herbicide	0.00	126.91	25.61	95.72
Herbicide application cost	0.00	13.61	13.61	13.61
Grain sorghum harvesting	60.32	60.32	60.32	60.32
Total variable cost	189.49	330.01	361.51	431.62
Net returns	−165.25 b	−111.13 a	−248.23 b	−115.06 a

[a]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Means followed by the same letter among treatments are not different according to Fisher's protected LSD at $P < 0.05$.
[b]Grain sorghum yield is in kg ha^{-1}.
[c]Grain sorghum price is in US$ kg^{-1}.

3-yr study period (Table 8). In the present study, the average grain sorghum yield was low (786 to 1,432 kg ha^{-1}). The estimated average grain sorghum yield in western Kansas ranged from 3,800 to 5,000 kg ha^{-1} (Ciampitti and Carcedo 2022); therefore, based on this yield scenario, the expected net returns would be US$404 ha^{-1} to US$668 ha^{-1} following CC terminated with GLY plus ACR/ATZ and US$506 ha^{-1} to US$770 ha^{-1} following chemical fallow at US$0.22 kg^{-1} sorghum price (Table 8). At the lowest grain sorghum price (US$0.09 ha^{-1}), a grain yield of 5,000 kg ha^{-1} was expected to cover the cost of CC seed and planting and obtain positive net returns (US$18 ha^{-1}) under CC terminated with GLY plus ACR/ATZ; however, following chemical fallow, a lower yield of 3,800 kg ha^{-1} was sufficient to obtain positive net returns (US$12 ha^{-1}) (Table 8). It is important to note that in the present study, greater weed control was observed following CC terminated with GLY plus ACR/ATZ over the grain sorghum growing season compared with chemical fallow. The postemergence herbicides were not applied in chemical fallow treatment, but farmers generally apply post-emergence herbicides to control later-emerged weeds, and this application would increase the cost of production and decrease the net returns following chemical fallow as compared with CC treatment. At the highest sorghum price (US$0.24 ha^{-1}), CC terminated with GLY plus ACR/ATZ would result in US$48 ha^{-1} net returns at only 2,000

https://doi.org/10.1017/wsc.2024.100

Table 7. Economic analyses of grain sorghum after fall-planted cover crop in 2023 growing season at Kansas State University Agricultural Research Center near Hays, KS

Variables	Treatments[a]			
	Weedy fallow	Chemical fallow	CC + GLY	CC + GLY + ACR/ATZ
	US$ ha^{-1}			
Grain sorghum yield[b]	257.00	1,323.00	432.00	905.00
Grain sorghum price[c]	0.20	0.20	0.20	0.20
Revenue from grain sorghum	51.40	264.60	86.40	181.00
Gross returns	51.40	264.60	86.40	181.00
Variable input costs				
Cover crop seed	0.00	0.00	95.70	95.70
Cover crop planting	0.00	0.00	37.10	37.10
Grain sorghum seed	30.38	30.38	30.38	30.38
Grain sorghum planting	32.10	32.10	32.10	32.10
Fertilizer with application cost	66.69	66.69	66.69	66.69
Herbicide	0.00	126.91	25.61	95.72
Herbicide application cost	0.00	13.61	13.61	13.61
Grain sorghum harvesting	60.32	60.32	60.32	60.32
Total variable cost	189.49	330.01	361.51	431.62
Net returns	−138.09 b	−65.41 a	−275.11 c	−250.62 c

[a]CC + GLY, cover crop terminated with glyphosate only; CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine. Means followed by the same letter among treatments are not different according to Fisher's protected LSD at $P < 0.05$.
[b]Grain sorghum yield is in kg ha^{-1}.
[c]Grain sorghum price is in US$ kg^{-1}.

Table 8. Net returns to possible grain sorghum yield (700 to 7,400 kg ha^{-1}) and prices (US$0.09 kg^{-1} to US$0.24 kg^{-1}) in the Central Great Plains region

Grain sorghum yield	Net returns													
	Chemical fallow							CC + GLY +ACR/ATZ[a]						
	0.09	0.12	0.16	0.18	0.20	0.22	0.24	0.09	0.12	0.16	0.18	0.20	0.22	0.24
kg ha^{-1}	$ ha^{-1}													
700	−267	−246	−218	−204	−190	−176	−162	−369	−348	−320	−306	−292	−278	−264
1,400	−204	−162	−106	−78	−50	−22	6	−306	−264	−208	−180	−152	−124	−96
2,000	−150	−90	−10	30	70	110	150	−252	−192	−112	−72	−32	8	48
2,600	−96	−18	86	138	190	242	294	−198	−120	−16	36	88	140	192
3,200	−42	54	182	246	310	374	438	−144	−48	80	144	208	272	336
3,800	12	126	278	354	430	506	582	−90	24	176	252	328	404	480
4,400	66	198	374	462	550	638	726	−36	96	272	360	448	536	624
5,000	120	270	470	570	670	770	870	18	168	368	468	568	668	768
5,600	174	342	566	678	790	902	1,014	72	240	464	576	688	800	912
6,200	228	414	662	786	910	1,034	1,158	126	312	560	684	808	932	1,056
6,800	282	486	758	894	1,030	1,166	1,302	180	384	656	792	928	1,064	1,200
7,400	336	558	854	1,002	1,150	1,298	1,446	234	456	752	900	1,048	1,196	1,344

[a]CC + GLY + ACR/ATZ, cover crop terminated with glyphosate plus a premix of acetochlor/atrazine.

kg ha^{-1} sorghum yield (Table 8). These results indicate the cost of integrating fall-planted CCs in the W-S-F exceeded the benefits of improved weed control.

Results from this 3-yr study indicate that integrating a fall-planted CC mixture after winter wheat harvest and terminating it with GLY in combination with residual herbicide before grain sorghum planting in the W-S-F rotation can provide an effective weed suppression in grain sorghum. Results showed that fall-planted CC terminated with GLY plus ACR/ATZ reduced total weed density by 34% to 81% and total weed biomass by 45% to 73% compared with chemical fallow over the grain sorghum growing season. No sorghum yield penalty was observed after CC terminated with GLY plus ACR/ATZ. However, due to the CC seed and planting costs, lower net returns were recorded in all 3 yr compared with chemical fallow. These results suggest that growing CCs for only weed suppression in the semiarid CGP would not be profitable at current commodity prices. If the CCs were used for hay or forage, then net returns would be increased due to alternative-use income (Holman et al. 2018, 2021, 2022, 2023; Obour et al. 2022a). However, weed control during the sorghum growing season would likely be affected after the CC residue removal from the field. Therefore, future studies should focus on understanding the timing for the removal of CC residue from the field and its interaction with weed control during the grain sorghum growing period.

Acknowledgments. We thank Taylor Lambert and Matthew Vredenburg for their assistance in conducting the field study.

Funding statement. Funding from the NC SARE Graduate Student Grant (GNC22-346) supported this work.

Competing interests. The authors declare no competing interests.

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https://doi.org/10.1017/wsc.2024.100