Weed Science

www.cambridge.org/wsc

Influence of cover crop residue and residual herbicide on emergence dynamics of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in grain sorghum

Research Article

Cite this article: Dhanda S, Kumar V, Dille JA, Obour A, Yeager EA, Holman J (2024). Influence of cover crop residue and residual herbicide on emergence dynamics of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in grain sorghum. Weed Sci. doi: 10.1017/wsc.2024.22

Received: 16 February 2024
Revised: 23 March 2024
Accepted: 29 March 2024

Associate Editor:
Nicholas Basinger, University of Georgia.

Keywords:
Central Great Plains; cover crop residue; cumulative emergence; growing degree days

Corresponding author:
Vipan Kumar; Email: vk364@cornell.edu

Sachin Dhanda[1], Vipan Kumar[2], J. Anita Dille[3], Augustine Obour[4], Elizabeth A. Yeager[5] and Johnathan Holman[6]

[1]Graduate Research Assistant, Kansas State University, Agricultural Research Center, Hays, KS, USA; [2]Associate Professor, Cornell University, School of Integrative Plant Science, Soil and Crop Sciences Section, Ithaca, NY, USA; [3]Professor, Department of Agronomy, Kansas State University, Manhattan, KS, USA; [4]Professor, Kansas State University, Agricultural Research Center, Hays, KS, USA; [5]Associate Professor, Department of Agricultural Economics, Kansas State University, Manhattan, KS, USA and [6]Professor, Kansas State University, Southwest Research and Extension Center, Garden City, KS, USA

Abstract

A field study was conducted from 2020 to 2023 at Kansas State University Agricultural Research Center near Hays, KS, to understand the emergence dynamics and periodicity of glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S. Watson) as influenced by cover crop (CC) residue and residual herbicide in grain sorghum [*Sorghum bicolor* (L.) Moench]. The study site was under a wheat (*Triticum aestivum* L.)–sorghum–fallow rotation with a natural seedbank of GR *A. palmeri*. Treatments included (1) fall-planted CC mixture [winter triticale (×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*])/winter peas (*Pisum sativum* L.)/rapeseed (*Brassica napus* L.)/radish (*Raphanus sativus* L.)] after wheat harvest and terminated at triticale heading stage (next spring before sorghum planting) with glyphosate alone or (2) glyphosate plus acetochlor/atrazine, (3) chemical fallow (no CC but treated with acetochlor/atrazine and dicamba before sorghum planting), and (4) nontreated control (no CC and no herbicide). Results indicated that CC terminated with glyphosate plus acetochlor/atrazine had a delayed and reduced cumulative emergence of GR *A. palmeri* as compared with chemical fallow and CC terminated with glyphosate alone across all 3 yr. Compared with chemical fallow, the CC terminated with glyphosate alone and glyphosate plus acetochlor/atrazine required 66 to 643 and 105 to 1,257 more cumulative growing degree days, respectively, to achieve 90% cumulative emergence of GR *A. palmeri* across all 3 yr. The combined effect of CC residue with glyphosate plus acetochlor/atrazine reduced the total emergence counts of GR *A. palmeri* by 42% to 56% and 82% to 94% as compared with chemical fallow and nontreated control, respectively. These results suggest that fall-planted CC combined with a residual herbicide at termination can be utilized for GR *A. palmeri* suppression in grain sorghum.

Introduction

Grain sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important crop grown in arid and semiarid regions worldwide (Visarada and Aruna 2019). It is a drought-tolerant crop that is productive in moisture-limited environments and is mainly used for food, feed, and fuel (Mundia et al. 2019). Grain sorghum is the fourth-largest crop after corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) in the United States (USDA-NASS 2023). In 2021, it was harvested from 2.63 million ha in the U.S., yielding 11,375 million kg of grain, with Kansas contributing 59% of this production (USDA-NASS 2023). Weeds are a serious production challenge in grain sorghum, and if weeds are not controlled in grain sorghum, U.S. farmers would lose approximately 5,700 million kg of grain sorghum annually valued at approximately US$953 million (Dille et al. 2020). Moore et al. (2004) reported that grain sorghum yield was reduced by 1.8% to 3.5% with one Palmer amaranth (*Amaranthus palmeri* S. Watson) plant in 15 m of sorghum row.

Amaranthus palmeri is the most troublesome broadleaf weed in grain sorghum in the United States (Van Wychen 2020). It is a summer annual C_4 dioecious plant belonging to the Amaranthaceae family. It is native to the southwestern United States and northwestern Mexico and is widely distributed in several countries across Africa, Asia, Europe, North America, and South America (Roberts and Florentine 2022; Sauer 1957). *Amaranthus palmeri* exhibits an extended emergence period, high photosynthetic rate, prolific seed production (up to 600,000 seeds per female plant), high genetic diversity within and among field populations, and ability to

https://doi.org/10.1017/wsc.2024.22 Published online by Cambridge University Press

evolve herbicide resistance (Chahal et al. 2015; Horak and Loughin 2000; Keeley et al. 1987; Ward et al. 2013). Resistance to 10 different herbicide sites of action has been identified in populations of *A. palmeri* (WSSA Groups 2, 3, 4, 5, 6, 9, 10, 14, 15, and 27) (Heap 2023). Multiple herbicide–resistant *A. palmeri* populations have been reported in the Central Great Plains (CGP) region, including Kansas (Chahal et al. 2015; Heap 2023; Jhala et al. 2014; Kumar et al. 2019b, 2020a).

Several studies have demonstrated the importance of different management strategies that can impact *A. palmeri* emergence. For instance, Chahal et al. (2021) reported that an early-season shallow tillage (10-cm depth) in the first week of June increased cumulative emergence of *A. palmeri* (1,674 plants m^{-2}) in the fallow field as compared with mid-season (mid-June) and late-season (first week of July) tillage operations (533 to 869 plants m^{-2}) in south-central Nebraska. DeVore et al. (2013) reported a 94% reduction of glyphosate-resistant (GR) *A. palmeri* emergence when cereal rye (*Secale cereale* L.) cover crop (CC) was used in combination with deep tillage (30-cm depth) before soybean compared with no deep tillage or cereal rye CC in Arkansas. Palhano et al. (2018) reported that cereal rye CC reduced *A. palmeri* emergence by 83% in cotton (*Gossypium hirsutum* L.) as compared with no CC in Arkansas. In a greenhouse study, Teasdale et al. (2005) found that hairy vetch (*Vicia villosa* Roth.) residue (500 g m^{-2}) and metolachlor (10 g ha^{-1}) had a synergistic effect and reduced smooth pigweed (*Amaranthus hybridus* L.) emergence by 86% compared with no metolachlor or no hairy vetch residue. Perkins et al. (2021) reported that a CC mixture of cereal rye and hairy vetch in combination with pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, or acetochlor delayed *A. palmeri* emergence by 27 to 34 d in soybean compared with CC with no residual herbicides. Similarly, Liu et al. (2022) documented a differential emergence pattern and periodicity among *A. palmeri* populations from Kansas, Nebraska, Colorado, Oklahoma, and Texas in a no-tillage (NT) field in western Kansas.

Winter wheat–sorghum–fallow (WSF) is a dominant crop rotation in the semiarid CGP region, where producers generally rely on postemergence herbicides for weed control during the fallow period (Holman et al. 2022; Kumar et al. 2019a, 2019b). In this 3-yr crop rotation, a fallow period of about 10 mo occurs after the winter wheat harvest and before grain sorghum planting in the following year (Kumar et al. 2020b). During this fallow period, late-season infestation of *A. palmeri* in postharvest wheat stubble can produce a significant number of seeds (58,300 seeds m^{-2} if left uncontrolled), contributing to the soil seedbank for infestations in the subsequent summer crops, including grain sorghum (Kumar et al. 2021). In these NT-based cropping systems, the majority of *A. palmeri* seeds are concentrated on the soil surface and can emerge easily (Buhler 1992; Buhler et al. 1996; Cardina et al. 1991; Oryokot et al. 1997). Replacing a portion of this fallow period with a CC may provide effective weed suppression in NT cropping systems of the CGP region (Kumar et al. 2020b). However, limited information exists on the combined effect of CC residue and residual herbicides on emergence of *A. palmeri* in NT grain sorghum in this dryland region. The main objective of this study was to determine the effect of fall-planted CC after wheat harvest and terminated in the following spring with glyphosate alone or glyphosate with acetochlor/atrazine on (1) emergence periodicity and (2) emergence pattern of GR *A. palmeri* in NT dryland grain sorghum.

Materials and Methods

Field Experiment

A field study was conducted at Kansas State University Agricultural Research Center near Hays (KSU-ARCH), KS (38.85196°N, 99.34279°W) from fall 2020 through fall 2023. The field site was under a NT dryland WSF rotation with a history of natural seedbank of GR *A. palmeri*. The 30-yr average annual precipitation at the study site was 596 mm, of which most occurred from May through September, and the average temperature ranged from −2 C in January to 26 C in July with a mean of 12 C (https://mesonet.k-state.edu). All three phases of the crop rotation (WSF) were present in each experimental year. The soil type at the experimental site was Roxbury silt loam (Taxonomic class: fine-silty, mixed, superactive, mesic Cumulic Haplustolls) with a pH of 6.9 and organic matter of 1.6%. A separate greenhouse study confirmed that an *A. palmeri* population from the study site survived 5,040 g ha^{-1} (4× the field use rate) of glyphosate (data not shown). Each year, a CC mixture of winter triticale (×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*]) (60%)/winter peas (*Pisum sativum* L.) (30%)/rapeseed (*Brassica napus* L.) (5%)/radish (*Raphanus sativus* L.) (5%) was drilled at a seeding rate of 67 kg ha^{-1} in wheat stubble during fall (September/October) and terminated in the following spring at the triticale heading stage (Table 1). During each spring, four treatments were established: (1) nontreated control (where no CC was planted and no herbicides were applied to control weeds); (2) chemical fallow (where no CC was planted but the plot area was treated with glyphosate [Roundup PowerMax®, Bayer Crop Science, St. Louis, MO, USA] at 1,260 g ae ha^{-1} plus a premix of acetochlor/atrazine [Degree Xtra®, Bayer Crop Science, St. Louis, MO, USA] at 1,665/826 g ai ha^{-1} plus dicamba [Clarity®, BASF Corporation, Research Triangle Park, NC, USA] at 560 g ae ha^{-1} at the same time as CC termination); (3) CC terminated with glyphosate at 1,260 g ae ha^{-1}; and (4) CC terminated with glyphosate at 1,260 g ae ha^{-1} plus a premix of acetochlor/atrazine at 1,665/826 g ai ha^{-1}. Despite the presence of GR *A. palmeri* at the study site, glyphosate was used in chemical fallow to control winter annuals and some grass weeds such as tumble windmill grass (*Chloris verticillata* Nutt.) that growers typically apply in the region. In addition, glyphosate is a cost-effective and commonly used herbicide for CC termination in the region. Each year, treatments were arranged in a randomized complete block design with four replications. During the 2020 to 2021 experimental year, the nontreated control 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, the original chemical fallow plot was further divided into two to have both nontreated control and chemical fallow treatments (each plot 45-m long and 6.5-m wide). The CC was left standing after termination and no additional management practices were performed after termination. A grain sorghum hybrid 'DKS 38-16' was planted at a seeding rate of 114,855 seeds ha^{-1} in rows spaced 76 cm apart within 3 to 4 wk of CC termination each year. The details for planting and termination dates of CC as well as grain sorghum planting and harvesting dates for each experimental year are presented in Table 1. All local agronomic practices for grain sorghum production as recommended by Kansas State University were followed (Ciampitti et al. 2022).

Data Collection

Each year, the aboveground shoot biomass of CC was manually harvested from two 1-m^2 quadrats from each plot just before CC

Table 1. Planting and termination dates for cover crops and planting and harvesting dates for grain sorghum over three growing seasons at Kansas State University Agricultural Research Center near Hays, KS

	Cover crop		Grain sorghum	
Growing season	Planting date	Termination date	Planting date	Harvesting date
2020–2021	September 28, 2020	May 13, 2021	June 9, 2021	November 4, 2021
2021–2022	October 7, 2021	May 11, 2022	June 2, 2022	October 26, 2022
2022–2023	September 30, 2022	May 22, 2023	June 15, 2023	October 19, 2023

termination and oven-dried at 72 C for 4 d to obtain dry biomass. Two permanent 1-m^2 quadrats were established in each plot immediately after the termination of CC for GR *A. palmeri* emergence counts. Newly emerged GR *A. palmeri* seedlings from each permanent quadrat were counted when cotyledons were fully expanded and removed manually every week starting from termination of CC throughout the sorghum growing season (Hartzler et al. 1999). Kochia [*Bassia scoparia* (L.) A.J. Scott] and puncturevine (*Tribulus terrestris* L.) were also present each year and were removed manually along with GR *A. palmeri* every week. The end date for the emergence count of GR *A. palmeri* was chosen when no new emergence occurred over 21-d period each year. The average number of *A. palmeri* seedlings from the two permanent quadrats in each plot at each count timing was used in the data analysis. Data on daily minimum and maximum air temperature and precipitation during each growing season were obtained from the Kansas State University Mesonet weather station (https://mesonet.k-state.edu) located approximately 400 m away from the study site (38.8495°N, 99.3446°W). Growing degree days (GDD) and cumulative GDD (cGDD) were calculated (started at the day of CC termination) from the daily minimum and maximum air temperatures using Equations 1 and 2, respectively (McMaster and Wilhelm 1997).

$$\mathrm{GDD_{daily}} = \left[\frac{T_{\max} + T_{\min}}{2}\right] - T_{\mathrm{base}} \quad [1]$$

$$\mathrm{cGDD} = \sum\nolimits_{i=1}^{n} \mathrm{GDD_{daily}} \quad [2]$$

where $\mathrm{GDD_{daily}}$ is the daily accumulated GDD (it is a nonnegative value, therefore negative $\mathrm{GDD_{daily}}$ was replaced by 0), $T_{\max}$ is the daily maximum air temperature (C), $T_{\min}$ is the daily minimum air temperature (C), T_{base} is the base temperature below which plant growth ceases and was considered as 10 C for *A. palmeri* (Norsworthy et al. 2008), and n is the number of days in each growing season for which the emergence counts were recorded.

Statistical Analyses

Data on weekly GR *A. palmeri* emergence were subjected to ANOVA using the PROC MIXED procedure and were tested for homogeneity of variance and normality of the residuals using the PROC UNIVARIATE procedure in SAS v. 9.3 (SAS Institute, SAS Campus Drive, Cary, NC). Data were log-transformed to improve the normality of the residuals and homogeneity of variance; however, back-transformed data were presented with mean separation based on the transformed data. The fixed effects in the ANOVA model included treatment, year, weekly emergence timings, and their interactions. The random effects in the ANOVA model included replication and all interactions involving replication. Due to significant year by treatment interaction ($P = 0.0321$), data were analyzed separately for each year. The interaction between treatment and weekly emergence timing was significant ($P < 0.001$); therefore, data were sorted by weekly emergence timings using PROC SORT. Total emergence counts were calculated by adding all the weekly emergence counts from each treatment. Treatment means were separated using Fisher's protected LSD test ($P < 0.05$) for each emergence timing.

The percent cumulative emergence of GR *A. palmeri* in each treatment from each replication was calculated as the sum of emergence on a sample date and all previous sample dates and expressed as a percentage of total emergence in each growing season (Jha and Norsworthy 2009). Data on percent cumulative emergence of GR *A. palmeri* from all four treatments were regressed against cGDD with a three-parameter log-logistic model using the DRC package in R software (Knezevic et al. 2007; Ritz and Streibig 2005; Seefeldt et al. 1995).

$$Y = \{d/1 + \exp[b(\log X - \log E_{50})]\} \quad [3]$$

where Y is the percent cumulative emergence of GR *A. palmeri*; X is the cGDD; parameter d in the model is the maximum cumulative emergence, which was fixed to 100, because the percent cumulative emergence was based on the total emergence; E_{50} is the cGDD required to reach 50% cumulative emergence; and the parameter b is the slope at the inflection point. The slope (b) represents the emergence rate of GR *A. palmeri* over cGDD, and the negative value of the slope indicates rapid emergence (Kumar et al. 2018). This model was selected based on Akaike's criteria as described in Ritz and Spiess (2008). The P-value > 0.05 for the lack-of-fit test indicated that the model (Equation 3) adequately explained the percent cumulative emergence of GR *A. palmeri* (Ritz and Streibig 2005). Parameter estimates, standard errors, and E_{50} values for each treatment were determined. The coefficient of determination (R^2), cGDD required for 10% (E_{10}) and 90% (E_{90}) cumulative emergence of GR *A. palmeri* and duration (cGDDs for 10% to 90% emergence, i.e., $E_{90} - E_{10}$) for each treatment were predicted from the fitted model. E_{10}, E_{50}, and E_{90} values were compared among treatments using the approximate *t*-test with the *compParm* and *EDcomp* functions in the DRC package in R software (Knezevic et al. 2007; Ritz et al. 2015).

Results and Discussion

Variable amount and frequency of precipitation were observed at KSU-ARCH during the experimental periods from 2020 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 dry CC biomass at the time of termination was 1,520, 1,130, and 1,470 kg ha^{-1} in 2021, 2022, and 2023, respectively. Total precipitation amount during the grain sorghum growing seasons (June to October) in 2021, 2022, and 2023, was 256, 171, and 237 mm, respectively (Figure 1).

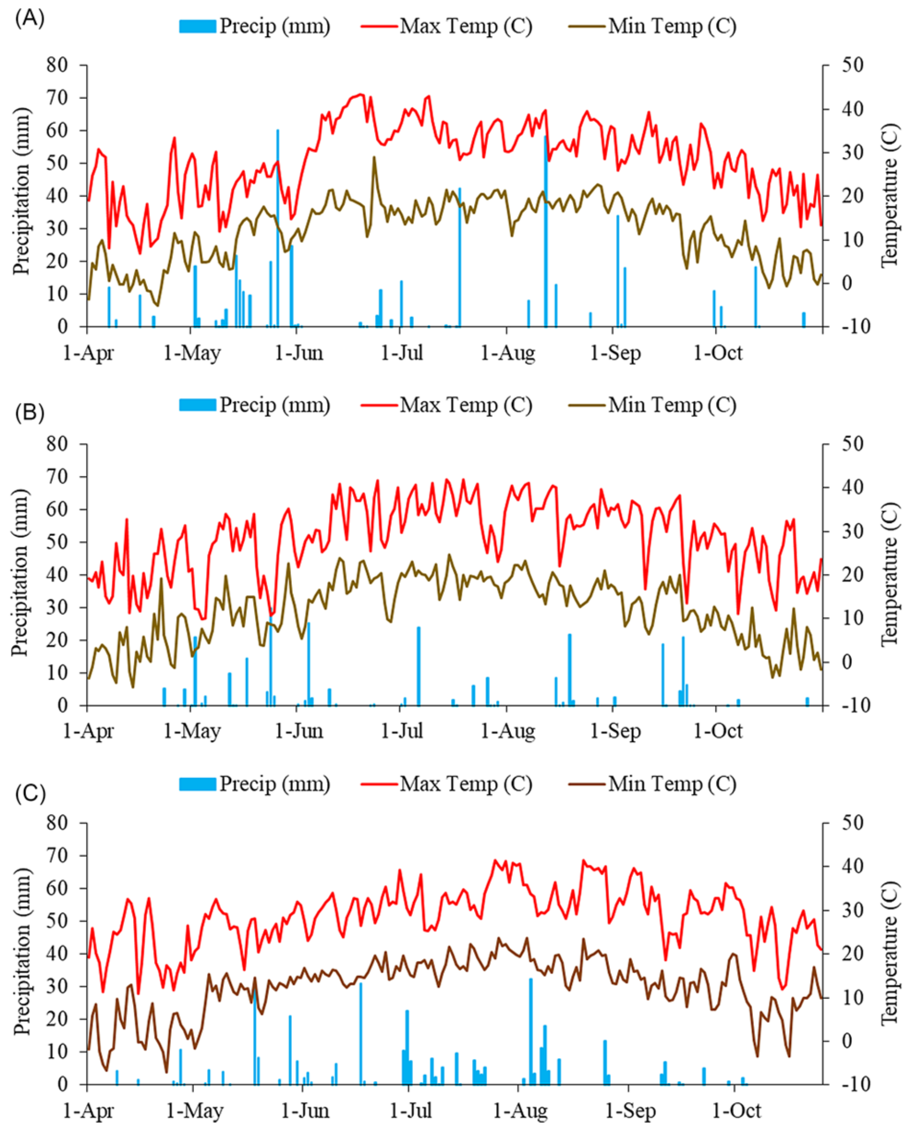

Figure 1. Daily minimum and maximum air temperature (C) and precipitation (mm) during the growing seasons of 2021 (A), 2022 (B), and 2023 (C).

Emergence Periodicity of GR Amaranthus palmeri

Amaranthus palmeri seedlings emerged from May 12 through September 15 in 2021, May 12 through July 14 in 2022, and June 2 through July 14 in 2023 (Figures 2 to 4). The prolonged emergence in 2021 might be due to relatively higher precipitation events (17) each of >10 mm from May to September as compared with the 2022 (9 events) and 2023 (10 events) growing seasons (Figure 1). Across 3 yr, the emergence initiation of GR *A. palmeri* was delayed by 0 to 21 d and 7 to 28 d under the CC terminated with glyphosate only and CC terminated with glyphosate plus acetochlor/atrazine, respectively, compared with chemical fallow (Figures 2 to 4). The CC terminated with glyphosate plus acetochlor/atrazine reduced the total emergence counts of GR *A. palmeri* by 42% to 56% compared with the chemical fallow and by 82% to 94% compared with the nontreated control across 3 yr (Figures 2 to 4).

The 2021 Growing Season

The total emergence counts of GR *A. palmeri* at the end of the grain sorghum growing season were 22 (SE = 4), 23 (SE = 4), and 11 (SE = 3) seedlings m^{-2} under chemical fallow, CC terminated with glyphosate, and CC terminated with glyphosate plus acetochlor/atrazine, respectively (Figure 2). GR *A. palmeri* in chemical fallow started to emerge on May 12 with a major emergence observed from the end of May through the end of June (Figure 2). In contrast, both CC treatments had a GR *A. palmeri* emergence delayed by 21 to 28 d, with the first seedlings emerging between June 2 and June 9 and a major emergence occurring from early June to mid-July. Out of the total rainfall (358 mm), 64% occurred from mid-May to mid-July with 10 rainfall events of >10 mm that coincided with the major emergence period of GR *A. palmeri* (Figures 1 and 2). These results indicate that CC residue suppressed GR *A. palmeri* emergence and provided less initial weed competition to grain sorghum in 2021.

The 2022 Growing Season

The total emergence counts of GR *A. palmeri* at the end of the grain sorghum growing season were 33 (SE = 6), 12 (SE = 4), 31 (SE = 6), and 7 (SE = 2) seedlings m^{-2} under nontreated, chemical fallow, CC terminated with glyphosate, and CC terminated with

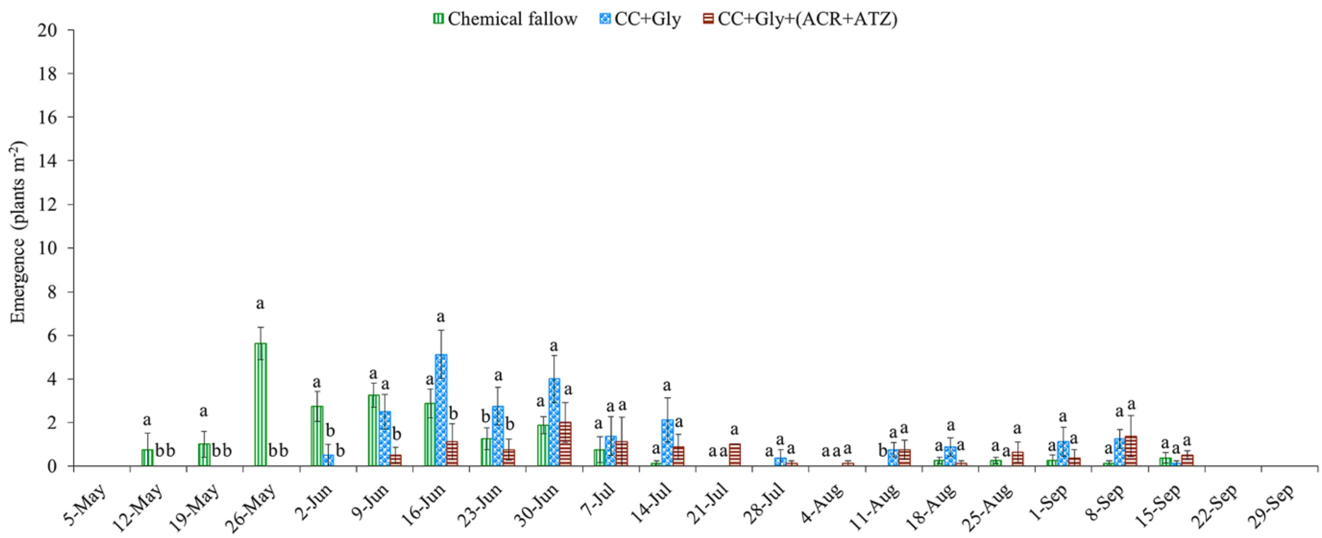

Figure 2. Weekly emergence counts of glyphosate-resistant (GR) *Amaranthus palmeri* under different treatments in 2021. Chemical fallow had no cover crop (CC) and was treated with glyphosate + acetochlor/atrazine + dicamba at the same time as CC termination. CC+Gly indicates cover crop terminated with glyphosate; CC+Gly+(ACR+ATZ) indicates cover crop terminated with glyphosate plus acetochlor/atrazine. The same letter above columns within each timing are not significantly different according to Fisher's protected LSD test at P < 0.05. Error bars represent standard error of the mean.

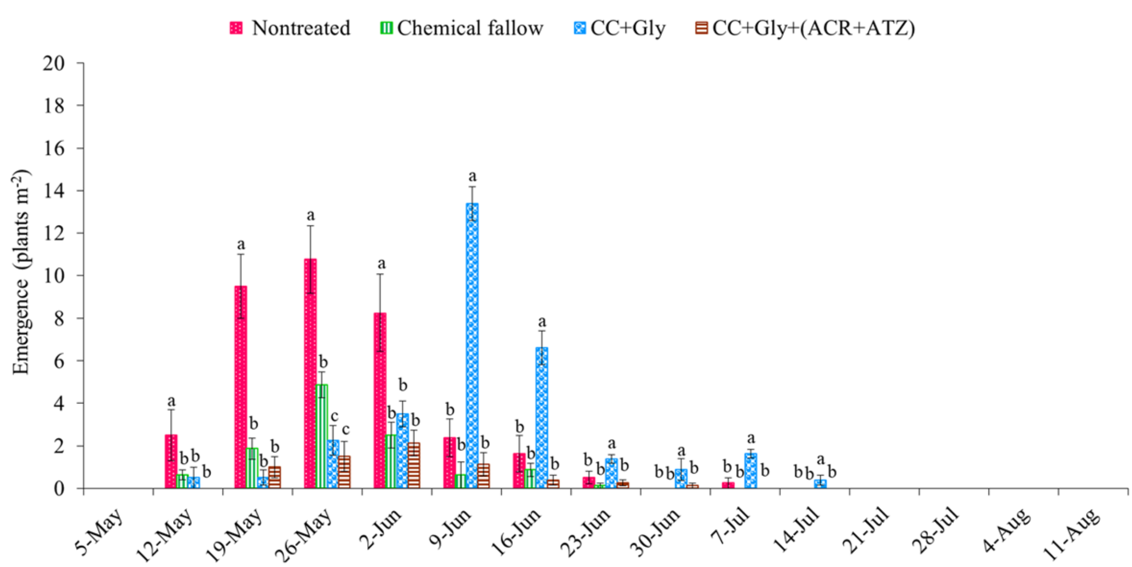

Figure 3. Weekly emergence counts of glyphosate-resistant (GR) *Amaranthus palmeri* under different treatments in 2022. Chemical fallow had no cover crop (CC) and was treated with glyphosate + acetochlor/atrazine + dicamba at the same time as CC termination. CC+Gly indicates cover crop terminated with glyphosate; CC+Gly+(ACR+ATZ) indicates cover crop terminated with glyphosate plus acetochlor/atrazine. The same letter above columns within each timing are not significantly different according to Fisher's protected LSD test at P < 0.05. Error bars represent standard error of the mean.

glyphosate plus acetochlor/atrazine, respectively (Figure 3). *Amaranthus palmeri* seedlings started to emerge at nearly the same time (May 12 through May 19) under all treatments except CC terminated with glyphosate plus acetochlor/atrazine (delayed by 7 d) in the 2022 growing season (Figure 3). The CC dry biomass was relatively low (1,130 kg ha^{-1}) at termination because of relatively low precipitation (99 mm) during the CC growing season; thus only CC without any residual herbicide was possibly not sufficient to suppress/delay the emergence of *A. palmeri* (Figures 1 and 3). Although GR *A. palmeri* seedlings emerged at nearly the same time, the total seasonal emergence counts of GR *A. palmeri* were reduced by 68% under chemical fallow, by 14% under CC terminated with glyphosate, and by 82% under CC terminated with glyphosate plus acetochlor/atrazine as compared with the nontreated control. Interestingly, both CC treatments significantly reduced early-season (May 12 through June 2) emergence of GR *A. palmeri* by 66% to 92% as compared with the nontreated control. Our results are consistent with those of Cornelius and Bradley (2017), who also reported that cereal rye CC reduced early-season emergence of common waterhemp (*Amaranthus rudis* Sauer) by 35% compared with the nontreated control in soybean. The majority of the GR *A. palmeri* seedlings emerged from mid-May through early June under nontreated control and chemical fallow treatments. In contrast, the emergence of GR *A. palmeri* was mostly observed from late May through the end of June under CC terminated with glyphosate alone and from

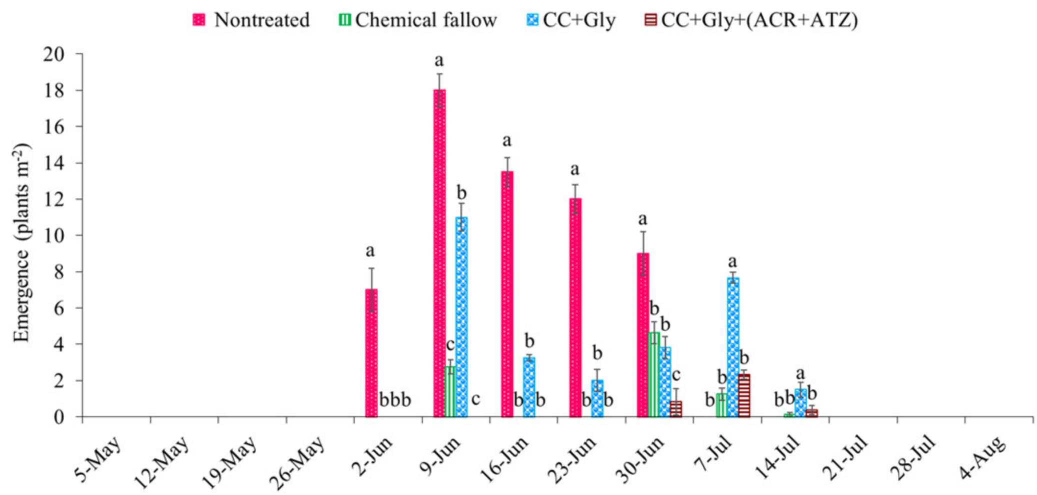

Figure 4. Weekly emergence counts of glyphosate-resistant (GR) *Amaranthus palmeri* under different treatments in 2023. Chemical fallow had no cover crop (CC) and was treated with glyphosate + acetochlor/atrazine + dicamba at the same time as CC termination. CC+Gly indicates cover crop terminated with glyphosate; CC+Gly+(ACR+ATZ) indicates cover crop terminated with glyphosate plus acetochlor/atrazine. The same letter above columns within each timing are not significantly different according to Fisher's protected LSD test at P < 0.05. Error bars represent standard error of the mean.

late May through early June under CC terminated with glyphosate plus acetochlor/atrazine (Figure 3). The CC residue on the soil surface could reduce the soil temperature, altering the quantity and quality of light reaching the soil surface (Teasdale 2018; Weisberger et al. 2024), which might have delayed the emergence of GR *A. palmeri* under CC treatments. Furthermore, all the major emergence periods of GR *A. palmeri* in May and June coincided with the precipitation events, with 60% of the total seasonal rainfall occurring during these 2 mo (Figure 1). Similar observations were also reported by Liu et al. (2022) and Jha and Norsworthy (2009), who found that peak *A. palmeri* emergence coincided with precipitation events. These findings are consistent with Wiggins et al. (2015), who concluded that CC alone was not sufficient for season-long control of GR *A. palmeri* and suggested integrating residual herbicides to complement the suppressive effect of CC.

The 2023 Growing Season

The total emergence counts of GR *A. palmeri* at the end of the grain sorghum growing season were 60 (SE = 8), 9 (SE = 2), 29 (SE = 6), and 4 (SE = 1) seedlings m^{-2} under nontreated, chemical fallow, CC terminated with glyphosate, and CC terminated with glyphosate plus acetochlor/atrazine, respectively (Figure 4). The GR *A. palmeri* seedlings started to emerge on June 2 in the nontreated control and on June 9 in chemical fallow and CC terminated with glyphosate alone (Figure 4). In contrast, the emergence of GR *A. palmeri* in CC terminated with glyphosate plus acetochlor/atrazine was delayed and was first observed on June 30, indicating the emergence was delayed by 28 d as compared with the nontreated control and by 21 d compared with chemical fallow (Figure 4). This might be due to the synergistic effect of CC and residual herbicide, as also reported by previous researchers (Perkins et al. 2021; Teasdale et al. 2005). Perkins et al. (2021) reported that a CC mixture of cereal rye and hairy vetch in combination with pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, or acetochlor delayed *A. palmeri* emergence by 27 to 34 d in soybean compared with CC with no residual herbicides. The majority of the GR *A. palmeri* seedlings emerged from June 2 through June 30 in the nontreated control, June 9 through July 7 in chemical fallow, June 9 through July 14 in CC terminated with glyphosate alone, and June 30 through July 7 in CC terminated with glyphosate plus acetochlor/atrazine. Most of the GR *A. palmeri* seedlings emerged in June and July, which coincided with eight major precipitation events (each event >5 mm) and two events of >20 mm contributing 44% of the total season rainfall (312 mm) in 2023 (Figures 1 and 4). The total seasonal emergence counts of GR *A. palmeri* were reduced by 85% in chemical fallow, 51% in CC terminated with glyphosate alone, and 94% in CC terminated with glyphosate plus acetochlor/atrazine as compared with the nontreated control (Figure 4). These results agree with those of DeVore et al. (2012), who reported that fall-planted cereal rye CC reduced the emergence of GR *A. palmeri* by 67% in cotton compared with no CC. Similarly, McCall (2018) observed a delayed emergence of GR *A. palmeri* under winter wheat, spring oat (*Avena sativa* L.), or spring oat/spring pea CC terminated with glyphosate plus flumioxazin/pyroxasulfone as compared with CC terminated with glyphosate only.

Emergence Pattern of GR Amaranthus palmeri

Across 3 yr, 66 to 643 and 105 to 1,257 more cGDD were required to achieve 90% cumulative emergence of GR *A. palmeri* under the CC terminated with glyphosate alone and CC terminated with glyphosate plus acetochlor/atrazine, respectively, compared with chemical fallow (Table 2; Figure 5).

The 2021 Growing Season

Only 230 to 286 cGDD were required for 10% cumulative emergence (E_{10} value) of GR *A. palmeri* under chemical fallow and CC terminated with glyphosate alone, whereas about 498 cGDD were required to achieve 10% cumulative emergence of GR *A. palmeri* under CC terminated with glyphosate plus acetochlor/atrazine (Table 2). Similarly, about 205 and 580 more cGDD were required to achieve 50% cumulative emergence (E_{50} values) of GR *A. palmeri* for CC terminated with glyphosate and CC terminated with glyphosate plus acetochlor/atrazine, respectively, as compared with chemical fallow. For 90% cumulative emergence (E_{90} value) of GR *A. palmeri*, about 1,000, 1,643, and 2,257 cGDD were required for chemical fallow, CC terminated with glyphosate, and CC terminated with glyphosate plus acetochlor/atrazine,

https://doi.org/10.1017/wsc.2024.22 Published online by Cambridge University Press

Table 2. Regression parameters estimated from the log-logistic model (Equation 3) for percent cumulative emergence of glyphosate-resistant (GR) *Amaranthus palmeri*, duration of *A. palmeri* emergence, and coefficient of determination (R^2) during the 2021 to 2023 growing seasons at Kansas State University Agricultural Research Center near Hays, KS

	Regression parameters[b]					
Treatment[a]	*b* (SE)	E_{10} (SE)	E_{50} (SE)	E_{90} (SE)	Duration of emergence ($E_{90} - E_{10}$)	R^2
			cGDD			
2021						
Chemical fallow	−2.9 (0.5)	230 (46) b	480 (45) c	1,000 (100) c	770	0.90
CC+Gly	−2.5 (0.2)	286 (45) b	685 (50) b	1,643 (142) b	1,357	0.95
CC+Gly+(ACR+ATZ)	−2.9 (0.3)	498 (74) a	1,060 (66) a	2,257 (167) a	1,759	0.97
2022						
Nontreated	−2.4 (0.5)	27 (8) d	67 (8) d	168 (24) d	141	0.89
Chemical fallow	−2.3 (0.2)	47 (6) c	118 (8) c	296 (31) c	249	0.90
CC+Gly	−2.5 (0.2)	70 (9) b	170 (11) b	409 (36) b	339	0.91
CC+Gly+(ACR+ATZ)	−2.8 (0.3)	116 (16) a	254 (17) a	557 (37) a	441	0.90
2023						
Nontreated	−2.9 (0.4)	97 (16) d	204 (15) c	429 (42) c	332	0.90
Chemical fallow	−3.6 (0.6)	192 (28) b	349 (21) b	634 (53) b	442	0.94
CC+Gly	−2.6 (0.3)	132 (18) c	304 (20) b	700 (26) b	568	0.93
CC+Gly+(ACR+ATZ)	−8 (1.5)	427 (28) a	562 (16) a	739 (39) a	312	0.95

[a]Chemical fallow had no cover crop (CC) and was treated with glyphosate + acetochlor/atrazine + dicamba at the same time as CC termination; CC+Gly indicates cover crop terminated with glyphosate; CC+Gly+(ACR+ATZ) indicates cover crop terminated with glyphosate plus acetochlor/atrazine.
[b]Regression parameters: *b* is the slope at the inflection point of each curve; E_{10}, E_{50}, and E_{90} are cumulative GDD (cGDD) required for 10%, 50%, and 90% cumulative emergence of GR *A. palmeri*, respectively; SE is the standard error of mean. E_{10}, E_{50}, and E_{90} estimates followed by the same letter are not different based on an approximate *t*-test using the *CompParm* and *EDcomp* functions in the DRC package in R software (Ritz et al. 2015).

respectively (Table 2; Figure 5). The CC terminated with glyphosate or with glyphosate plus acetochlor/atrazine exhibited a prolonged emergence duration ($E_{90} - E_{10}$) of GR *A. palmeri* and required an additional 587 and 989 cGDD, respectively, as compared with chemical fallow. The greater cGDD requirements for 10%, 50%, and 90% cumulative emergence of GR *A. palmeri* under CC treatments might be due to alteration in the soil microenvironment with decreasing light penetration and soil temperature as compared with no CC treatments (Teasdale and Mohler 1993). Furthermore, the CC residue on the soil surface could reduce evaporation, thereby contributing to increased soil water storage (Holman et al. 2020), which could possibly benefit *A. palmeri* for its longer emergence period. Our results are consistent with those of Perkins et al. (2021), who previously reported that applications of pyroxasulfone + flumioxazin, flumioxazin, pyroxasulfone, or acetochlor at 3 wk after fall-planted cereal rye + hairy vetch CC termination delayed *A. palmeri* emergence by 27 to 34 d compared with CC termination with glyphosate + dicamba in soybean.

The 2022 Growing Season

GR *A. palmeri* seedlings emerged quickly in the nontreated control and required only 27 cGDD to achieve 10% cumulative emergence in the absence of CC and residual herbicide (Table 2; Figure 5). In contrast, GR *A. palmeri* under the chemical fallow treatment required 47 cGDD for 10% cumulative emergence followed by CC terminated with glyphosate alone (70 cGDD), and CC terminated with glyphosate plus acetochlor/atrazine (116 cGDD) (Table 2; Figure 5). To reach 50% cumulative emergence, the CC terminated with glyphosate alone required 103 and 52 more cGDD compared with nontreated and chemical fallow, respectively. Similarly, the CC terminated with glyphosate plus acetochlor/atrazine required 187 and 136 additional cGDD to achieve 50% cumulative emergence of GR *A. palmeri* compared with nontreated and chemical fallow, respectively. Furthermore, to reach 90% cumulative emergence, the CC terminated with glyphosate plus acetochlor/atrazine required 557 cGDD and had a prolonged period of emergence ($E_{90} - E_{10} = 441$ cGDD). In contrast, the nontreated control required only 168 cGDD to achieve 90% cumulative emergence of GR *A. palmeri* and had a short period of emergence ($E_{90} - E_{10} = 141$ cGDD) (Table 2). These results are consistent with those of McCall (2018), who reported that an additional 80 cGDD were required to reach 50% emergence of GR *A. palmeri* under winter wheat CC terminated with glyphosate plus flumioxazin/pyroxasulfone as compared with CC terminated with glyphosate only in soybean.

The 2023 Growing Season

Only 97 cGDD were required to achieve 10% cumulative emergence of GR *A. palmeri* in the nontreated control. Compared with the 2021 and 2022 growing seasons, the CC terminated with glyphosate alone required fewer cGDD (132) than chemical fallow (192) to achieve 10% cumulative emergence of GR *A. palmeri* (Table 2; Figure 5). This might be because of frequent precipitation events during late May and early June. Among all treatments, CC terminated with glyphosate plus acetochlor/atrazine required the greatest cGDD (427) for 10% cumulative emergence of GR *A. palmeri* (Table 2; Figure 5). In the nontreated control, GR *A. palmeri* required 204 cGDD for 50% cumulative emergence, while CC terminated with glyphosate plus acetochlor/atrazine required significantly higher cGDD (562) (Table 2; Figure 5). Similarly, to achieve 90% cumulative emergence of GR *A. palmeri*, the highest cGDD (739) were required under the CC terminated with glyphosate plus acetochlor/atrazine, while only 429 cGDD were required under nontreated control. These results are consistent with those of Teasdale et al. (2003), who previously reported that hairy vetch residue and preemergence application of metolachlor delayed weed emergence by 7 to 10 d compared with herbicide alone. The delay in emergence of GR *A. palmeri* would provide an initial competitive benefit to grain sorghum.

Overall, the results from this study indicate that fall-planted CC after winter wheat harvest and terminated in the following spring with glyphosate plus acetochlor/atrazine can delay and reduce the cumulative emergence of GR *A. palmeri* in grain sorghum.

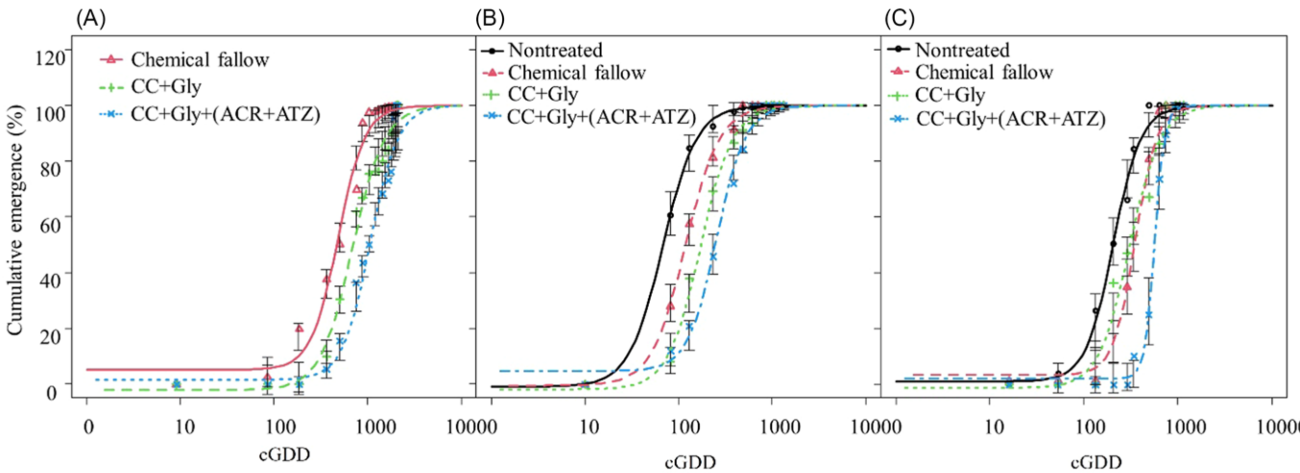

Figure 5. Cumulative emergence of glyphosate-resistant (GR) *Amaranthus palmeri* under different treatments during 2021 (A), 2022 (B), and 2023 (C) growing seasons in relation to cumulative growing degree days (cGDD). Chemical fallow had no cover crop (CC) and was treated with glyphosate + acetochlor/atrazine + dicamba at the same time as CC termination. CC+Gly indicates cover crop terminated with glyphosate; CC+Gly+(ACR+ATZ) indicates cover crop terminated with glyphosate plus acetochlor/atrazine. Vertical bars indicate ± standard error of the mean at each observation date. Model is based on Equation 3 with parameter estimates in Table 2.

Nevertheless, these results emphasize the need for a season-long integrated *A. palmeri* management strategy in grain sorghum. Previous studies have also established that adequate CC biomass is highly crucial to achieve suppression and delayed emergence of *A. palmeri* (Devore et al. 2013; Palhano et al. 2018; Perkins et al. 2021), and infrequent rainfall patterns are a major constraint to the widescale adoption of CC in the NT dryland CGP region. As evident from this research, limited precipitation during winter months in some years can result in low CC biomass accumulation and inactivation of residual herbicides, resulting into loss of suppressive effect of CC and residual herbicide on *A. palmeri* emergence. Considering these challenges with CC plus residual herbicides and rapid evolution of *A. palmeri* with multiple resistance to postemergence herbicides, additional novel weed control strategies (such as electric weeders and harvest weed seed control [chaff lining and seed impact mill]) should also be integrated for managing GR *A. palmeri* seedbanks in this NT dryland region.

Different *A. palmeri* populations within a CGP region could exhibit a differential emergence pattern, as previously observed by Liu et al. (2022). Therefore, the findings of the current study will help to further improve the prediction models for *A. palmeri* emergence under CC plus residual herbicide strategy to build decision support tools for cost-effective and sustainable management of GR *A. palmeri* in the region. These combined practices of CC and residual herbicides would also help growers to target smaller GR *A. palmeri* seedings with postemergence herbicides for effective in-season control. Fewer and late-emerging GR *A. palmeri* plants would have lower biomass accumulation, and ultimately lower seed production, which can further help to prevent replenishment of the soil seedbank. Although this study investigated only one residual herbicide, sorghum producers should diversify their residual herbicide programs annually to prevent the selection of *A. palmeri* populations with resistance to residual herbicides. Future studies should investigate weed suppression with CC plus residual herbicides by considering the soil water budget and subsequent crop yield implications in the WSF rotation. Furthermore, based on available soil moisture, the fallow phase after grain sorghum harvest in the WSF rotation could also be replaced with the spring-planted CC such as barley (*Hordeum vulgare* L.), oat, or pea for summer annual weed suppression (Obour et al. 2022).

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

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

Competing Interests. The authors declare no competing interests.

References

Buhler DD (1992) Population dynamics and control of annual weeds in corn (*Zea mays*) as influenced by tillage. Weed Sci 40:241–248

Buhler DD, Mester TC, Kohler KA (1996) The effect of maize residues and tillage on emergence of *Setaria faberi*, *Abutilon theophrasti*, *Amaranthus retroflexus*, and *Chenopodium album*. Weed Res 36:153–165

Cardina J, Regnier E, Harrison K (1991) Long-term tillage effects on seed banks in three Ohio soils. Weed Sci 39:186–194

Chahal PS, Aulakh JS, Jugulam M, Jhala AJ (2015) Herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in the United States—mechanisms of resistance, impact, and management. Pages 1–29 *in* Price A, Kelton J, Sarunaite L, eds. Herbicides: Agronomic Crops and Weed Biology. London: IntechOpen

Chahal PS, Barnes ER, Jhala AJ (2021) Emergence pattern of Palmer amaranth (*Amaranthus palmeri*) influenced by tillage timings and residual herbicides. Weed Technol 35:433–439

Ciampitti IA, Diaz DR, Onofre R, Lancaster S, Whitworth RJ, Aguilar J (2022) Kansas Sorghum Management 2022. Manhattan: Kansas State University Agricultural Experiment Station and Cooperative Extension Service Extension Bulletin MF3208. 8 p

Cornelius CD, Bradley KW (2017) Influence of various cover crop species on winter and summer annual weed emergence in soybean. Weed Technol 31:503–513

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832–838

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263–270

Dille JA, Stahlman PW, Thompson CR, Bean BW, Soltani N, Sikkema PH (2020) Potential yield loss in grain sorghum (*Sorghum bicolor*) with weed interference in the United States. Weed Technol 34:624–629

Hartzler RG, Buhler DG, Stoltenberg DE (1999) Emergence characteristics of four annual weed species. Weed Sci 47:578–584
Heap I (2023) The International Herbicide-Resistant Weed Database. http://www.weedscience.org. Accessed: August 28, 2023
Holman JD, Assefa Y, Obour AK (2020) Cover-crop water use and productivity in the high plains wheat-fallow crop rotation. Crop Sci 61:1374–1385
Holman JD, Obour AK, Assefa Y (2022) Productivity and profitability with fallow replacement forage, grain, and cover crops in W-S-F rotation. Crop Sci 62:913–927
Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 1:347–355
Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seedbank. Weed Sci 57:644–651
Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28–38
Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204
Knezevic SZ, Streibig JC, Ritz C (2007) Utilizing R software package for dose–response studies: the concept and data analysis. Weed Technol 21:840–848
Kumar V, Jha P, Dille JA, Stahlman PW (2018) Emergence dynamics of kochia (*Kochia scoparia*) populations from the US Great Plains: a multi-site-year study. Weed Sci 66:25–35
Kumar V, Jha P, Jugulam M, Yadav R, Stahlman PW (2019a) Herbicide-resistant kochia (*Bassia scoparia*) in North America: a review. Weed Sci 67:4–15
Kumar V, Liu R, Boyer G, Stahlman PW (2019b) Confirmation of 2,4-D resistance and identification of multiple resistance in a Kansas Palmer amaranth (*Amaranthus palmeri*) population. Pest Manag Sci 75:2925–2933
Kumar V, Liu R, Jhala AJ, Jha P, Manuchehri M (2021) Palmer amaranth (*Amaranthus palmeri*) control in postharvest wheat stubble in the Central Great Plains. Weed Technol 35:945–949
Kumar V, Liu R, Stahlman PW (2020a) Differential sensitivity of Kansas Palmer amaranth populations to multiple herbicides. Agron J 112:2152–2163
Kumar V, Obour A, Jha P, Liu R, Manuchehri MR, Dille JA, Holman J, Stahlman PW (2020b) Integrating cover crops for weed management in the semiarid US Great Plains: opportunities and challenges. Weed Sci 68:311–323
Liu R, Kumar V, Jha P, Stahlman PW (2022) Emergence pattern and periodicity of Palmer amaranth (*Amaranthus palmeri*) populations from southcentral Great Plains. Weed Technol 36:110–117
McCall CM (2018) Integrating Cover Crops and Herbicides for Horseweed and Palmer Amaranth Management in No-Till Soybean. MS thesis. Manhattan: Kansas State University. 51 p
McMaster G, Wilhelm W (1997) Growing degree-days: one equation, two interpretations. Agric For Meteorol 87:291–300
Moore JW, Murray DS, Westerman RB (2004) Palmer amaranth (*Amaranthus palmeri*) effects on the harvest and yield of grain sorghum (*Sorghum bicolor*). Weed Technol 18:23–29
Mundia CW, Secchi S, Akamani K, Wang G (2019) A regional comparison of factors affecting global sorghum production: the case of North America, Asia and Africa's Sahel. Sustainability 11:2135
Norsworthy JK, Oliveira MJ, Jha P, Malik M, Buckelew JK, Jennings KM, Monks DW (2008) Palmer amaranth and large crabgrass growth with plasticulture-grown bell pepper. Weed Technol 22:296–302
Obour AK, Dille J, Holman J, Simon LM, Sancewich B, Kumar V (2022) Spring-planted cover crop effects on weed suppression, crop yield, and net returns in no-tillage dryland crop production. Crop Sci 62:1981–1996
Oryokot JOE, Murphy SD, Swanton CJ (1997) Effect of tillage and corn on pigweed (*Amaranthus* spp.) seedling emergence and density. Weed Sci 45:120–126
Palhano MG, Norsworthy JK, Barber T (2018) Cover crops suppression of Palmer amaranth (*Amaranthus palmeri*) in cotton. Weed Technol 32:60–65
Perkins CM, Gage KL, Norsworthy JK, Young BG, Bradley KW, Bish MD, Hager A, Steckel LE (2021) Efficacy of residual herbicides influenced by cover-crop residue for control of *Amaranthus palmeri* and *A. tuberculatus* in soybean. Weed Technol 35:77–81
Ritz C, Baty F, Streibig JC, Gerhard D (2015) Dose-response analysis using R. PLoS ONE 10:e0146021
Ritz C, Spiess AN (2008) qpcR: an R package for sigmoidal model selection in quantitative real-time polymerase chain reaction analysis. Bioinformatics 24:1549–1551
Ritz C, Streibig JC (2005) Bioassay analysis using R. J Stat Softw 12:1–22
Roberts J, Florentine S (2022) A review of the biology, distribution patterns and management of the invasive species *Amaranthus palmeri* S. Watson (Palmer amaranth): current and future management challenges. Weed Res 62:113–122
Sauer J (1957) Recent migration and evolution of the dioecious amaranths. Evolution 1:11–31
Seefeldt SS, Jensen JE, Fuerst EP (1995) Log-logistic analysis of herbicide dose-response relationships. Weed Technol 9:218–227
Teasdale JR (2018) The use of rotations and cover crops to manage weeds. Pages 227–260 *in* Zimdahl R, ed. Integrated Weed Management for Sustainable Agriculture. Cambridge, UK: Burleigh Dodds Science Publishing
Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85:673–680
Teasdale JR, Pillai P, Collins RT (2005) Synergism between cover crop residue and herbicide activity on emergence and early growth of weeds. Weed Sci 53:521–527
Teasdale JR, Shelton DR, Sadeghi AM, Isensee AR (2003) Influence of hairy vetch residue on atrazine and metolachlor soil solution concentration and weed emergence. Weed Sci 51:628–634
[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service (2023) Quick Stats Tools. https://www.nass.usda.gov/Quick_Stats/index.php. Accessed: August 30, 2023
Van Wychen L (2020) 2020 Survey of the Most Common and Troublesome Weeds in Grass Crops, Pasture and Turf in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. http://wssa.net/wp-content/uploads/2020-Weed-Survey_grass-crops.xlsx
Visarada KBRS, Aruna C (2019) Sorghum: a bundle of opportunities in the 21st century. Pages 1–14 *in* Aruna C, Visarada KBRS, Bhat BV, Tonapi VA, eds. Breeding Sorghum for Diverse End Uses. Cambridge, UK: Woodhead Publishing
Ward M, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12–27
Weisberger DA, Leon RG, Gruner CE, Levi M, Gaur N, Morgan G, Basinger NT (2024) Demographics of Palmer amaranth (*Amaranthus palmeri*) in annual and perennial cover crops. Weed Sci 72:96–107
Wiggins MS, McClure MA, Hayes RM, Steckel LE (2015) Integrating cover crops and POST herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in corn. Weed Technol 29:412–418