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Effect of fall- and spring-planted cover crops and residual herbicide on emergence dynamics of glyphosate-resistant kochia (*Bassia scoparia*)

Research Article

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Abstract

Two separate field experiments were conducted during the 2021 to 2022 and 2022 to 2023 growing seasons at Kansas State University Agricultural Research Center near Hays, KS, to understand the emergence dynamics of glyphosate-resistant (GR) kochia [*Bassia scoparia* (L.) A. J. Scott] as influenced by fall- and spring-planted cover crops (CC) and residual herbicide. Study sites were under winter wheat (*Triticum aestivum* L.)–sorghum [*Sorghum bicolor* (L.) Moench]–fallow rotation with a natural seedbank of GR *B. scoparia*. In Experiment 1, fall-planted CC mixture (triticale/winter peas/radish/canola) was planted after wheat harvest and terminated at triticale [×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*] heading stage (next spring before sorghum planting). In Experiment 2, spring-planted CC mixture (oats/barley/spring peas) was planted in sorghum stubbles and terminated at oats (*Avena sativa* L.) heading stage. Four treatments were established in each experiment: (1) nontreated control (no CC and no herbicide), (2) chemical fallow (no CC but glyphosate acetochlor/atrazine or flumioxazin/pyroxasulfone dicamba were used to control weeds), (3) CC terminated with glyphosate, and (4) CC terminated with glyphosate plus residual herbicide (acetochlor/atrazine for fall-planted CC and flumioxazin/pyroxasulfone for spring-planted CC). Results indicated that fall-planted CC delayed GR *B. scoparia* emergence by 3 to 5 wk, whereas spring-planted CC delayed emergence by 0 to 2 wk compared with nontreated control. Fall-planted CC terminated with glyphosate plus acetochlor/atrazine reduced the cumulative emergence of GR *B. scoparia* by 90% to 95% compared with nontreated control across both years. Similarly, spring-planted CC terminated with glyphosate plus flumioxazin/pyroxasulfone reduced the cumulative emergence of GR *B. scoparia* by 83% to 90% compared with nontreated control. These results suggest that fall- or spring-planted CC in combination with residual herbicide at termination can be utilized for GR *B. scoparia* suppression. Results from this study will help in developing prediction models for GR *B. scoparia* emergence under different CC strategies.

Introduction

Kochia [*Bassia scoparia* (L.) A. J. Scott] is an invasive summer annual broadleaf weed belonging to the Chenopodiaceae family (Kumar et al. 2019). It is tolerant to various abiotic stresses, including drought, heat, cold, and salinity (Christoffoleti et al. 1997; Friesen et al. 2009). *Bassia scoparia* is a C_4 summer annual plant that can thrive well under hot temperatures. It can germinate early in the spring, and seedlings can survive spring freezing night temperatures (Dille et al. 2017; Friesen et al. 2009; Kumar et al. 2018). *Bassia scoparia* exhibits wide genetic diversity due to a high degree of outcrossing and pollen-mediated gene flow (Beckie et al. 2016; Mengistu and Messersmith 2002). It is a prolific seed producer, and single plant can produce up to 100,000 seeds that can be dispersed over long distances via a wind-mediated tumbling mechanism (Christoffoleti et al. 1997; Friesen et al. 2009; Kumar et al. 2019).

Bassia scoparia has been reported to reduce the grain yield of many field crops, including corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr.], sugar beet (*Beta vulgaris* L.), sunflower (*Helianthus annuus* L.), alfalfa (*Medicago sativa* L.), canola (*Brassica napus* L.), spring wheat (*Triticum aestivum* L.), and spring oats (*Avena sativa* L.) (Geddes and Sharpe 2022; Kumar and Jha 2015; Lewis and Gulden 2014; Wicks et al. 1994, 1997). The magnitude of crop yield loss depends on the *B. scoparia* density and time of emergence (Geddes and Sharpe 2022; Wicks et al. 1994, 1997). For instance, *B. scoparia* reduced yield by 95% in grain sorghum at a density of 184 plants m^{-2} (Wicks et al. 1994), 23% to 77% in soybean at 20 to 135 plants m^{-2} (Geddes and Sharpe 2022; Wicks et al. 1997), 60% in sugar beet at 268 plants m^{-2} (Kumar and Jha 2015), and 62% to 95% in sunflower at 34 to 905 plants m^{-2} (Lewis and Gulden 2014).

Bassia scoparia has high tendency to evolve herbicide resistance (Heap 2024). Currently, *B. scoparia* populations have evolved resistance to five different herbicide sites of action, including inhibitors of acetolactate synthase (ALS) (Group 2), synthetic auxins (Group 4), photosystem II (Group 5), 5-enolpyruvylshikimate-3-phosphate synthase (Group 9), and protoporphyrinogen oxidase (Group 14) (Heap 2024). Among all reported resistance cases, multiple resistance to glyphosate and ALS inhibitors has been reported as widespread among *B. scoparia* populations across the U.S. Great Plains (Beckie et al. 2013; Heap 2024; Kumar et al. 2015; Sharpe et al. 2023; Westra et al. 2019). Effective and alternative strategies are urgently needed to mitigate the further evolution and spread of herbicide-resistant *B. scoparia* (Kumar et al. 2019).

Bassia scoparia exhibits an extended period of emergence during the growing season (Dille et al. 2017). In addition, differential emergence patterns have been reported among different *B. scoparia* populations from the U.S. Great Plains (Dille et al. 2017; Kumar et al. 2018). For instance, Dille et al. (2017) reported that 168 cumulative growing degree days (GDD) were needed for 10% emergence of *B. scoparia* populations from Kansas, while only 90 GDD were needed for Wyoming and Nebraska populations in a fallow study. Similarly, Kumar et al. (2018) reported that 151 to 346 cumulative GDD were needed for 10% emergence of *B. scoparia* populations from Kansas, 241 to 266 GDD for an Oklahoma population, and 185 to 291 GDD for a Montana population in a common garden study conducted in Montana. These studies also found that the emergence of most *B. scoparia* populations from the U.S. Great Plains occurred between April 9 and May 31, which could overlap with the planting window of cash crops based on the region (Dille et al. 2017; Kumar et al. 2018)

Winter wheat–grain sorghum–fallow (W-S-F) is a dominant crop rotation in the semiarid central Great Plains (CGP) region, including Kansas (Holman et al. 2022). This 3-yr crop rotation includes a fallow period of about 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). Replacing these fallow periods with cover crops (CC) may provide effective weed suppression in no-till (NT) cropping systems of the CGP region (Kumar et al. 2020). For instance, Petrosino et al. (2015) reported 78% to 94% reduction in *B. scoparia* density with fall-planted CC (triticale/triticale–hairy vetch mixture) compared with chemical fallow in winter wheat–fallow rotation. Obour et al. (2022) reported that spring-planted CC (oats/triticale/spring peas) during the fallow phase of a W-S-F rotation reduced total weed biomass (dominated by *B. scoparia* with 36% mean relative abundance) by 86% to 99% compared with weedy fallow. Nonetheless, limited information exists on the impact of fall- or spring-planted CC in combination with residual herbicides at termination on the emergence of GR *B. scoparia* in the NT dryland W-S-F rotation. Therefore, the main objective of this study was to determine the effect of fall- and spring-planted CC terminated with glyphosate alone or glyphosate with residual herbicide on emergence dynamics and periodicity of GR *B. scoparia* in NT dryland W-S-F crop rotation.

Materials and Methods

Experiment 1. Effect of Fall-planted CC on GR B. scoparia Emergence

A field study was conducted at Kansas State University Agricultural Research Center near Hays (KSU-ARCH), KS (38.85196°N, 99.34279°W; semiarid CGP region) from fall 2021 through fall 2023. Detailed information about this study has previously been described in Dhanda et al. (2024). The field site was under an NT dryland W-S-F rotation with a history of natural seedbank of GR *B. scoparia* and Palmer amaranth (*Amaranthus palmeri* S. Watson). All three phases of the crop rotation (W-S-F) were present in each experimental year. Each year, a CC mixture of winter triticale [×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*] (60%)/winter peas (*Pisum sativum* L.) (30%)/canola (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). The design was a randomized complete block with four replications. Treatments were (1) nontreated control, (2) chemical fallow, (3) CC terminated with glyphosate (Roundup PowerMax®, Bayer Crop Science, St Louis, MO) at 1,260 g ae ha^{-1}, and (4) CC terminated with glyphosate at 1,260 g ha^{-1} plus a premix of acetochlor/atrazine (Degree Xtra®, Bayer Crop Science) at 1,665/826 g ai ha^{-1}. In the nontreated control, no CC was planted and no herbicides were applied to control weeds, whereas in chemical fallow, no CC was planted but the plot area was treated with glyphosate at 1,260 g ha^{-1} plus a premix of acetochlor/atrazine at 1,665/826 g ha^{-1} plus dicamba (Clarity®, BASF, Research Triangle Park, NC) at 560 g ae ha^{-1} at the same time as CC termination in the spring. The individual plot size was 45-m long and 6.5-m wide each year. 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. Table 1 provides the details of CC planting and termination dates as well as the dates for planting and harvesting grain sorghum for each experimental year.

Table 1. Planting and termination dates for cover crops and planting and harvesting dates for grain sorghum and winter wheat during 2021–2023 and 2022–2024 seasons at Kansas State University Agricultural Research Center near Hays, KS.

Crop	Operation	2021–2023	2022–2024
Fall-planted cover crop	Planting	October 7, 2021	September 30, 2022
	Termination	May 11, 2022	May 22, 2023
Grain sorghum	Planting	June 2, 2022	June 15, 2023
	Harvesting	October 26, 2022	October 19, 2023
Spring-planted cover crop	Planting	March 16, 2022	March 3, 2023
	Termination	June 23, 2022	June 13, 2023
Winter wheat	Planting	September 30, 2022	October 2, 2023
	Harvesting	July 6, 2023	July 10, 2024

Experiment 2. Effect of Spring-planted CC on GR B. scoparia Emergence

A field study was conducted at KSU-ARCH during the 2022 and 2023 growing seasons. Similar to Field Experiment 1, the field site was under an NT dryland W-S-F rotation with a history of natural seedbank of GR *B. scoparia* and *A. palmeri*. The soil type at the experimental site was a Roxbury silt loam with a pH of 6.9 and organic matter of 1.6%. Each year, all three phases of the crop rotation (W-S-F) were present. A CC mixture of oats (40%)/barley (*Hordeum vulgare* L.) (40%)/spring peas (*Pisum sativum* L.) (20%) was drilled at a seeding rate of 67 kg ha^{-1} in sorghum stubble in March and terminated at the oats heading stage (Table 1). The design was a randomized complete block with four replications.

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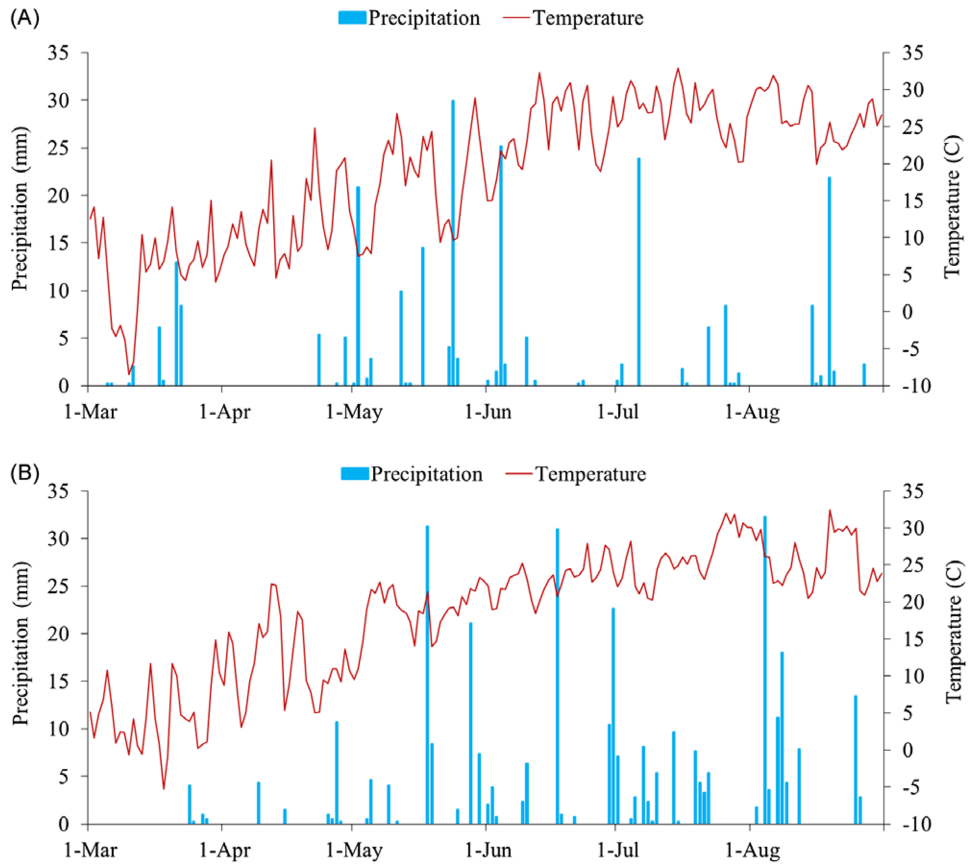

Figure 1. Daily average air temperature (C) and precipitation (mm) during the 2022 (A) and 2023 (B) growing seasons (Kansas State University Mesonet weather station).

Treatments were (1) nontreated control, (2) chemical fallow, (3) CC terminated with glyphosate (Roundup PowerMax®, Bayer Crop Science) at 1,260 g ha^{-1}, and (4) CC terminated with glyphosate at 1,260 g ha^{-1} plus a premix of flumioxazin/pyroxasulfone (Fierce® EZ, Valent USA, Walnut Creek, CA) at 106/134 g ai ha^{-1} were established each year. In the nontreated control, no CC was planted and no herbicides were applied to control weeds, whereas in chemical fallow, no CC was planted, but the plot area was treated with glyphosate at 1,260 g ha^{-1} plus a premix of flumioxazin/pyroxasulfone at 106/134 g ha^{-1} plus dicamba (Clarity®, BASF) at 560 g ha^{-1} at the same time as CC termination. The individual plot size was 45-m long and 6.5-m wide each year. Winter wheat variety 'Joe' was planted at a seeding rate of 67 kg ha^{-1} in rows spaced 19.1 cm apart. Details for CC planting and termination dates and dates for planting and harvesting winter wheat for each experimental year are provided in Table 1.

Data Collection

Both fall- and spring-planted CC biomass was recorded by manually harvesting aboveground shoots from two 1-m^2 quadrats from each plot just before CC termination and oven-drying it at 72 C for 4 d to obtain dry biomass. For both experiments, each year, two permanent 1-m^2 quadrats were established in each plot during mid-February for GR *B. scoparia* emergence counts. Newly emerged GR *B. scoparia* seedlings from each permanent quadrat were counted when cotyledons were fully expanded and were removed manually every week starting from their first appearance (Hartzler et al. 1999). *Amaranthus palmeri* and puncturevine (*Tribulus terrestris* L.) were also present each year and were removed manually along with GR *B. scoparia* every week. The end date for counting the emergence of GR *B. scoparia* was chosen each year when no new emergence was observed over 21 d in both experiments. The average number of GR *B. scoparia* seedlings from the two permanent quadrats in each plot at each sample timing was used for data analysis. Data on daily minimum and maximum air temperatures 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) (Figure 1).

Weekly emergence data from both experiments were used to calculate the cumulative and daily emergence of GR *B. scoparia*. Cumulative emergence of GR *B. scoparia* under each treatment was determined by adding average emergence counts from both quadrats on a sample date and the previously sampled date. The daily emergence of GR *B. scoparia* under each treatment was calculated by dividing the average emergence counts from both quadrats on a sample date with the number of days between a sample date and the previously sampled date. The peak emergence period for GR *B. scoparia* was determined using a quality-control method (Jha and Norsworthy 2009; Montgomery et al. 2001). The peak emergence was considered when the daily emergence was greater than the total emergence in a season divided by the number of days between the first

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Figure 2. Daily emergence of glyphosate-resistant *Bassia scoparia* under different fall-planted cover crop treatments in 2022 and 2023 at Kansas State University Agricultural Research Center near Hays, KS. The horizontal solid line for each treatment represents the daily mean emergence, and the dashed line represents the mean plus the SD for each treatment.

and the last day of emergence plus the standard deviation of daily emergence of all replications in a treatment.

Statistical Analyses

Data for cumulative emergence from both experiments at each sample timing were subjected to ANOVA separately 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, Cary, NC). Cumulative emergence counts at each sample timing were log transformed to improve the normality of the residuals and homogeneity of variance; however, back-transformed data are presented with mean separation based on the transformed data. For each experiment, treatment, year, sample timing (CC termination and last emergence timing), and their interactions were considered as fixed effects, and replication and all interactions involving replication were considered as random effects. The year-by-treatment interaction for each experiment was significant ($P < 0.05$); therefore, data for each experiment were analyzed separately for each year. The interaction between treatment and sampling timing for both experiments was significant ($P < 0.05$); therefore, data were sorted by sampling timings using PROC SORT. Treatment means were separated using Fisher's protected LSD test ($P < 0.05$) for each emergence sampling timing.

Results and Discussion

The total amount of precipitation received during the fall-planted CC growing season (September to May) in 2021 to 2022 and 2022 to 2023 were 99 and 130 mm, respectively. The average fall-planted CC biomass at the time of termination was 1,130 kg ha^{-1} in 2022 and 1,470 kg ha^{-1} in 2023. Similarly, the total amount of precipitation received during the spring-planted CC growing season (March to June) was 164 mm in 2022 and 184 mm in 2023 (Figure 1). Average spring-planted CC biomass at the time of termination was 1,290 kg ha^{-1} in 2022 and 4,060 kg ha^{-1} in 2023.

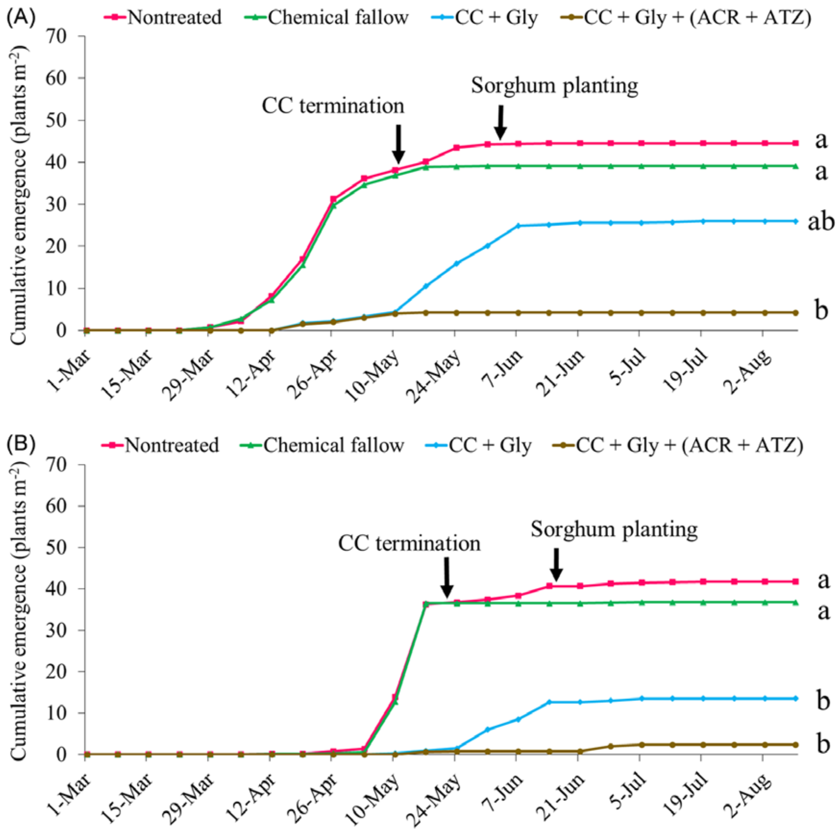

Figure 3. Cumulative emergence of glyphosate-resistant *Bassia scoparia* under different fall-planted cover crop (CC) treatments in 2022 (A) and 2023 (B) at Kansas State University Agricultural Research Center near Hays, KS. Arrows indicate the dates for fall-planted CC termination and planting of grain sorghum. Means for the cumulative emergence at the end of the line followed by the same letters are not significantly different based on Fisher's protected LSD test. CC Gly, CC terminated with glyphosate only; CC Gly (ACR ATZ), CC terminated with glyphosate plus a premix of acetochlor and atrazine.

Relatively higher CC biomass in 2023 compared with 2022 might be due to the higher rainfall and better growth of CC in 2023.

Experiment 1. Effect of Fall-planted CC on GR B. scoparia Emergence

In 2022, the GR *B. scoparia* in nontreated control emerged between March 29 and June 20 with two emergence peaks from April 19 to May 2 (Figure 2). These peak emergence periods coincided with precipitation events (Figures 1 and 2). There were three rainfall events (each event >5 mm) from April 19 to May 2, with a total rainfall of 32 mm during this period (Figure 1). The emergence of GR *B. scoparia* at the end of March indicates its early emergence in spring as previously reported in several studies (Dille et al. 2017; Friesen et al. 2009; Kumar et al. 2018). Herbicide application was made on May 11 in chemical fallow treatment; therefore, the emergence of GR *B. scoparia* in chemical fallow was similar to nontreated control before May 11 (Figure 3). After herbicide application in chemical fallow, the cumulative emergence of GR *B. scoparia* was reduced by 65% compared with nontreated control (Figure 3). Both CC treatments delayed GR *B. scoparia* emergence by 3 wk compared with nontreated control and chemical fallow, with the first emergence observed on April 19. These results indicate the suppressive effect of live CC on GR *B. scoparia* emergence. Previous studies have also noted a delayed emergence of weeds with live CC or dry biomass as residue (Moore et al. 1994; Norsworthy et al. 2007; Teasdale and Pillai 2005). Actively growing CC (green) could reduce weed emergence by changing the quality of light mainly red-to-far red ratio that reaches the weed seeds on the soil surface and ultimately changes their physiological development (Silva and Bagavathiannan 2023). Also, *B. scoparia* seedlings might have died rapidly just after germination due to light restriction and root competition from CC plants. The peak emergence of GR *B. scoparia* in CC terminated with glyphosate only occurred from May 17 to June 13, which coincided with precipitation events. There were three rainfall events (each event >10 mm) from May 17 to June 13, with a total rainfall of 82 mm during this period (Figure 1). No peak emergence of GR *B. scoparia* was observed under CC terminated with glyphosate plus acetochlor/atrazine. This indicates the synergistic effect of CC and residual herbicide to suppress *B. scoparia* emergence. The cumulative emergence of GR *B. scoparia* under CC terminated with glyphosate plus acetochlor/atrazine was reduced by 90% and 84% compared with nontreated control and CC terminated with glyphosate alone, respectively. Petrosino et al. (2015) also reported 78% to 94% reduction in *B. scoparia* density with fall-planted CC (triticale/triticale–hairy vetch mixture) compared with chemical fallow in winter wheat–fallow rotation. Results indicated >95% emergence of GR *B. scoparia* occurred before grain sorghum planting (June 2) in all treatments, indicating the importance of early-season control of *B. scoparia.*

In 2023, the emergence of GR *B. scoparia* seedlings was first observed on April 12 in nontreated control and chemical fallow, and emergence continued up to July 25 in nontreated control and July 11 in chemical fallow (Figure 2). The relatively late emergence of GR *B. scoparia* in 2023 (April 12) compared with 2022 (March 29) could

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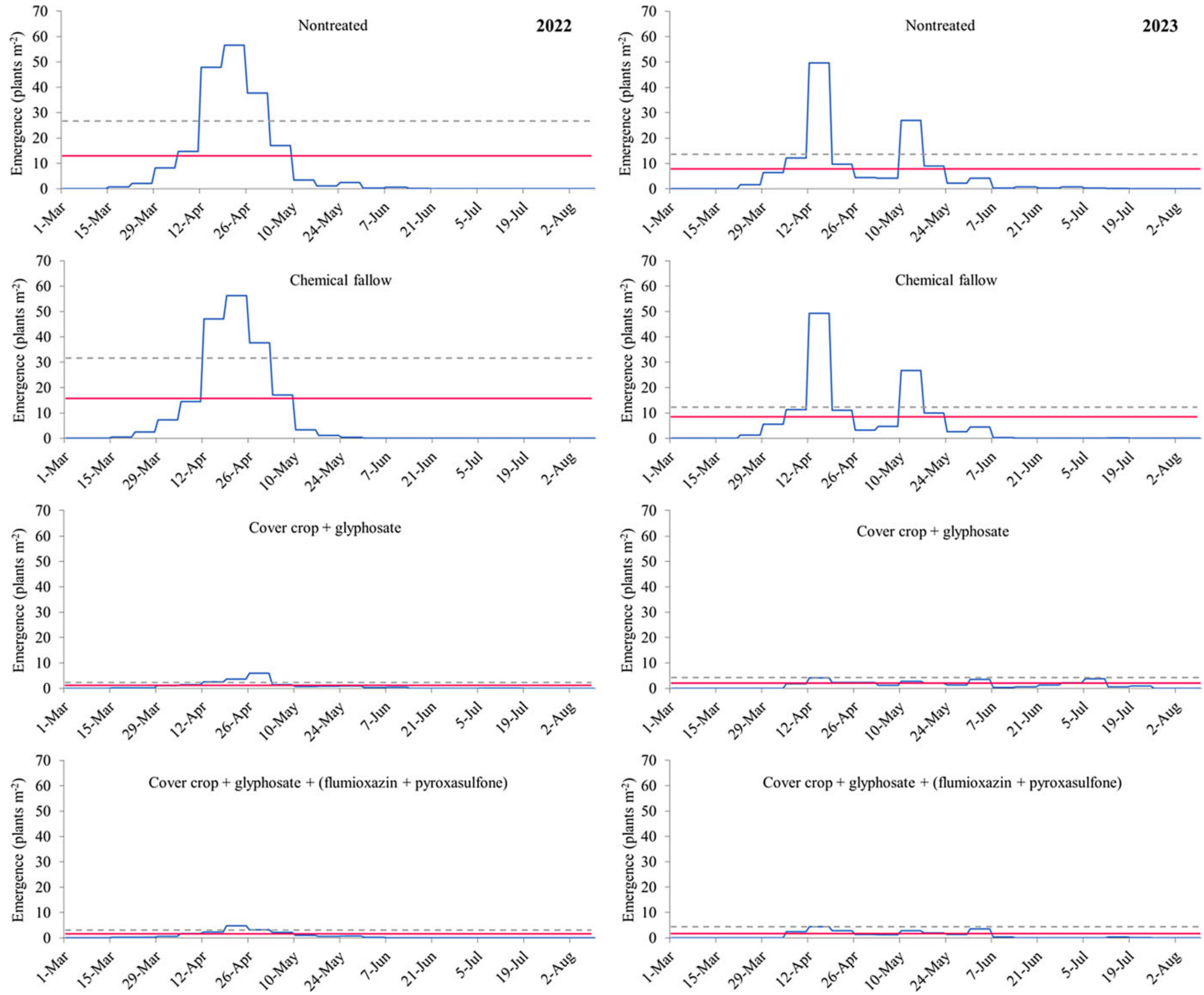

Figure 4. Daily emergence of glyphosate-resistant *Bassia scoparia* under different spring-planted cover crop treatments in 2022 and 2023 at Kansas State University Agricultural Research Center near Hays, KS. The horizontal solid line for each treatment represents the daily mean emergence, and the dashed line represents the mean plus the SD for each treatment.

be because of lower precipitation from March 15 to April 15 in 2023 (12 mm) compared with 2022 (28 mm). The peak emergence under both nontreated control and chemical fallow occurred from May 10 to May 23, coinciding with rainfall events with a total of 44 mm (13% of total rainfall from March to August) (Figures 1 and 2). Herbicide application in chemical fallow was made on May 22; therefore, the emergence of GR *B. scoparia* in chemical fallow and nontreated control was similar before May 22 (Figure 3). After herbicide application in chemical fallow, the cumulative emergence was reduced by 95% compared with nontreated control. Both CC treatments delayed the GR *B. scoparia* emergence by 5 wk compared with nontreated control and chemical fallow, with the first emergence observed on May 17. Delayed emergence of GR *B. scoparia* coincides with that of *A. palmeri* emergence in the south-central Great Plains (Liu et al. 2022). This timing provides an opportunity to control both *B. scoparia* and *A. palmeri* simultaneously, saving on herbicide applications that would otherwise be necessary in early spring (March or April) to control *B. scoparia* separately. Additionally, the weak and less vigorous seedlings resulting from CC suppression can be easily killed with herbicides to start clean for the subsequent cash crop (Brainard et al. 2005; Steckel et al. 2003). It was interesting to note that no peak emergence was observed in both CC treatments, indicating the effective suppression of GR *B. scoparia* through fall-planted CC. The cumulative emergence of GR *B. scoparia* under CC terminated with glyphosate plus acetochlor/atrazine was reduced by 95% compared with nontreated control and chemical fallow and by 82% compared with CC terminated with glyphosate only. Several previous research studies have also reported the importance of residual herbicides in combination with CC termination for a season-long weed control (Dhanda et al. 2024; Whalen et al. 2020).

Experiment 2. Effect of Spring-planted CC on GR B. scoparia Emergence

In 2022, GR *B. scoparia* emerged from March 15 to June 20 in nontreated control and March 15 to June 13 in chemical fallow, with peak emergence from April 12 to May 2 (Figure 4). The peak

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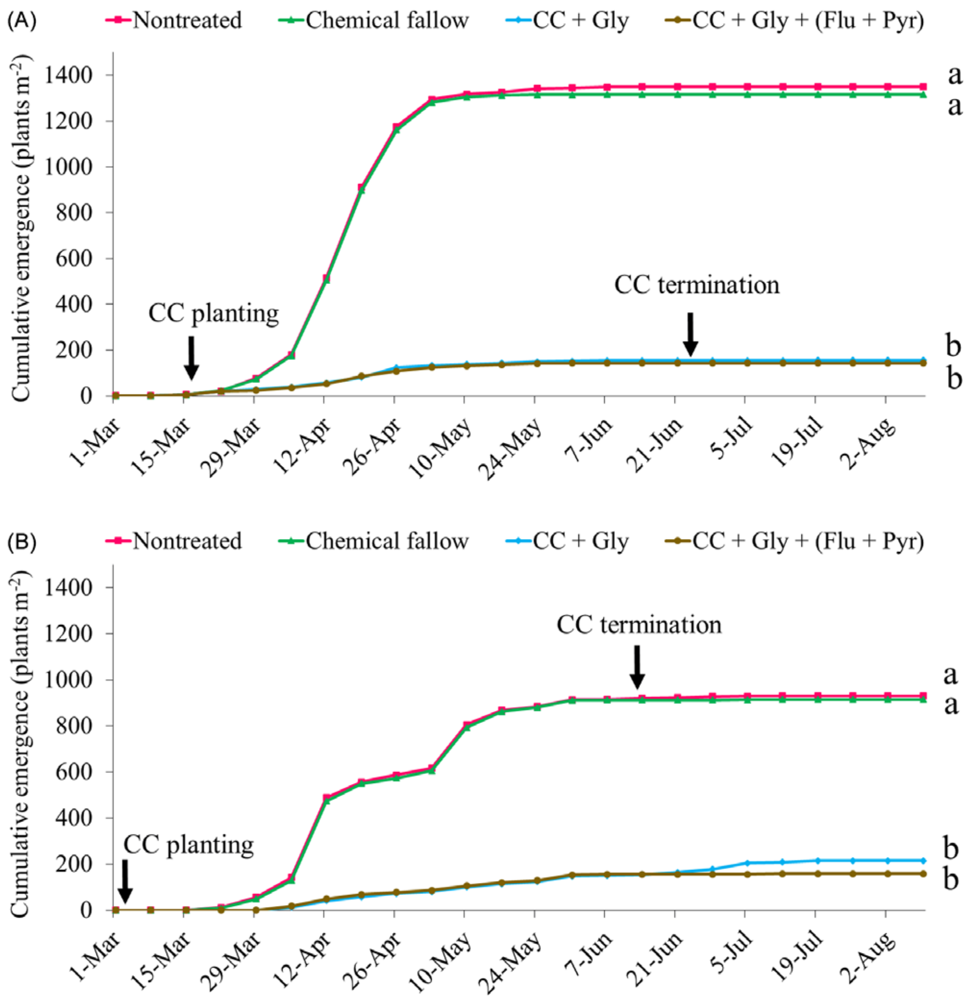

Figure 5. Cumulative emergence of glyphosate-resistant *Bassia scoparia* under different spring-planted cover crop (CC) treatments in 2022 (A) and 2023 (B) at Kansas State University Agricultural Research Center near Hays, KS. Arrows indicate the dates for planting and termination of spring-planted CC. Means for the cumulative emergence at the end of the line followed by the same letters are not significantly different based on Fisher's protected LSD test. CC Gly, CC terminated with glyphosate only; CC Gly (Flu Pyr), CC terminated with glyphosate plus a premix of flumioxazin and pyroxasulfone.

emergence periods coincided with three rainfall events (each event >5 mm) with a total of 32 mm during this period of April 12 to May 2 (Figure 1). Emergence of GR *B. scoparia* from nontreated control and chemical fallow was similar before herbicide application in chemical fallow (June 23). GR *B. scoparia* under both CC treatments emerged at the same time (March 15) as nontreated control and chemical fallow (Figures 4 and 5). This could be because of the early emergence of *B. scoparia* compared with CC planting (March 16). Peak emergence occurred under both CC treatments from April 12 to May 2 and was similar to nontreated control and chemical fallow, but the peaks were smaller (3 to 6 seedlings m^{-2}) under both CC treatments than nontreated control and chemical fallow (38 to 48 seedlings m^{-2}) (Figure 4). There was no emergence of GR *B. scoparia* after CC terminated with glyphosate plus flumioxazin/pyroxasulfone, however; seedlings emerged (0.1 seedlings m^{-2}) from July 5 to July 17 in CC terminated with glyphosate only. These results further corroborate the importance of adding residual herbicide with CC for season-long weed control. These results are consistent with those of Perkins et al. (2021), who reported 75% to 94% lower density of *A. palmeri* with a CC mixture of cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) and residual herbicides (flumioxazin/pyroxasulfone, flumioxazin, pyroxasulfone, or acetochlor) compared with CC without residual herbicide. The cumulative emergence of GR *B. scoparia* under both CC treatments was reduced by 90% compared with nontreated control. These results are consistent with those of Petrosino et al. (2015), who also reported a 94% reduction in *B. scoparia* density in western Kansas with spring-planted CC (triticale or a triticale–hairy vetch mixture).

In 2023, GR *B. scoparia* emerged from March 22 to July 18 in both nontreated control and chemical fallow, with peak emergence from April 12 to April 18 and May 10 to May 16 (Figure 4). In both CC treatments, the emergence of GR *B. scoparia* was delayed by 2 wk and occurred from April 5 to July 25. The CC was planted relatively early in 2023 (March 3) compared with 2022 (March 16); this might have resulted in emergence delay in 2023 compared with no delay in 2022 (Figures 3 and 5). There was no peak emergence in both CC treatments, indicating effective suppression of GR *B. scoparia*. Both CC treatments reduced GR *B. scoparia* emergence by 77% to 83% compared with nontreated control or chemical fallow. Interestingly, more than 95% of GR *B. scoparia* emerged before CC termination in nontreated control, chemical fallow, and CC terminated with glyphosate plus flumioxazin/pyroxasulfone, and 70% emerged before CC termination in CC terminated with glyphosate only (Figure 5). These results indicate the role of live (green) CC for the spring-planted window, whereas for fall-planted CC, both live CC and residue can play a role for GR *B. scoparia* suppression. Significantly lower cumulative emergence of GR *B. scoparia* in CC terminated with glyphosate only compared with chemical fallow suggests reduced herbicide selection pressure (Figure 5), which could ultimately delay or mitigate the evolution of further herbicide resistance. Obour et al. (2022) also reported that spring-planted CC (oats/triticale/spring peas) in W-S-F rotation reduced total weed density by 82% compared with weedy fallow.

In summary, these results indicate that integration of either fall- or spring-planted CC can reduce GR *B. scoparia* emergence in the W-S-F rotation in a semiarid environment. Furthermore, fewer and late-emerging GR *B. scoparia* with reduced vigor would produce lower biomass with lower seed production potential, which can further help in reducing the weed seedbank (Brainard et al. 2011; Sias et al. 2021). However, it is important to note that growing CC under a moisture-limited environment sometimes could also negatively impact the yield of the successive cash crops (Holman et al. 2018; Nielsen et al. 2016). Conversely, beyond weed suppression, CC can enhance soil health, control erosion, and improve nutrient cycling, thereby increasing the overall sustainability of cropping systems (Ghimire et al. 2018; Yousefi et al. 2024). These results will be helpful in developing prediction models for a GR *B. scoparia* emergence under CC plus residual herbicide strategy, which can play an important role in scheduling GR *B. scoparia* control measures (Reinhardt Piskackova et al. 2021). Future studies should evaluate the economics of growing CC in the NT dryland W-S-F rotation. Additionally, research should assess the effects of integrating other weed control tactics (such as harvest weed seed control, strategic tillage, spray drones, etc.) in combination with fall- or spring-planted CC and residual herbicides on the seedbank dynamics of GR *B. scoparia* in the region.

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Competing interests. The authors declare no conflicts of interest.

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