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Using soybean chaff lining to manage waterhemp (*Amaranthus tuberculatus*) in a soybean–corn rotation

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Abstract

Waterhemp (*Amaranthus tuberculatus* [Moq.] Sauer) escapes are common in midwestern U.S. soybean [*Glycine max* (L.) Merr.] fields due to the continued rise in herbicide-resistant (HR) populations. In a conventional harvesting system, weed seeds are harvested with the crop grain and spread back on to the field. Harvest weed seed control methods such as chaff lining concentrate weed seed-bearing crop and weed chaff into a narrow row (chaff line). These chaff lines (30- to 50-cm wide) are undisturbed the following growing seasons, under the assumption that the chaff line creates an environment less favorable for weed seed germination and survival. Field experiments were conducted in a soybean–corn (*Zea mays* L.) rotation in 2020 and 2021 in Ames, IA, and Roland, IA, to quantify the effectiveness of chaff lining for managing *A. tuberculatus* seeds. About 70% of the *A. tuberculatus* seeds were retained on the mother plant at soybean harvest in 2020. The chaff lining system concentrated more than 99% of the *A. tuberculatus* seeds exiting the combine into the chaff line. Although *A. tuberculatus* population density in 2021 was 76% higher inside the chaff line than outside the chaff line, *A. tuberculatus* aboveground biomass was 63% lower inside the chaff line than outside the chaff line at 12 wk after corn planting. Similarly, *A. tuberculatus* inside the chaff line had delayed emergence compared with *A. tuberculatus* outside the chaff line. Application of preemergence herbicides in corn inside the chaff line delayed *A. tuberculatus* emergence by more than 2 wk compared with *A. tuberculatus* outside the chaff line. Additionally, a follow-up postemergence herbicide application in corn was needed only inside the chaff line to manage *A. tuberculatus*, suggesting the possibility of lower overall herbicide use. These results support implementing chaff lining in soybean-based crop systems of the U.S. Midwest to help manage HR *A. tuberculatus* seedbanks.

Introduction

Waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] is one of the most common and troublesome weeds in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production systems of the midwestern United States (Van Wychen 2019, 2020). *Amaranthus tuberculatus* is well adapted to no-till crop systems and can reduce corn and soybean grain yields by more than 40% if left uncontrolled (Hager et al. 2002; Steckel and Sprague 2004). It has evolved resistance to seven different herbicide groups, including synthetic auxins (2,4-D and dicamba) and inhibitors of enolpyruval shikimate phosphate synthase (glyphosate), acetolactate synthase, photosystem II, protoporphyrinogen oxidase, 4-hydroxyphenylpyruvate dioxygenase, and very-long-chain fatty-acid synthesis (Bobadilla et al. 2022; Tranel 2021).

Amaranthus tuberculatus emergence commences in mid-May and continues until early August (Hartzler et al. 1999). This prolonged emergence window typically requires multiple herbicide applications to manage this species (Hager et al. 1997). Increased herbicide use has resulted in widespread occurrence of multiple herbicide resistant (MHR) *A. tuberculatus* populations across the U.S. Midwest (Heap 2023). Therefore, *A. tuberculatus* plants surviving herbicide applications and/or emerging after herbicides have degraded are an increasingly serious problem due to their potential to add large numbers of seeds to the soil seedbank (Hager et al. 1997; Hartzler et al. 2004). Furthermore, widespread occurrence of MHR populations increases weed control costs by causing a reversion to tillage and increased herbicide use, hence increasing the risk of adverse environmental impacts (Price et al. 2011). Therefore, there is a need to implement nonchemical weed management strategies in soybean–corn rotations of the U.S. Midwest (Tranel 2021)

Chaff lining is a harvest weed seed control (HWSC) method that targets weed seeds during crop harvest (Walsh et al. 2018). Several HWSC methods such as chaff carts, narrow-windrow burning, bale direct system, chaff tramlining, chaff lining, and weed seed destruction have been used in Australian small grain production fields to help manage herbicide-resistant (HR) weeds

Figure 1. Chaff lining system attached to John Deere S660 combine concentrating weed seed–bearing soybean chaff in a narrow row.

(Walsh et al. 2018). About 50% of Australian growers are currently using HWSC methods (Walsh et al. 2017). Among these, chaff lining is the most widely used and inexpensive HWSC method (Walsh and Newman 2007; Walsh et al. 2017). The chaff lining method uses a chute attached to the rear of the combine to divert the weed seed–bearing chaff fraction into a narrow row/chaff line (Figure 1). These chaff lines (30- to 50-cm wide) are undisturbed during the following growing seasons, under the assumption that an environment less favorable for germination and seed survival will develop (Walsh et al. 2021).

Crop residue on the soil surface physically suppresses weed seed germination and seedling emergence (Brecke and Shilling 1996; Purvis et al. 1985). Chaff lining creates a thick layer of crop residue that can prolong the physical suppression of weed seedling emergence. Walsh et al. (2021) reported more than 80% reduction in rigid ryegrass (*Lolium rigidum* Gaudin) emergence from wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) chaff.

Despite a high adoption rate of chaff lining in Australian small grain production fields, limited information is available on its potential for implementation in U.S. production fields. Therefore, there is a need to evaluate the usefulness of this tactic for combating MHR *A. tuberculatus* populations in the midwestern United States. We hypothesized that the mulch effect of crop and weed chaff residue (chaff lining) would suppress *A. tuberculatus* emergence and growth in the following growing seasons. The specific objectives of this research were: (1) to determine *A. tuberculatus* seed retention at soybean harvest, (2) to quantify the proportion of combine-collected *A. tuberculatus* seeds that are concentrated into a chaff line, and (3) to evaluate the effect of soybean chaff line on *A. tuberculatus* population density and biomass in corn.

Materials and Methods

Experimental Site

Field experiments were conducted during 2020 and 2021 at two sites: the Iowa State University Curtiss Farm, Ames IA (42.004°N, 93.674°W) and a private farm near Roland, IA (42.004°N, 93.674°W). Sites had been planted with corn–soybean rotations for the past 8 yr. Fields were chisel plowed followed by a cultivator before the establishment of the experiments. The soil at the Ames site was a mixture of Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) and Clarion sandy clay loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls), with pH 7.4 and 4.4% organic matter. Soil at the Roland site was a mixture of Clarion sandy clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet clay loam soil profile (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), with pH 6.5 and 2.8% organic matter. Sites had a history of high *A. tuberculatus* population densities.

Experimental Design

A randomized split-split-plot design with three replications across 2 yr in a soybean–corn rotation was used. The study design included three factors. The first and second factors were established in soybean in 2020, and the third factor was established in corn in 2021 (Figure 2). The first factor consisted of two levels of *A. tuberculatus* infestation (low and high) in soybean. Two different herbicide treatments were used to achieve two levels of *A. tuberculatus* infestation to determine the impact of different amounts of crop–weed chaff/residue passing through the combine on the functionality of the chaff lining system(Table 1). The first factor was assigned to the whole plots (9.1-m wide by 48.8-m long). A 3-m-wide alleyway between the whole plots was included to prevent movement of *A. tuberculatus* seeds from one plot to another during soybean harvest.

The second factor was established at soybean harvest, when a chaff lining system concentrated *A. tuberculatus* seed–bearing soybean chaff into a 0.5-m-wide row (chaff line) in the center of each plot. Therefore, the second factor included plot area inside the chaff line (0.5-m wide by 48.8-m long) versus plot area outside the chaff line (8.6-m wide by 48.8-m long).

The third factor, established in the following corn crop in 2021, evaluated the efficacy of corn herbicide treatments in managing *A. tuberculatus* inside and outside the chaff lines. This factor was assigned to the sub-subplots across the subplots. The sub-subplots inside the chaff line were 0.5-m wide by 12.8-m long, whereas the sub-subplots outside the chaff line were 8.6-m wide and 12.2-m long. A 1.5-m-wide alleyway was left between the sub-subplots to prevent herbicide movement during herbicide applications. The third factor included four different corn

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Table 1. List of herbicides applied at the V3 growth stage of soybean to achieve low and high levels of *Amaranthus tuberculatus* infestation in 2020.

A. tuberculatus infestation	Herbicide	Rate	Trade name	Manufacturer
		g ai or ae ha^{-1}		
High	Glyphosate + glufosinate	1,261 + 656	Roundup PowerMAX® + Liberty®	Bayer Crop Science, St Louis, MO 63167 BASF Corp., Research Triangle Park, NC 27709
Low	Glyphosate + glufosinate + 2,4D	1,261 + 656 + 454	Roundup PowerMAX® + Liberty® + Enlist One™	Bayer Crop Science, St Louis, MO 63167 BASF Corp., Research Triangle Park, NC 27709 Corteva Agriscience, Johnston, IA 50131

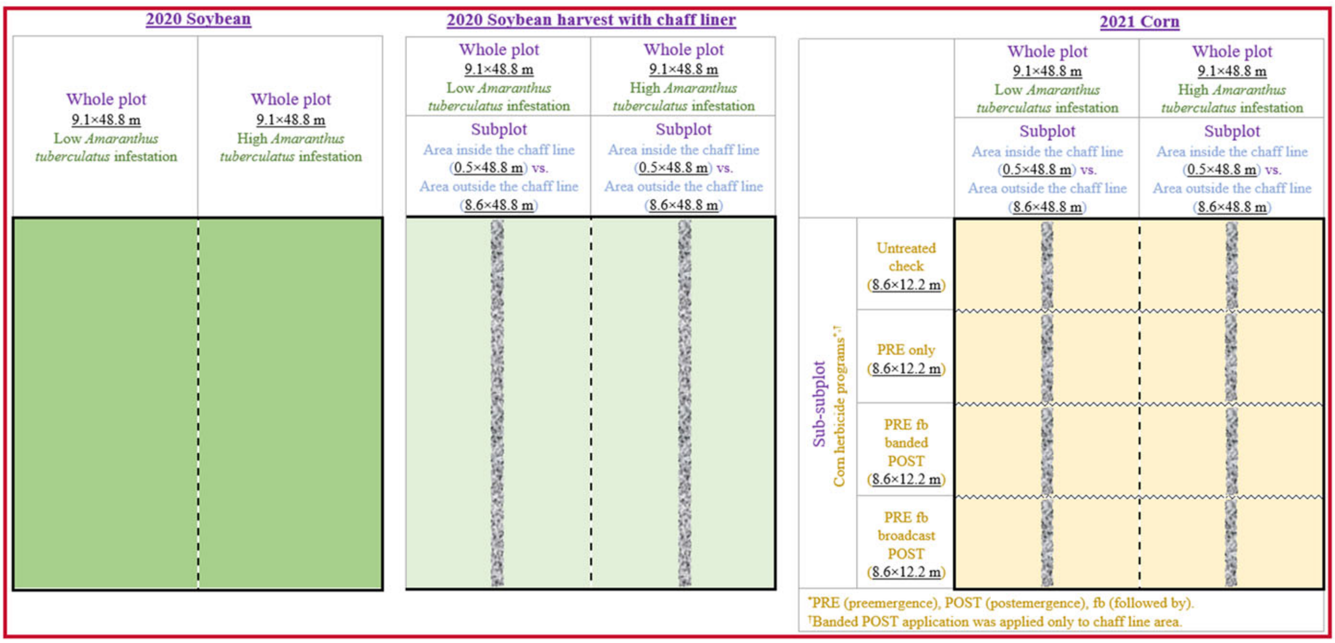

Figure 2. Plot layout of the field experiments conducted across 2 yr (2020 to 2021) in a soybean–corn rotation at the Iowa State University Research Farms near Ames, IA, and Boone, IA.

herbicide treatments: (1) an untreated control, (2) a preemergence herbicide application, (3) a preemergence herbicide application followed by (fb) a banded postemergence herbicide application, and (4) a preemergence herbicide application fb a broadcast postemergence herbicide application (Table 2). The banded postemergence herbicide application was made only to the area inside the chaff line, whereas the broadcast postemergence herbicide application was made to the entire area (inside and outside the chaff line).

Field Operations

A glyphosate-, glufosinate-, and 2,4-D–resistant soybean ('S20-E3', NK® Seeds, Syngenta, Greensboro, NC 27419) was planted in the main plots in 2020 at both sites. Soybean was planted in 76-cm-wide rows on May 14, 2020, at both sites. Herbicide applications were made on June 15 and 17, 2020, at the Ames and Roland sites, respectively, when soybean was at the V3 growth stage. All herbicides were applied using a tractor-mounted sprayer (Frontier LS11 series, John Deere, Moline, IL 61265) equipped with Turbo TeeJet® Induction nozzles (TTI110015VS, TeeJet® Technologies, Glendale Heights, IL 60139). The sprayer was calibrated to deliver 140 L ha^{-1} at 241 kPa. Soybean was harvested with a John Deere S660 combine equipped with the chaff lining system on October 1, 2020, at both sites. The chaff lining system included a commercially made chaff lining kit purchased from WestOZ Boilermaking Services (Cockburn Central, WA 6164, Australia).

A glyphosate- and glufosinate-resistant corn ('PO589AM', Pioneer®, Johnston, IA 50131) was planted in 2021. Corn was planted in 76-cm-wide rows on April 23, 2021, at both sites. The chaff lines were undisturbed during planting. All herbicides were applied using an ATV-mounted CO_2-pressurized boom sprayer equipped with TTI110015VS nozzles calibrated to deliver 140 L ha^{-1} at 241 kPa. All the preemergence herbicides were applied immediately after planting, and the postemergence herbicides were applied on June 8, 2021, when corn was at the V4 growth stage.

Data Collection

Amaranthus tuberculatus population density and seed production were recorded in 2020 to quantify the infestation levels and percent seed retention at soybean harvest. *Amaranthus tuberculatus* population density was measured by counting *A. tuberculatus* plants in ten 0.25-m^2 quadrats in each main plot before soybean harvest. Quadrats were placed in a zigzag pattern spaced 5 m apart.

Amaranthus tuberculatus percent seed retention on the mother plant was measured by enclosing two female plants in seed traps in each plot at the seed development stage. Seed traps were custom designed by making an open-ended bag from Noseeum Mosquito

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Table 2. List of herbicides applied to manage *Amaranthus tuberculatus* in corn in 2021.[a]

Herbicide treatments	Herbicides	Rate	Application[b]	Trade name	Manufacturer
		g ai or ae ha^{-1}			
1	Untreated control	—	—	—	—
2	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor	560 + 34 + 135 + 1,199	PRE	Acuron®	Syngenta Crop Protection, Greensboro, NC 27419
3	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor fb *S*-metolachlor + mesotrione + glyphosate + glufosinate	560 + 34 + 135 + 1,199 fb 1,171 + 117 + 1,171 + 458	PRE fb banded POST	Acuron® fb Halex®GT + Liberty®	Syngenta Crop Protection Greensboro, NC 27419 Syngenta Crop Protection BASF Corp., Research Triangle Park, NC 27709
4	Atrazine + bicyclopyrone + mesotrione + *S*-metolachlor fb *S*-metolachlor + mesotrione + glyphosate + glufosinate	560 + 34 + 135 + 1,199 fb 1,171 + 117 + 1,171 + 458	PRE fb broadcast POST	Acuron® fb Halex®GT + Liberty®	Syngenta Crop Protection, Greensboro, NC 27419 Syngenta Crop Protection, Greensboro, NC 27419 BASF Corp., Research Triangle Park, NC 27709

[a]Abbreviations: fb, followed by; PRE, preemergence; POST, postemergence.
[b]Preemergence herbicides were applied at corn planting and postemergence herbicides were applied at V4 growth stage of corn. The banded postemergence herbicide application was made only to the area inside the chaff line, whereas the broadcast postemergence herbicide application was made to the entire area (inside and outside the chaff line).

Netting Fabric (Online Fabric Store, West Springfield, MA 01089). One end of the bag was secured around the *A. tuberculatus* stem with a plastic cable tie and the other end of the bag was kept open and tied to three PVC pipes anchored in the ground around the plant. *Amaranthus tuberculatus* shattered seeds were collected at 1-wk intervals starting August 27 until soybean harvest on October 1, 2020. The bottom of the bag was opened and shattered seeds were poured into a plastic container at each collection time. Seeds collected at each timing were placed in separate paper envelopes. Plants were cut off at the ground immediately before crop harvest and then air-dried for 2 wk. *Amaranthus tuberculatus* seeds were then threshed by hand-rubbing the inflorescences and cleaned with sieves and an air-column blower (Seedburo® Equipment Company, Des Plaines, IL 60018). Seed samples were weighed, and average seed weight was determined by weighing three subsamples of 1,000 seeds from each sample, and seed production was calculated by dividing the total sample weight with the average seed weight. However, when the total number of seeds in a sample was lower than 1,000, all seeds were counted individually.

The effectiveness of the chaff lining system concentrating *A. tuberculatus* seeds within the chaff line was quantified at soybean harvest. Threshed residue from the back of the combine was collected in aluminum pans (38 cm by 24 cm) placed inside and outside the chaff line. Four pans were placed inside the chaff line, whereas eight pans were placed outside the chaff line (four on each side of the chaff line). Chaff material from each pan was hand threshed to separate the seeds from the chopped *A. tuberculatus* inflorescences. Hand-threshed seeds were cleaned with a series of sieves, and finally with an air-column blower. *Amaranthus tuberculatus* seeds from each sample were counted using the method described previously.

The effect of the soybean chaff line on *A. tuberculatus* emergence rate, population density, and aboveground biomass in corn was quantified in 2021. Four different herbicide treatments in corn were used to quantify the interaction of soybean chaff line with herbicides for *A. tuberculatus* control. *Amaranthus tuberculatus* emergence, inside versus outside the chaff line (sub-subplot), was recorded from two permanently established 0.25-m^2 quadrats in each area. Permanent quadrats inside the chaff lines were established with plastic flags and were spaced 3 m apart. Quadrats outside the chaff lines were established parallel to the quadrats inside the chaff line, but 2 m away from the chaff lines. *Amaranthus tuberculatus* emergence was recorded on a weekly basis from April 28 to July 21, 2021. Emerged seedlings were counted and removed without disturbing the chaff lines at each observation time.

Amaranthus tuberculatus aboveground biomass was recorded for plants growing inside and outside the chaff line in untreated plots to quantify the effect of the soybean chaff line on *A. tuberculatus* growth. Biomass was collected from a 0.25-m^2 quadrat in each area on a weekly basis from June 2 to July 21, 2021. Quadrats were established using the same method described for *A. tuberculatus* population density, except quadrats were spaced 0.5 m apart. *Amaranthus tuberculatus* plants within the quadrats were clipped from the base and placed in paper bags. *Amaranthus tuberculatus* samples were oven-dried at 60 C for 5 d and weighed to determine the dry biomass accumulation.

Statistical Analysis

Data on *A. tuberculatus* population density, seed production, aboveground biomass, and chaff lining system effectiveness were analyzed using PROC MIXED in SAS v. 9.4 software (SAS Institute, Cary, NC 27513). Experimental site and replication were considered random effects. Herbicide treatments in soybean and corn, the chaff lining system, and their interactions were considered fixed effects in the model. Appropriate degrees of freedom in the model were obtained using the Satterthwaite approximation method (Satterthwaite 1946). Estimated means of response variables for inside versus outside the chaff line area were compared using a two-sample *t*-test ($\alpha = 0.05$). Estimated means of *A. tuberculatus* population density in corn were compared using a Tukey test at a significance level of $\alpha = 0.05$.

Percent *A. tuberculatus* seed retention in soybean and *A. tuberculatus* emergence and aboveground biomass in corn were analyzed in the statistical programming language R (R Core Team 2019) using the R extension package DRC (Ritz et al. 2015). A three-parameter log-logistic model was fit using Equation 1 (Ritz et al. 2015) to plot the percent *A. tuberculatus* seed retention and biomass accumulation over time:

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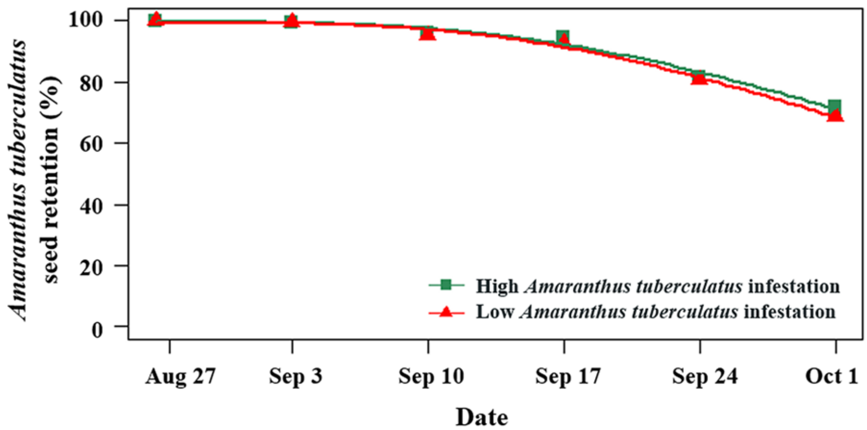

Figure 3. *Amaranthus tuberculatus* seed retention in soybean in 2020. Curves were generated using a three-parameter log-logistic model (Equation 1). Symbols on the curves are the observed means. The parameter estimates are included in Table 3. Soybean was harvested on October 1, 2020, at both sites.

$$y = \frac{d}{1 + \exp\{b[\log x \ - \ \log e]\}} \qquad [1]$$

In Equation 1, y denotes the percent of seeds retained on the mother plant, and x denotes the time; d denotes the upper limit; e denotes the t_{50} (time required to reduce percent of seeds retained on the plant by 50%); and b denotes the relative slope around e. The value of t_{10} was calculated using the *ED* function of the DRC package. Similarly, for *A. tuberculatus* biomass accumulation, y denotes the percent of biomass accumulated, and x denotes time; d denotes the upper limit; e denotes the t_{50} (time required to achieve 50% of the maximum biomass); and b denotes the relative slope around e.

Amaranthus tuberculatus emergence over time in corn was analyzed using an event-time approach (Ritz et al. 2013). A three-parameter log-logistic model was fit using Equation 2:

$$F(t) = \frac{d}{1 + \exp\{b[\log(t) - \log(t_{50})]\}} \qquad [2]$$

In equation 2, F(t) denotes the percent of *A. tuberculatus* that emerged between time 0 (day of corn planting) and time t; d denotes the upper limit (expected maximum emergence); t_{50} denotes the time (days after corn planting) to achieve 50% of the maximum emergence (relative to the upper limit, d); and b denotes the slope of emergence curves around t_{50}. Time to achieve 10% and 90% of the maximum emergence (t_{10} and t_{90}, respectively) were calculated using the *ED* function of the DRC package.

Results and Discussion

Site by treatment interactions for the response variables were not significant; therefore, data were pooled. Soybean herbicide treatments had no significant interaction with chaff line or corn herbicide treatments. However, there was a significant interaction between chaff line and corn herbicide treatments. Therefore, means from chaff line and corn herbicide treatments are presented separately.

Amaranthus tuberculatus Infestation and Seed Retention

The two levels of *A. tuberculatus* infestation differed in plant population density ($P = 0.01$) but not in seed production ($P = 0.58$) and seed retention ($P = 0.77$) at soybean harvest. The high level of *A. tuberculatus* infestation had an *A. tuberculatus* population density of 7 plants m^{-2}, whereas, the *A. tuberculatus* population density in the low level of infestation was 4 plants m^{-2}. *Amaranthus tuberculatus* seed production ranged from 110,000 to 130,000 seeds m^{-2} at soybean harvest.

The percent seed retention over time did not differ between *A. tuberculatus* infestation levels (Figure 3). *Amaranthus tuberculatus* seed shattering commenced on September 3 at both sites 4 wk before soybean harvest. Overall, 90% of seeds were retained on the plant until September 19 or about 2 wk before soybean harvest (Figure 3; Table 3). *Amaranthus tuberculatus* seed retention declined to 70% by soybean harvest on October 1, 2020. Schwartz-Lazaro et al. (2021) previously reported more than 95% *A. tuberculatus* seed retention at soybean maturity (mid-September) in the midwestern United States. Parameter estimation by log-logistic model indicated that 50% reduction in *A. tuberculatus* seed retention would not occur until October 11. These results suggested that a large portion of *A. tuberculatus* seeds may be retained on the plants until the typical dates of Iowa soybean harvest (USDA-NASS 2020). However, weather events such as windstorms, temperature fluctuations, or rainfall events can increase weed seed shattering before crop harvest (Forcella et al. 1996; Nielsen and Vigil 2017).

Effectiveness of the Chaff Lining System at Soybean Harvest

The chaff lining system concentrated into the chaff line more than 99% of *A. tuberculatus* seeds collected during soybean harvest. The number of *A. tuberculatus* seeds inside the chaff line was 75,000 seeds m^{-2}, while the number of *A. tuberculatus* seeds outside the chaff line was 200 m^{-2}. However, all *A. tuberculatus* seeds on the plant may not enter the combine. This can be due to seed-shattering losses associated with combine harvest. *Amaranthus tuberculatus* seeds can shatter before entering the combine when shaken by the combine header during harvest or seeds may not separate from soybeans and can enter the grain tank instead of the chaff line (Davis 2008).

Effect of Soybean Chaff line on *Amaranthus tuberculatus* in Corn

Amaranthus tuberculatus population density was higher inside the chaff line than outside the chaff line in corn because more than

Table 3. Parameter estimates using the log-logistic model (Equation 1) for *Amaranthus tuberculatus* seed retention on the plant over time in soybean in 2020.

A. tuberculatus infestation	Parameter estimates (±SE)[a]			
	b	t_{10}	t_{50}	d
High	3.17 (1.03)	3.22 (0.43)	6.68 (0.80)	99.64 (2.42)
Low	3.19 (0.98)	3.34 (0.44)	6.41 (0.66)	99.50 (2.46)

[a]Parameter b is the relative slope around t_{50}; t_{50} is the time (weeks after the start of the observation period, August 27) required to reduce seed retention on *A. tuberculatus* plants by 50%; t_{10} is the time required to reduce seed retention on *A. tuberculatus* plants by 10%; and d is the maximum seed retention (%) at the start of the observation period. Values in parentheses represent standard errors of means.

Table 4. Effect of soybean chaff line and corn herbicide programs on *Amaranthus tuberculatus* population density in corn in 2021.[a]

Area of the plot	Herbicide treatments	Herbicide application[b]	*A. tuberculatus* density[c] 6 WAPRE	6 WAPOST
			no. plants m^{-2}	
Inside the chaff line	1	Untreated control	123 a	213 a
	2	PRE	13 c	46 bc
	3	PRE fb banded POST	6 c	6 d
	4	PRE fb broadcast POST	10 c	10 cd
Outside the chaff line	1	Untreated control	40 b	52 b
	2	PRE	2 c	2 d
	3	PRE fb banded POST	1 c	1 d
	4	PRE fb broadcast POST	1 c	1 d

[a]Abbreviations: fb, followed by; PRE, preemergence; POST, postemergence; WAPRE, weeks after PRE; WAPOST, weeks after POST.
[b]Preemergence herbicides were applied at corn planting and postemergence herbicides were applied at the V4 growth stage of corn. The banded postemergence herbicide application was made only to the area inside the chaff line, whereas the broadcast postemergence herbicide application was made to the entire area (inside and outside the chaff line).
[c]Treatment means within a column with same letter(s) are not significantly different (Tukey test, $\alpha = 0.05$).

99% of *A. tuberculatus* seeds were exiting the combine in the chaff line during soybean harvest (Table 4). *Amaranthus tuberculatus* population density in corn was 67% higher inside the chaff line (123 plants m^{-2}) than outside the chaff line (40 plants m^{-2}) at 6 wk after planting (WAP) (Table 4). Similarly, *A. tuberculatus* population density was 76% higher inside the chaff line (213 plants m^{-2}) than outside the chaff line (52 plants m^{-2}) at 12 WAP.

Amaranthus tuberculatus inside the chaff line took 1 wk longer to achieve 50% of the maximum emergence (t_{50}) compared with *A. tuberculatus* outside the chaff line (Table 5). Similarly, *A. tuberculatus* inside the chaff line emerged (t_{10}) 5 d later than the *A. tuberculatus* outside the chaff line and required 63 d to achieve 90% of the maximum emergence inside the chaff line compared with only 54 d outside the chaff line. The delayed *A. tuberculatus* emergence inside the chaff line was most likely due to lower temperatures during the early growing season (data not shown). Crop residue on the soil surface can decrease both soil temperatures and temperature fluctuations (Teasdale and Mohler 1993; Yang et al. 2021), which can reduce *A. tuberculatus* emergence rate (Guo and Al-Khatib 2003; Leon et al. 2004; Steckel et al. 2004).

Amaranthus tuberculatus aboveground biomass was lower inside the chaff line than outside the chaff line at 12 WAP (Table 6). However, *A. tuberculatus* biomass accumulation was slower outside the chaff line during the early growing season. *Amaranthus tuberculatus* inside the chaff line accumulated 10% of the maximum biomass 1 wk earlier than *A. tuberculatus* outside the chaff line (Table 6). Nonetheless, the trend was reversed over time, and *A. tuberculatus* inside the chaff line accumulated 90% of the maximum biomass 1 wk later than outside the chaff line (Table 6). Wilson et al. (1995) found that field violet (*Viola arvensis* Murray) population density increased the biomass until 10 wk after emergence. However, biomass after 10 wk of emergence did not increase with population density due to intraspecific competition.

Interaction Effects of the Chaff Line and Corn Herbicides on *Amaranthus tuberculatus*

Application of either preemergence-only or preemergence fb postemergence herbicides inside or outside the chaff line reduced *A. tuberculatus* population density by ≥90% compared with the untreated control at 6 WAP (Table 4). *Amaranthus tuberculatus* population density in herbicide treatments did not differ between inside and outside the chaff line until 6 WAP. However, at 12 WAP, preemergence-only herbicides had higher *A. tuberculatus* population density inside the chaff line than outside the chaff line (Table 5). The difference in *A. tuberculatus* population density at 12 WAP was eliminated by a banded postemergence herbicide application over the chaff line area only. This indicates that the additional postemergence herbicide treatment on the chaff line was needed due to higher *A. tuberculatus* seed population density and a high amount of soybean chaff inside the chaff line, which could have intercepted parts of the preemergence herbicides. High weed population density can decrease the net amount of preemergence herbicides absorbed by individual plants (Hoffman and Lavy 1978; Winkle et al. 1981). Ghadiri et al. (1984) reported wheat residue intercepted about 60% of atrazine applied on the surface. The intercepted herbicides can be lost through rainfall wash-off, biodegradation, and volatilization (Locke and Bryson 1997).

Addition of a preemergence herbicide treatment influenced *A. tuberculatus* emergence rate more inside the chaff line than outside the chaff line (Table 6). *Amaranthus tuberculatus* located in the chaff line with the preemergence herbicide treatment took 1 wk longer to achieve 50% of the maximum emergence (t_{50}) compared with the untreated control, whereas, *A. tuberculatus* located outside the chaff line took a similar amount of time with or without the preemergence herbicide treatment to achieve 50% of the maximum emergence (t_{50}). A similar pattern was observed for the time required to achieve 10% and 90% of the maximum *A. tuberculatus* emergence. This delayed emergence inside the chaff line was likely due to a cumulative effect from preemergence herbicides and soybean chaff residue (Teasdale et al. 2003).

Management Implications

The inclusion of chaff lining in current weed management programs in soybean has the potential to help manage the *A. tuberculatus* seedbank in soybean–corn rotations in the U.S. Midwest. Although *A. tuberculatus* population density in corn was higher inside the chaff

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Table 5. Parameter estimates using the log-logistic model (Equation 2) for the effect of soybean chaff line and corn herbicides on *Amaranthus tuberculatus* emergence in 2021.[a]

Area of the plot	Herbicide treatments	Herbicide application[b]	Parameter estimates (±SE)[c]				
			b	t_{10}	t_{50}	t_{90}	d
Inside the chaff line	1	Untreated control	−8.23 (0.2)	36.80 (0.2)	48.06 (0.2)	62.76 (0.4)	100 (0.13)
	2	PRE	−9.31 (0.3)	44.74 (0.5)	56.65 (0.5)	71.73 (0.8)	100 (0.20)
	3	PRE fb banded POST	−19.07 (2.1)	40.99 (0.7)	46.00 (0.5)	51.61 (0.9)	98 (1.42)
	4	PRE fb broadcast POST	−25.43 (2.8)	39.70 (0.4)	43.29 (0.3)	47.19 (0.6)	99 (0.88)
Outside the chaff line	1	Untreated control	−8.61 (0.3)	32.24 (0.4)	41.61 (0.4)	53.70 (0.7)	98 (0.54)
	2	PRE	−7.76 (1.3)	29.60 (2.2)	39.29 (2.2)	52.15 (3.7)	96 (3.51)
	3	PRE fb banded POST	−8.21 (2.0)	33.60 (2.9)	43.91 (2.4)	57.39 (4.7)	93 (6.53)
	4	PRE fb broadcast POST	−14.78 (3.8)	37.16 (1.9)	43.11 (1.4)	50.02 (2.4)	92 (6.91)

[a]Abbreviations: fb, followed by; PRE, preemergence; POST, postemergence.
[b]Preemergence herbicides were applied at corn planting and postemergence herbicides were applied at the V4 growth stage of corn. The banded postemergence herbicide application was made only to the area inside the chaff line, whereas the broadcast postemergence herbicide application was made to the entire area (inside and outside the chaff line).
[c]Parameter b is the relative slope around t_{50}; t_{50} is the time (days after corn planting) required to achieve 50% of the maximum emergence (d); t_{10} and t_{90} are the time required to achieve 10% and 90% of the maximum emergence, respectively; and d is the maximum emergence (%) at the end of the observation period. Values in parentheses represent standard errors of means.

Table 6. Parameter estimates using the log-logistic model (Equation 1) for the effect of soybean chaff line on *Amaranthus tuberculatus* aboveground biomass accumulation in corn in 2021.

Area of the plot	Parameter estimates (±SE)[a]				
	b	t_{10}	t_{50}	t_{90}	d
Inside the chaff line	−6.90 (1.51)	40.47 (1.97)	55.64 (2.33)	76.50 (7.97)	15.87 (3.78)
Outside the chaff line	−11.70 (2.80)	46.86 (2.08)	56.55 (1.00)	68.23 (3.53)	42.67 (3.23)

[a]Parameter b is the relative slope around t_{50}; t_{50} is the time (days after corn planting) required to achieve 50% of the maximum biomass (d); t_{10} and t_{90} are the time required to achieve 10% and 90% of the maximum biomass, respectively; and d is the maximum biomass (g m^{-2}) accumulated at the end of observation period. Values in parentheses represent standard errors of means.

line, the rate of emergence and overall biomass accumulation was lower. This may be particularly important, as the competitiveness of weeds in a crop is determined by the time of emergence and population density–dependent biomass accumulation (Aldrich 1987). The delayed *A. tuberculatus* emergence inside the chaff line would likely result in a competitive disadvantage with the crop (Hartzler et al. 2004). A high weed seed population density in the chaff line is more likely to be consumed by vertebrates and is more vulnerable to microbial decay than weed seeds in low-population densities (Baraibar et al. 2011). The efficacy of preemergence herbicides inside the chaff line declined later in the season, likely due to high population density (Hoffman and Lavy 1978; Winkle et al. 1981). A postemergence herbicide treatment with multiple effective sites of action may be needed to achieve season-long *A. tuberculatus* control in the chaff lines. The preemergence-only herbicide treatment provided season-long control outside the chaff line, resulting in lower herbicide use overall. Future research should investigate the effect of soybean chaff lining on *A. tuberculatus* seed viability and microbial seed decay. Studies focused on managing *A. tuberculatus* inside the chaff lines using alternative weed control tactics can help promote the adoption of chaff lining in soybean–corn rotations.

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