

## Research Article

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**Author for correspondence:**

Elizabeth G. Mosqueda, Department of Plant Sciences, University of Wyoming, 1000 E. University Avenue, Laramie, WY 82071. (Email: [elmosqueda@csumb.edu](mailto:elmosqueda@csumb.edu))

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# Effect of crop canopy and herbicide application on kochia (*Bassia scoparia*) density and seed production

Elizabeth G. Mosqueda<sup>1</sup> , Charlemagne A. Lim<sup>2</sup>, Gustavo M. Sbatella<sup>3</sup>, Prashant Jha<sup>4</sup>, Nevin C. Lawrence<sup>5</sup> and Andrew R. Kniss<sup>6</sup>

<sup>1</sup>Graduate Research Assistant, Department of Plant Sciences, University of Wyoming, Laramie, WY, USA; <sup>2</sup>Graduate Research Assistant, Southern Agricultural Research Center, Montana State University, Huntley, MT, USA; <sup>3</sup>Assistant Professor, Department of Plant Sciences, University of Wyoming, Powell, WY, USA; <sup>4</sup>Associate Professor, Southern Agricultural Research Center, Montana State University, Huntley, MT, USA; <sup>5</sup>Assistant Professor, Panhandle Research and Extension Center, University of Nebraska–Lincoln, Scottsbluff, NE, USA and <sup>6</sup>Professor, Department of Plant Sciences, University of Wyoming, Laramie, WY, USA

**Abstract**

Understanding the effects of crop management practices on weed survival and seed production is imperative in improving long-term weed management strategies, especially for herbicide-resistant weed populations. Kochia [*Bassia scoparia* (L.) A.J. Scott] is an economically important weed in western North American cropping systems for many reasons, including prolific seed production and evolved resistance to numerous herbicide sites of action. Field studies were conducted in 2014 in a total of four field sites in Wyoming, Montana, and Nebraska to quantify the impact of different crop canopies and herbicide applications on *B. scoparia* density and seed production. Crops used in this study were spring wheat (*Triticum aestivum* L.), dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.), and corn (*Zea mays* L.). Herbicide treatments included either acetolactate synthase (ALS) inhibitors effective on non-resistant *B. scoparia* or a non-ALS inhibiting herbicide effective for both ALS-resistant and ALS-susceptible *B. scoparia*. *Bassia scoparia* density midseason was affected more by herbicide choice than by crop canopy, whereas *B. scoparia* seed production per plant was affected more by crop canopy compared with herbicide treatment. Our results suggest that crop canopy and herbicide treatments were both influential on *B. scoparia* seed production per unit area, which is likely a key indicator of long-term management success for this annual weed species. The lowest germinable seed production per unit area was observed in spring wheat treated with non-ALS inhibiting herbicides, and the greatest germinable seed production was observed in sugar beet treated with ALS-inhibiting herbicides. The combined effects of crop canopy and herbicide treatment can minimize *B. scoparia* establishment and seed production.

**Introduction**

Kochia [*Bassia scoparia* (L.) A.J. Scott] is a summer annual weed in the Chenopodiaceae (goosefoot) family commonly found throughout the United States (Forcella 1985; Friesen et al. 2009). Throughout North America, *B. scoparia* is present in arid and semiarid regions of disturbed sites and cropping systems (Friesen et al. 2009). *Bassia scoparia* has been documented to be problematic in many major crops grown in the Great Plains such as sugar beet (*Beta vulgaris* L.), corn (*Zea mays* L.), and dry bean (*Phaseolus vulgaris* L.) (Blackshaw 1990; Schweizer 1981; Weatherspoon and Schweizer 1970; Wilson et al. 1980). It is often one of the first summer annual weed species to emerge in regions where it is naturalized, making it a highly competitive species (Friesen et al. 2009). *Bassia scoparia* populations have been documented to begin emerging with as low as 151 accumulated growing degree days (GDD) and have an emergence duration of 556 GDD when a base temperature of 0 °C was selected for calculating daily GDD (Kumar et al. 2018). In the Northern Great Plains, 151 GDD will typically accumulate by early to mid-April (30-yr average of April 7 in Scottsbluff, NE, and April 12 in Huntley, MT), with an additional 556 GDD accumulating by the end of May.

Seed persistence and dormancy in the soil is relatively short, with more than 95% of *B. scoparia* seed not persisting for more than 2 yr (Dille et al. 2017). *Bassia scoparia* success in cropping systems is also attributed to rapid growth and prolific seed production, which is further augmented by evolved resistance to numerous herbicide sites of action (Derksen et al. 2002; Evetts and Burnside 1972; Friesen et al. 1993; Heap and Duke 2018; Nussbaum et al. 1985; Varanasi et al. 2015). Herbicide-resistant weed populations pose economic challenges to growers by rendering once efficacious herbicides useless (Dille et al. 2017). In Wyoming, Nebraska, and Montana, *B. scoparia* populations have evolved resistance to

photosystem II inhibitors, enzyme 5-enolpyruvylshikimate 3-phosphate synthase inhibitors, synthetic auxins, and acetolactate synthase (ALS) inhibitors, with some populations exhibiting multiple resistance (Heap 2018; Varanasi et al. 2015).

Understanding the effects of crop management practices on *B. scoparia* emergence, survival, and seed production is imperative in improving long-term weed management strategies, especially for herbicide-resistant weed populations (Walsh et al. 2018). To better understand how *B. scoparia* emergence and crop management are related, the impacts of crop canopy and herbicide use pattern on weed seedling emergence, survival, and development need to be examined. Light is commonly a limiting factor in developed crop canopies, as a well-developed crop canopy blocks the necessary stimuli for weed seed germination and seedling emergence (Ballaré and Casal 2000; Rajcan and Swanton 2001). Crop canopies associated with higher leaf area, height, and rapid development are more proficient in inhibiting weed seedling emergence (Seavers and Wright 1999). A study conducted in Kansas found that *B. scoparia* plants grown in the absence of a surrounding plant canopy had greater seed production than in the presence of a canopy, with grain sorghum [*Sorghum bicolor* (L.) Moench] and corn inhibiting *B. scoparia* seed production more than soybean [*Glycine max* (L.) Merr.] and wheat (*Triticum aestivum* L.) stubble (Esser 2014).

Additional crop management practices such as planting and harvest dates could also impact weed seedling emergence and recruitment (Parish 1990). Growers commonly control weeds before planting with tillage or preplant burndown herbicides, which result in reduced competition with weeds as crops emerge and mature (Heatherly and Hodges 1999; Price et al. 2002). However, if a weed species has an extended emergence pattern or emerges in multiple flushes and grows tall quickly, then preplant weed control will be less efficacious. Therefore, weeds will continue to emerge after crop emergence and may have the ability to grow above the crop canopy (Rajcan and Swanton 2001; Roberts and Potter 1980; Schwinghamer and Van Acker 2008).

Herbicide use pattern has been extensively shown to impact the evolution of herbicide-resistant weeds. Selection pressure caused by using the same herbicide mechanism of action season after season results in the buildup of resistant weed species (Jasieniuk et al. 1996; Powles et al. 1996; Young 2006). Alternating herbicide chemistries through effective mixtures and, to a lesser extent, herbicide rotation has been documented to reduce the buildup of herbicide-resistant weed populations (Beckie and Reboud 2009; Evans et al. 2018; Norsworthy et al. 2012). Although all of these management practices are often recommended for herbicide-resistant weed management, to date there is little information available showing how the combined effects of crop rotation, which includes diversity in planting and harvest dates as well as diversity in crop canopy and architecture, paired with herbicide use impact weed emergence and seed production. Understanding how these practices impact weed survival and fecundity is imperative to long-term management of herbicide-resistant weed populations. Such findings could lead to more proactive, long-term approaches to managing weeds while minimizing grower dependence on herbicides. The objective of this study was to quantify the impact of varying crop canopies and ALS-inhibiting herbicide applications on *B. scoparia* density and seed production under field conditions.

## Materials and Methods

Field studies were conducted in 2014 at four different university research sites where *B. scoparia* was known not to be a

management problem in order to ensure low initial density. Study sites included the Sustainable Agriculture Research and Extension Center (42.1°N, 104.4°W at 1,390-m elevation) located near Lingle, WY; the Powell Research and Extension Center (44.8°N, 108.7°W at 1,331-m elevation) in Powell, WY; the Panhandle Research and Extension Center (41.9°N, 103.7°W at 1,199-m elevation) in Scottsbluff, NE; and the Southern Agricultural Research Center (45.9°N, 108.2°W at 914-m elevation) in Huntley, MT. Studies were conducted on a Heldt silty clay (fine, smectitic, mesic Ustertic Haplocambids) with 1.8% organic matter and a pH of 7.8, in Lingle, WY; Garland loam (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Haplargids), with 1.6% organic matter and a pH of 8.2 in Powell, WY; Tripp very fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls) with 0.7% organic matter and a pH of 8.3, in Scottsbluff, NE; and Lohmiller silty clay (fine, smectitic, calcareous, mesic Torrtic Ustifluvents) with 2.8% organic matter and a pH of 8.1, in Huntley, MT. *Bassia scoparia* seed was collected from different areas in Goshen County, WY, in fall of 2013. Six different seed lots encompassing a variety of field histories were collected, from which a 5% ALS-resistant seed blend was made (Supplementary Table 1). To create the 5% resistant population used in the study, we tested germination rate and ALS-resistant proportion from each seed lot individually by counting the total number of emerged *B. scoparia* from a subsample of each seed lot. Immediately after counting emergence, each subsample was treated with chlorsulfuron at 35 g ai ha<sup>-1</sup>. Approximately 10 d after treatment, the number of resistant *B. scoparia* was estimated by counting the number of live *B. scoparia* within each subsample. These counts were used to estimate the resistant proportion of seed within each lot. All lots contained relatively low resistant proportions (<20%), with some containing no detectable resistance. Lots were then mixed to create the 5% ALS-resistant seed blend used at all four locations in the study. *Bassia scoparia* was seeded at a rate of 2,000 g ha<sup>-1</sup> to ensure that approximately 8 germinable seeds m<sup>-2</sup> were present across each study site (40 germinable seeds g<sup>-1</sup>). A rotary hand spreader was used to seed *B. scoparia* in each plot just before each crop was planted. Thus, a uniform population of *B. scoparia* was used to quantify its response to varying crop canopies and herbicide treatments. Although sites were chosen to minimize existing *B. scoparia* density, *B. scoparia* is common in the region and we could not completely exclude preexisting *B. scoparia* from our study sites.

The experiment was arranged in a split-plot randomized complete block design with four replicates. Crop treatments included corn, dry bean, spring wheat, or sugar beet. Because this study was part of a larger ongoing study, the number of plots for each crop differed (Table 1). Each crop whole plot was split and treated with either an ALS-inhibiting herbicide that effectively controls ALS-susceptible *B. scoparia* or a non-ALS inhibiting herbicide that is effective in controlling ALS-resistant and ALS-susceptible *B. scoparia* (Table 2). All herbicides (ALS-inhibiting herbicides and non-ALS inhibiting herbicides) were selected and applied based on grower preference and practice throughout the region. PPI herbicides were applied before planting in dry bean plots. Herbicide treatments for spring wheat consisted of only one POST herbicide application when *B. scoparia* reached approximately 3 cm in height. Corn and sugar beet were treated with two POST herbicide applications (one early season when *B. scoparia* was approximately 3-cm tall, and one at least 14 d later once additional *B. scoparia* emergence was observed or at the latest crop stage allowed by the label). Acetochlor was added to the second POST application in corn and sugar beet to help control other weed

**Table 1.** Cultural practices for establishing corn, dry bean, spring wheat, and sugar beet, and number of plots at four sites in Huntley, MT, Powell and Lingle, WY, and Scottsbluff, NE, in 2014.

Crop	Seeding rate	Planting date range	Harvest date range	Number of plots per site
Corn	83,980 seed ha <sup>-1</sup>	May 5 to May 21	October 25 to November 27	54
Dry bean	160,550 seed ha <sup>-1</sup>	May 22 to June 4	September 17 to October 7	12
Spring wheat	112 kg seed ha <sup>-1</sup>	April 22 to April 29	August 25 to September 9	6
Sugar beet	172,900 seed ha <sup>-1</sup>	April 24 to May 19	September 23 to October 3	24

**Table 2.** Non-ALS inhibitor and ALS inhibitor-only herbicide treatments and rates used for corn, spring wheat, dry bean, and sugar beet at four sites in Huntley, MT, Powell and Lingle, WY, and Scottsbluff, NE, in 2014.

Crop	Non-ALS inhibitor			ALS inhibitor		
	Treatment	Rate	Timing <sup>a</sup>	Treatment	Rate	Timing <sup>a</sup>
Corn	Dicamba <sup>b</sup>	280 g ae ha <sup>-1</sup>	POST	Thifensulfuron + rimsulfuron <sup>c</sup>	19.6 g ai ha <sup>-1</sup>	POST
	Glyphosate <sup>d</sup>	1,260 g ae ha <sup>-1</sup>		COC <sup>e</sup>	2% v/v	
Spring wheat	Acetochlor <sup>f</sup>	1,050 g ai ha <sup>-1</sup>	LAYBY	UAN <sup>17</sup> (28-0-0)	2.5% v/v	
	Pyrasulfotole + bromoxynil <sup>g</sup>		POST	Acetochlor <sup>f</sup>	1,050 g ai ha <sup>-1</sup>	LAYBY
	MCPA-ester <sup>h</sup>	280 g ae ha <sup>-1</sup>		Thifensulfuron <sup>h</sup>	35 g ai ha <sup>-1</sup>	POST
Dry bean	Ammonium sulfate	1.9 g 100 ml <sup>-1</sup>		NIS <sup>j</sup>	0.25% v/v	
	Pendimethalin <sup>l</sup>	1,330 g ai ha <sup>-1</sup>	PRE	UAN <sup>k</sup> (28-0-0)	2.5% v/v	
	Bentazon <sup>n</sup>	1,120 g ai ha <sup>-1</sup>	POST	EPTC <sup>m</sup>	3,920 g ai ha <sup>-1</sup>	PPI
	COC <sup>e</sup>	1% v/v		Imazomox <sup>o</sup>	35 g ai ha <sup>-1</sup>	POST
Sugar beet	Glyphosate <sup>d</sup>	1,260 g ae ha <sup>-1</sup>	POST	NIS <sup>j</sup>	0.25% v/v	
	Ammonium sulfate	1.9 g 100 ml <sup>-1</sup>		UAN <sup>k</sup> (28-0-0)	2.5% v/v	
	Acetochlor <sup>f</sup>	1,050 g ai ha <sup>-1</sup>	LAYBY	Triflurosulfuron <sup>p</sup>	35 g ai ha <sup>-1</sup>	POST
				COC <sup>16e</sup>	1% v/v	
				Acetochlor <sup>f</sup>	1,050 g ai ha <sup>-1</sup>	LAYBY

<sup>a</sup>POST applications in corn and sugar beet were applied twice, with the first application initiated when *Bassia scoparia* was approximately 3-cm tall, and the second at least 14 d afterward. LAYBY acetochlor was applied with the second POST application to control late-emerging weeds like *Amaranthus retroflexus* and *Solanum physalifolium*; this herbicide is not effective for controlling emerged *B. scoparia*.

<sup>b</sup>Dicamba, Clarity®, BASF, Research Triangle Park, NC.

<sup>c</sup>Resolve Q®, DuPont, Wilmington, DE.

<sup>d</sup>Glyphosate, Roundup PowerMax®, Monsanto Company, St Louis, MO.

<sup>e</sup>COC, crop oil concentrate, Prime Oil®, WinField United, Arden Hills, MN.

<sup>f</sup>Warrant®, Monsanto Company, St Louis, MO.

<sup>g</sup>Huskie®, Bayer CropScience, Research Triangle Park, NC.

<sup>h</sup>Harmony SG®, DuPont, Wilmington, DE.

<sup>i</sup>MCPA-ester®, WinField United, Arden Hills, MN.

<sup>j</sup>NIS, nonionic surfactant, Preference®, WinField United, Arden Hills, MN.

<sup>k</sup>UAN, urea ammonium nitrate.

<sup>l</sup>Prowl H<sub>2</sub>O®, BASF, Research Triangle Park, NC.

<sup>m</sup>EPTC was incorporated with overhead irrigation; EPTC applied PPI was used to control weeds other than *B. scoparia* and was expected to provide little to no control of *B. scoparia* based on previous experience. Eptam® 7E, Gowan Company, Yuma, AZ.

<sup>n</sup>Basagran®, BASF, Research Triangle Park, NC.

<sup>o</sup>Raptor®, BASF, Research Triangle Park, NC.

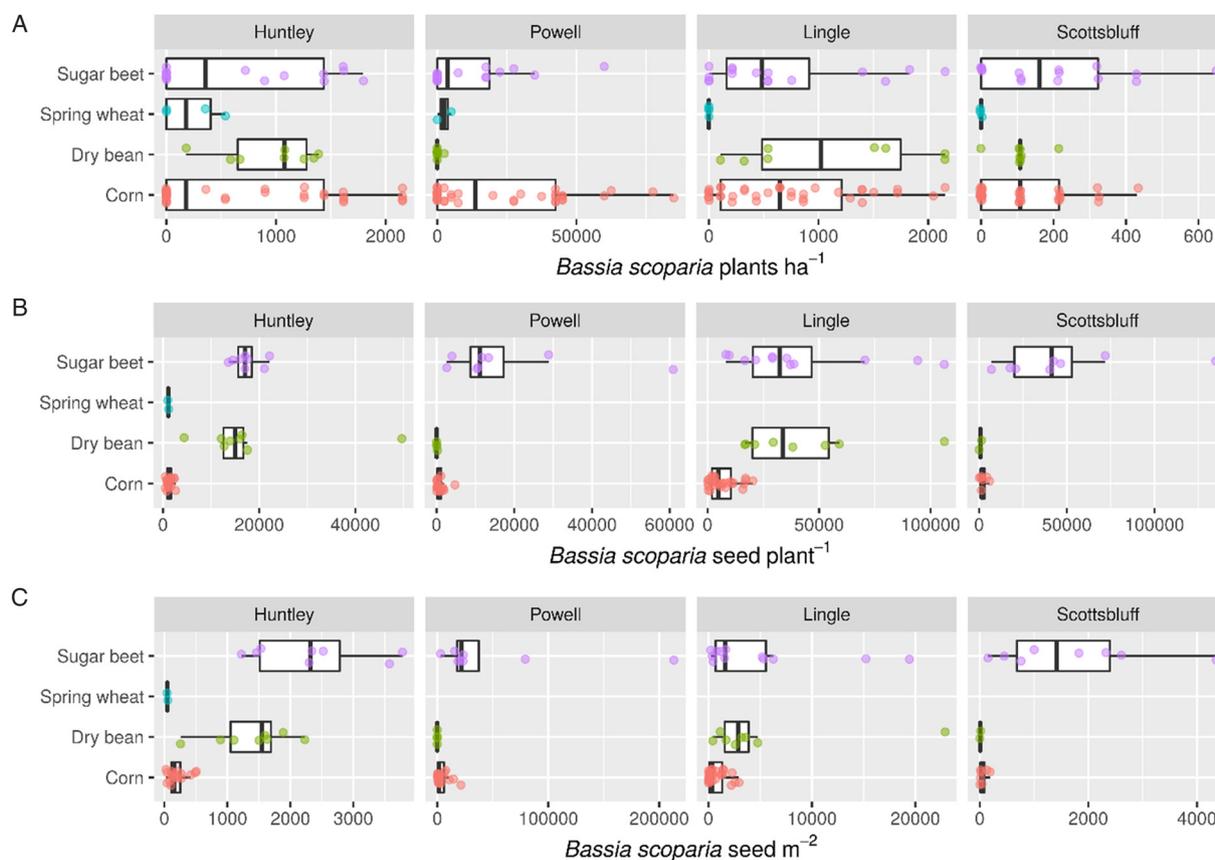
<sup>p</sup>UpBeet®, DuPont, Wilmington, DE.

species that were present, namely redroot pigweed (*Amaranthus retroflexus* L.) and hairy nightshade (*Solanum physalifolium* Rusby). Acetochlor applied POST did not control any emerged *B. scoparia*. Herbicide treatments for dry bean consisted of only a PRE herbicide followed by one POST herbicide application. EPTC was applied preplant in the ALS-inhibitor treatment at all sites except Lingle to control other weed species; our previous experience has shown that EPTC applied PRE is ineffective for *B. scoparia* control.

Plot lengths were 15.2 m at all sites, but plot width varied by location due to crop row spacing and equipment availability. Split-plot widths were 6.1, 6.7, 3.4, and 3.7 m for Lingle, Powell, Scottsbluff, and Huntley locations, respectively. Throughout the season, plots were kept free of any weed species except *B. scoparia* by regular hand weeding.

*Bassia scoparia* density data were recorded midway through crop maturity (at least 14 d after the final herbicide applications

had been made) by sampling two random 1-m<sup>2</sup> areas per plot and counting the number of *B. scoparia* plants within them. *Bassia scoparia* seed production per plant was estimated by placing up to three pollination bags, per plant, on three different *B. scoparia* plants per plot. Bags were placed on the *B. scoparia* plants as pollination neared completion but before *B. scoparia* seed maturity, both determined through field scouting. Bags were tied around the stem to ensure no seed escape. Immediately before crop harvest, the percentage of each plant covered by pollination bags was estimated. All seeds within the three pollination bags per *B. scoparia* plant were then aggregated and weighed. A 5-g subsample of *B. scoparia* seed from each plant was removed, placed in a paper envelope, and left to air-dry for approximately 2 mo to mimic quiescence. Subsamples were then planted into 25 by 25 cm trays filled with approximately 2.5-cm-deep potting soil in a greenhouse, where they were watered daily. Seedlings were counted weekly and then removed for approximately 8 wk, and



**Figure 1.** Distribution of *Bassia scoparia* density per square meter (A), seed production per plant (B), and seeds per square meter (C) as affected by crop in Huntley, MT, Powell and Lingle, WY, and Scottsbluff, NE, in 2014.

the cumulative number of emerged seedlings was totaled. The number of germinable seeds per *B. scoparia* plant was then calculated using Equation 1:

$$\frac{\text{Total number of seed germinated}/(\text{sub sample seed weight}/\text{total seed sample weight})}{\text{estimated \% plant coverage}/100}$$

[1]

*Bassia scoparia* seed production per square meter was then calculated by multiplying the mean number of germinable seeds per plant for each plot by the *B. scoparia* density per plot. The effect of crop and herbicide treatment on *B. scoparia* density and seed production were analyzed using a linear mixed-effects model appropriate for count data and unbalanced design (Bates et al. 2015). For all response variables, the effect of site was considered a random effect, and the effects of crop, herbicide, and crop by herbicide interaction were considered fixed effects.

For all response variables, preliminary analysis suggested a log-normal distribution, so a log transformation was used, first adding half of the minimum value for each variable to each observation to account for zeros in the data set. The contribution of crop and herbicide treatments in explaining variance in each response was quantified using mean squares from type III analysis of variance, using Satterthwaite's method to estimate denominator degrees of freedom (Kuznetsova et al. 2017). For significant fixed effects, estimated marginal means (also sometimes called least-squares means) were calculated using the EMMEANS package and presented in the back-transformed, original scale (Lenth et al.

2018). Tukey-adjusted pairwise comparisons between treatments were made at the  $\alpha = 0.05$  level and presented using the mean separation algorithm proposed by Piepho (2004). All data were analyzed using R statistical software v. 3.6.1 (R Core Team, Vienna, Austria, <https://www.R-project.org>).

## Results and Discussion

*Bassia scoparia* density, seed production per plant, and seed production per square meter differed by location; however, overall treatment trends were generally consistent throughout all four locations of the study (Figure 1).

### *Bassia Scoparia* Density

There was a significant herbicide by crop interaction for *B. scoparia* density (Table 3). After accounting for the interaction, herbicide had a greater effect on *B. scoparia* density compared with crop choice, as type III mean squares were 13 times greater for herbicide than crop. The non-ALS-inhibiting herbicides, which controlled both resistant and susceptible biotypes, resulted in less *B. scoparia* density compared with the ALS-inhibiting herbicides alone in all crops, although differences were only statistically significant at the 5% level in corn and sugar beet (Table 4). Within the less-effective ALS-inhibiting herbicide treatment, dry bean and spring wheat had significantly less *B. scoparia* density (180 to 329 plants  $\text{ha}^{-1}$ ) compared with either corn (1,870 plants  $\text{ha}^{-1}$ ) or sugar beet (1,740 plants  $\text{ha}^{-1}$ ). The lowest *B. scoparia* density in both herbicide treatments was observed in spring wheat, suggesting this crop had

**Table 3.** ANOVA table showing fixed-effects mean squares and variance components for *Bassia scoparia* density and seed production.

Response variable	Source of variation		F-ratio	P-value
<i>B. scoparia</i> plants ha <sup>-1</sup>	Fixed effects:	Mean squares (df)		
	Crop	8.48 (3, 121)	9.39	<0.001
	Herbicide	116.66 (1, 122)	16.58	<0.001
	Crop * herbicide	17.01 (2, 121)	8.47	<0.001
	Random effects:	Variance		
	Location	1.00		
<i>B. scoparia</i> seeds plant <sup>-1</sup>	Fixed effects:	Mean squares (df)		
	Crop	31.35 (3, 121)	20.61	<0.001
	Herbicide	14.78 (1, 122)	9.72	0.002
	Crop * herbicide	11.97 (2, 121)	7.87	<0.001
	Random effects:	Variance		
	Location	1.48		
<i>B. scoparia</i> seeds m <sup>-2</sup>	Fixed effects:	Mean squares (df)		
	Crop	28.33 (3, 121)	9.39	<0.001
	Herbicide	50.03 (1, 122)	16.58	<0.001
	Crop * herbicide	25.56 (2, 121)	8.47	<0.001
	Random effects:	Variance		
	Location	1.87		
	Residual	3.02		

**Table 4.** *Bassia scoparia* density and seed production (estimated marginal means) as affected by ALS-inhibiting herbicide treatment and crop at four locations near Huntley, MT, Powell and Lingle, WY, and Scottsbluff, NE, in 2014.

Herbicide	Crop	<i>B. scoparia</i>		
		plants ha <sup>-1</sup>	seeds plant <sup>-1</sup>	seeds m <sup>-2</sup>
ALS inhibitors	Corn	1,870 d <sup>a</sup>	1,480 n	297 y
	Dry bean	329 c	2,660 n	173 y
	Spring wheat	180 abc	952 mn	53.4 xy
	Sugar beet	1,740 d	23,800 o	3,980 z
Non-ALS inhibitors	Corn	61.8 ab	225 m	10.8 x
	Dry bean	204 bc	5,330 n	310 y
	Spring wheat	10.9 abc	0	0
	Sugar beet	22.8 a	3,260 no	171 xy

<sup>a</sup>Means within a response variable followed by the same letter are not statistically different (Tukey-adjusted pairwise comparisons,  $\alpha = 0.05$ ).

the greatest ability to suppress *B. scoparia* establishment. Even when paired with the less-effective ALS-inhibiting herbicide treatment, spring wheat resulted in *B. scoparia* density similar to the non-ALS inhibiting herbicide treatments in all crops.

### *Bassia Scoparia* Seed Production

There was a significant herbicide by crop interaction for *B. scoparia* seed production per plant, and seed production per square meter (Table 3). Variance in *B. scoparia* seed production per plant was influenced more by crop (mean squares<sub>[df = 3, 121]</sub> = 31.35) compared with herbicide (mean squares<sub>[df = 1, 122]</sub> = 14.78), indicating crop selection is an important factor driving *B. scoparia* seed production in plants that survive or escape herbicide treatment.

*Bassia scoparia* seed production was not observed in any replicate at three of four locations where spring wheat was treated with a non-ALS inhibiting herbicide (Table 4), and this treatment was therefore excluded from the statistical analysis. A total lack of seed production in nearly all plots across four experimental sites is a notable result and suggests the combination of spring grains with effective herbicides can be a powerful combination for *B. scoparia*

seedbank management. In treatments where *B. scoparia* seed production was observed, seed production per plant was lowest in corn treated with non-ALS inhibiting herbicides (225 seeds plant<sup>-1</sup>), or spring wheat treated with ALS-inhibiting herbicides (952 seeds plant<sup>-1</sup>). These differences are likely due, in part, to the relative height of corn and wheat compared with other crops in the study. The taller corn and spring wheat are relatively more competitive for light compared with either dry bean or sugar beet (Kasperbauer 1987; Seavers and Wright 1999; Smith et al. 1990). It is also notable that spring wheat, which was the earliest harvested crop, had the lowest *B. scoparia* seed production per plant within both herbicide treatments. The early harvest date reduced the ability of *B. scoparia* to produce viable seed, as most of the *B. scoparia* plants were still in the vegetative or early flowering stages at the time of wheat harvest. Low *B. scoparia* seed production could also be due to a dense spring wheat crop canopy, which has been shown to suppress weed pressure (Weiner et al. 2001). Spring wheat was one of the first crops planted in this study (throughout late April), which is similar to the primary emergence window for *B. scoparia* the region (Dille et al. 2017; Kumar et al. 2018; Schwinghamer and Van Acker 2008). Because spring wheat was planted before or during the peak emergence time for *B. scoparia* within the region, this likely put *B. scoparia* at a disadvantage trying to emerge amongst the densely seeded wheat crop, and likely contributed to low seed production per *B. scoparia* plant. Sugar beet was planted shortly after spring wheat, but allowed the greatest *B. scoparia* seed production per plant. Sugar beet is a poor competitor against *B. scoparia* (Mesbah et al. 1994; Weatherspoon and Schweizer 1971), in part due to slow early-season canopy development compared with many other crops. In addition, sugar beet was harvested well after *B. scoparia* had produced viable seed, so harvest operations had little impact on reducing seed production per plant.

Long-term reduction of weed seedbanks will require minimizing the seed produced per unit area, and this is most likely to be obtained through a combination of reducing weed establishment and minimizing viable seed production per plant. In this study, the proportion of variance explained by the main effects of crop and herbicide effects were more similar for *B. scoparia* seed production per square meter compared with either *B. scoparia* density or *B. scoparia* seed production per plant (Table 3), indicating both management tools were influential in impacting germinable *B. scoparia* seeds produced per unit area. Because no *B. scoparia* seed production was observed in spring wheat treated with non-ALS inhibiting herbicides, this treatment was once again excluded from statistical analysis (Table 4). The non-ALS inhibiting herbicide reduced *B. scoparia* seed production per square meter compared with the ALS-inhibiting herbicide in all crops except dry bean. Among the less-effective ALS-inhibiting herbicide treatment, sugar beet resulted in the greatest *B. scoparia* seed production of nearly 4,000 seeds m<sup>-2</sup>, compared with the other three crops, which resulted in 53 to 297 seeds m<sup>-2</sup>. Where non-ALS inhibiting herbicides were used, corn and spring wheat again resulted in the least *B. scoparia* seed production, at less than 11 seeds m<sup>-2</sup>.

For spring wheat, low seed production per unit area was due to a combined effect of reduced *B. scoparia* density plus little to no *B. scoparia* seed production among surviving plants. Early planting and harvest dates combined with dense crop canopy make spring wheat an effective crop choice for reducing *B. scoparia* seed production compared with the other crops in this study. Spring wheat was harvested in this study from August to early September. *Bassia scoparia* has been observed to produce flowers

and set seed between mid-July and late September (Anderson and Nielsen 1996; Mickelson et al. 2004). As stated by Mickelson et al. (2004), because spring wheat is harvested between mid-July and early August in this region, this could prevent seed set of *B. scoparia*, eliminating the unwanted plant during harvest before it is able to produce viable seed. Addition of an effective herbicide treatment (the non-ALS inhibiting herbicides) further reduced *B. scoparia* density and completely eliminated seed production across all four sites. For corn, which also has a competitive crop canopy, the impact of varying herbicide treatments was more evident. Implementation of an efficacious herbicide regime by using non-ALS inhibiting herbicides resulted in nearly 26 times less *B. scoparia* than treatment with ALS-inhibiting herbicides.

Dry bean and sugar beet typically contained more germinable *B. scoparia* seed produced per square meter compared with spring wheat. This could again be in part due to cropping practices. Both of these crops were harvested between mid-September and early October in this study. This time frame provided plenty of time for the *B. scoparia* that emerged and survived herbicide treatments within these plots to produce seed, considering it has been observed to produce flowers and set seed between mid-July and late September (Anderson and Nielsen 1996; Mickelson et al. 2004).

Sugar beet, unsurprisingly, allowed both high *B. scoparia* densities to persist and high seed production, making it the least favorable crop with respect to *B. scoparia* competition. This is consistent with grower experiences that *B. scoparia* is among the most troublesome and difficult to control weeds in this crop (Weatherspoon and Schweizer 1969, 1971). As was observed with corn, herbicide regime greatly exacerbated *B. scoparia* seed production per unit area in sugar beet, with approximately 23 times more germinable *B. scoparia* seed per unit area being produced when ALS-inhibiting herbicides were used compared with non-ALS inhibiting herbicides.

Long-term weed seedbank management will likely require implementing complementary practices that target different phases of the weed life cycle. This work demonstrates how herbicides and crop rotation interact to influence seed production in *B. scoparia*. Seed production per unit area, arguably the most important variable in determining the success of long-term weed seedbank management, was influenced by the combined effect of herbicides and crop selection. Herbicides primarily influenced the survival of weeds during the germination and early vegetative stages when the herbicide was applied and had a substantial impact on weed density. Crop choice had a lesser effect on weed density, but was the most important factor in influencing the amount of seed produced per surviving plant due to competitive effects as well as the timing of planting and harvest. This suppression of surviving weed seed production is likely to be especially important at the onset of herbicide-resistant weed evolution, when the herbicide is ineffective and it is important to reduce the buildup of resistant weed seed in the seedbank.

Improved knowledge of the combined effects of crop canopy and herbicide treatment on *B. scoparia* will aid in long-term management of herbicide-resistant weed populations, which is a major concern for growers in the Northern Great Plains and elsewhere. The results of this research show that combined effects of crop canopy and herbicide treatment can minimize *B. scoparia* establishment and seed production. Effective herbicides, when paired with a poorly competitive crop like sugar beet, can still allow substantial seed production and, therefore, a net increase in the soil weed seedbank. Conversely, even a relatively ineffective herbicide program may be sufficient if crop competitiveness and harvest

dates are optimized, as was observed with spring wheat. Pairing combinations of effective crop rotations with efficacious herbicides will result in the best long-term weed management, and identifying the relative contributions of these management practices under field conditions remains an important area of research.

These findings can be used to implement more proactive, long-term approaches to managing *B. scoparia*, while minimizing grower dependence on herbicide use. Therefore, future research is needed to address how these management practices would impact *B. scoparia* density, seed production, and evolution of herbicide resistance after multiple years of implementation and to determine the economic feasibility of integrating cultural weed control with herbicides within the Northern Great Plains.

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**Supplementary material.** To view supplementary material for this article, please visit <https://doi.org/10.1017/wsc.2020.23>

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