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ORIGINAL RESEARCH

Growing winter *Brassica carinata* as part of a diversified crop rotation for integrated weed management

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Abstract

Brassica carinata A. Braun is a non-edible, oilseed winter crop for biofuel production that can diversify crop rotations and improve integrated weed management. The research objective was to evaluate the influence of *B. carinata* on weed population dynamics in the southeastern United States cropping systems. *B. carinata* was grown after cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogea* L.), or a clean summer fallow, and winter weed pressure was modified with or without *S*-metolachlor. The emergence of *Lamium amplexicaule* L. increased at least 40% after cotton or peanut in 2018–2019 and 50% after cotton in 2019–2020 compared to summer fallow. *Stellaria media* (L.) Vill. emergence was increased over threefold after peanut or cotton in 2019–2020. *Senna obtusifolia* (L.) H.S. Irwin & Barneby emergence after cotton was increased at least 43% during both experimental years, whereas *Amaranthus hybridus* L. emergence was increased over 50% after peanut in 2019–2020 compared to summer fallow. Even without *S*-metolachlor, *B. carinata* reduced *A. hybridus* (>27%) and *S. obtusifolia* (>25%) emergence compared to weedy winter fallow. After *B. carinata* harvest, *A. hybridus* emergence was reduced >40% with or without *S*-metolachlor compared to winter fallow in 2018–2019. Overall, *B. carinata* biomass was highest after peanut for both seasons. *B. carinata* seed yield did not differ among crop history treatments in the first season, whereas in 2019–2020, the yield was higher after peanut (2417 kg ha^{-1}) or fallow (2520 kg ha^{-1}) compared to cotton (1710 kg ha^{-1}). Weed management treatments were not different for *B. carinata* biomass or yield in any year. The results indicate that *B. carinata* can enhance integrated weed management strategies at the rotational level for summer crops by reducing seed banks of summer weed species, in addition to its potential as a winter biofuel crop for the southeastern United States.

KEYWORDS

crop rotation, integrated weed management, summer weeds, weed population dynamics, weed seed bank, winter weeds

1 | INTRODUCTION

Brassica carinata A. Braun is a semi-wild species native to Ethiopia that originated from natural crosses between *Brassica oleracea* L. and *Brassica nigra* L. (Bozzini et al., 2007). It has been recently introduced as a non-edible winter biofuel crop in the southeastern United States (U.S.; Seepaul et al., 2019). *B. carinata* was selected because it has higher cold tolerance and greater yield potential compared to some other crops such as rapeseed (*Brassica napus* L.) and pennycress (*Thlaspi arvense* L.; Gesch et al., 2015) and suitable oil profile for biofuel production (Mulvaney et al., 2019). Since, this is a new crop to the region, there is limited information on agronomic practices for successful production. For this reason, research efforts have been made to determine fertilization requirements, and planting arrangements and densities (Mulvaney et al., 2019; Seepaul et al., 2019). Furthermore, research has been conducted to identify herbicides that could be both safe and effective for weed control in *B. carinata* (Leon et al., 2017). However, no research has been conducted to determine the effects of *B. carinata* on weed populations as part of diversified crop rotations practiced by farmers in the southeastern U.S.

In annual cropping systems, the rotation of crops over time has been an essential strategy for water, soil, pest, and production cost management (Bullock, 1992). Additionally, diversification of crops and weed control tools make it more difficult for a given weed species to become dominant (Davis et al., 2012; Leibman & Dyck, 1993). The inclusion of a rotational crop that can suppress weed growth by effectively limiting access to essential resources such as light, soil moisture, and nutrients is a crucial component of integrated and sustainable weed management strategies. Farmers can diversify crops in more intensive rotations for mitigating the weed problems related to monoculture cropping systems. Rotating crops with different life cycles assists weed management by disrupting weed associations to specific environmental or agricultural conditions (Blackshaw et al., 1994; Thomas & Dale, 1991). Furthermore, rotation design, particularly crop sequence, plays a significant role in the success of crop rotations to suppress weed populations (Anderson, 2005; Westerman et al., 2005). Likewise, reductions in overall weed seed banks depend on the crop sequence (Smith & Gross, 2006; Teasdale et al., 2004). This is because the crop phase determines weed population growth rate and the species composition of the seed bank (Leon & Wright, 2018; Leon et al., 2015).

In the southeastern U.S., rotations between cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) are common for row-crop production (Katsvairo et al., 2006). Considering that *B. carinata* introduction to the local cropping systems could influence weed communities in the existing crop rotation, it is critical to determine what changes growers should expect. For example, if growing *B. carinata* during the winter exacerbates weed problems in the summer cash crops, then growers might not adopt this new bioenergy crop. Conversely, if incorporating *B. carinata* assists in solving or mitigating weed pressure in the summer cash crops while fulfilling the oil production goal, this could increase adoption and favor the development of robust and sustainable cropping systems for managing weed problems.

Farming intensification could also have undesirable ecological impacts, such as reduced biodiversity. While in most cases, in cotton–peanut rotations, growers maintain a weedy fallow or a cover crop with minimal to no weed control during the winter. Growing a biofuel crop during this time of the year might decrease the number of winter weed species, such as *Raphanus raphanistrum* L., *Sinapis arvensis* L., *Lamium amplexicaule* L., *Stellaria media* (L.) Vill., and *Oenothera laciniata* L. which can provide habitat for beneficial organisms such as bees and natural predators in the field. This is particularly likely if the biofuel crop requires intensive weed control throughout the entire growing season (Jose-Maria et al., 2010; Petit et al., 2015). If *B. carinata*has acceptable weed suppression that warrants minimal input for control of local winter weed species, farmers might be able to maximize yield while minimizing reductions in the plant diversity of the system.

In the present research, we studied how summer crops influence winter weed pressure during winter *B. carinata* production, as well as how this crop affects summer weed emergence. We hypothesized that (1) summer cash crops decrease weed pressure for *B. carinata*; (2) *B. carinata* reduces winter weed population during its growing/production season; and (3) *B. carinata* decreases weed populations for following summer crops. Therefore, the main objective of this research was to evaluate how winter *B. carinata* can affect winter and summer weed population dynamics in southeastern U.S. crop rotation systems.

2 | MATERIALS AND METHODS

2.1 | Experimental design

Field experiments were conducted from May 2018 to September 2019 and May 2019 to August 2020 at the West Florida Research and Education Center of the University of Florida (UF-WFREC), Jay, FL (30°46′37″N 87°8′20″W, 64 m a.s.l.). For the 2018–2019 site, the soil was a Dothan fine sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) with a pH of 6.3 and Orangeburg sandy loam (fine-loamy, kaolinitic, thermic Typic Kandiudult) mosaic with a pH of 6.0. At the 2019–2020 site, the soil was a mosaic of Orangeburg sandy loam (fine-loamy, kaolinitic, thermic Typic Kandiudult) with a pH of 6.0 and Tifton sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) with a pH of 5.8. Weather data were collected from an automated weather station located within 1 km of the research sites.

The experiment was a randomized complete block design arranged as a split-plot with seven and eight replications in the 2018–2019 and 2019–2020 seasons, respectively. The main plot was the crop during the previous summer growing season (i.e., crop history): (1) cotton (DP 1646); (2) peanut (Georgia 06G); and (3) non-crop summer fallow. The subplot was weed management during the winter *B. carinata* growing season: (1) *B. carinata* (Avanza 641) with *S*-metolachlor (1.42 kg a.i. ha^{-1}, Syngenta Crop Protection) applied preemergence (PRE); (2) *B. carinata* without *S*-metolachlor; and (3) weedy winter fallow (without *B. carinata* or *S*-metolachlor). These treatments were intended to compare winter weed populations with and without *B. carinata*, and how the performance of this crop is affected by low weed pressure, that is, environment created with the *S*-metolachlor application, compared with a high weed pressure in the absence of this herbicide.

The main plots were 21 m wide by 11 m long, and subplots were 7 m wide by 11 m long. For the 2018–2019 and 2019–2020 season, cotton and peanuts were planted during early May. The fertilization was done to provide a total of 101 kg ha^{-1} of nitrogen (N), 106 kg ha^{-1} of phosphorous (P), 100 kg ha^{-1} of potash (K), and 37 kg ha^{-1} of sulfur (S) for cotton. Likewise, a total of 78 kg ha^{-1} of P, 56 kg ha^{-1} of K, and 33 kg ha^{-1} of S was applied to peanut. The agronomic management and cultural practices for cotton and peanut followed the local recommendations (Wright et al., 2016; 2017). Preemergence and postemergence herbicides were applied to control weeds following local recommendations for cotton (Ferrell et al., 2020) and peanut (Ferrell et al., 2020) production. In the meantime, summer fallow was kept weed-free throughout the crop growing season by applying glyphosate (1.26 kg ae ha^{-1}, Roundup PowerMax, Monsanto Company).

Conventional tillage was implemented for the entire *B. carinata* research site. After cotton and peanut harvest, fields were disked twice and roto-tilled prior to *B. carinata* planting. *Senna obtusifolia* (L.) Irwin & Barneby seeds were collected from natural populations at the UF/IFAS-WFREC in 2018–2019 and obtained from Azlin Seed Service for the 2019–2020 season. *Amaranthus hybridus* L. seeds were obtained from Azlin Seed Service during both years. These species were chosen because they are weeds of economic importance in summer crops in the southeastern U.S. and they have large and small seeds, respectively, which includes the wide range of weed sizes in the local seed bank. Prior to planting *B. carinata*, three 1 m^2 quadrats were randomly placed within each subplot. In the first quadrat, *S. obtusifolia* seeds were hand-spread uniformly at 2000 seeds m^{-2} in November 2018 and seeding rate was increased 3500 seeds m^{-2} in November 2019 to account for seed mortality and ensure consistent seedling emergence. Likewise, *A. hybridus* seeds were hand-spread at 25,000 seeds m^{-2} for both years in the second quadrat, while the last quadrat was left for monitoring the emergence of local seed bank of winter weed species: *L. amplexicaule*, *O. laciniata*, and *S. media*. The plots were lightly cultivated to incorporate *S. obtusifolia* and *A. hybridus* seeds in the soil. *S. obtusifolia* and *A. hybridus* were chosen to represent summer weed species with large seeds with hard seed coats and small seeds with soft seed coats, respectively.

Brassica carinata seeds were planted at 6 kg ha^{-1} at 36 cm row spacing using a 4 m grain-drill planter (Great Plains 1206 NT) in all the plots except winter fallow (Seepaul et al., 2016). *B. carinata* was planted on February 4, 2019 in the first year and on November 18, 2019 in the second year. In 2019, although earlier planting was planned, heavy and frequent rainfall events delayed *B. carinata* planting until February (Table 1). *S*-metolachlor was applied 1 day after planting *B. carinata* with a tractor mounted sprayer using XR 11002 nozzles (TeeJet Technologies) to deliver 187 L ha^{-1}. Liming and fertilization were applied according to soil tests and recommendations for canola except for N, which was applied at 22 kg ha^{-1} immediately after planting, and an additional 68 kg ha^{-1} was applied during early bolting. Lambda-cyhalothrin (Winfield, USA) was applied at 18 g a.i. ha^{-1} twice during the 2018–2019 season for aphid (*Aphidoidea*) and armyworm (*Spodoptera frugiperda*) control. To control armyworm (*S. frugiperda*), zeta-cypermethrin (FMC Corporation) was applied at 28 g a.i. ha^{-1} once during the

TABLE 1 Total rainfall and mean air temperature for 2018–2019 and 2019–2020 during and after *Brassica carinata* growing seasons

	Total rainfall		**Mean temperature**	
	2018–2019	**2019–2020**	**2018–2019**	**2019–2020**
Months	**mm**		**°C**	
November	201	20	13	13
December	336	156	12	12
January	84	162	10	12
February	46	178	16	13
March	51	40	15	19
April	140	55	19	19
May	82	92	24	22
June	141	210	26	25
July	95	261	27	26
August	187	134	26	26
Total/mean[a]	1363	1308	18.8	18.7

Note: Data were obtained from the Florida Automated Weather Network (FAWN) located at the University of Florida/IFAS West Florida Research and Education Center (UF/IFAS-WFREC) in Jay, FL.

Abbreviations: °C, degree Celsius; mm, millimeters.

[a] Total is presented for rainfall, but the mean is presented for temperature.

2019–2020 season. Prothioconazole (Bayer CropScience) was applied at 165 g a.i. ha^{-1} twice during the 2019–2020 season for controlling Sclerotinia Stem Rot (*Sclerotinia sclerotiorum*).

2.2 | Data collection and analysis

After planting *B. carinata*, seedlings of *L. amplexicaule*, *S. media*, and *O. laciniata* were counted in the designated 1 m^2 quadrat and removed at weekly intervals during the crop growing season. Similarly, *S. obtusifolia* and *A. hybridus* seedling emergence was collected from the respective 1 m^2 quadrat on a weekly interval during *B. carinata* growing season and the subsequent summer season after the *B. carinata* harvest.

Aboveground *B. carinata* biomass was hand-harvested at maturity from a randomly assigned 1 m^2 area within the sub-plot on June 4, 2019 and May 13, 2020. Harvested *B. carinata* samples were air-dried at 65°C to determine dry biomass weight. The dry samples were hand threshed, and seed yield was recorded by adjusting at 8% moisture content.

After harvesting *B. carinata*, the field was mowed, and glyphosate (Roundup PowerMax; Bayer CropSciences) was applied at 1542 g a.e. ha^{-1} to eliminate the remaining weeds. The field was strip-tilled once, and a 1 m^2 sampling area was marked in each sub-plot to track summer weeds emergence after *B. carinata* harvest. *S. obtusifolia* and *A. hybridus* seedlings were counted and removed every week until emergence ceased.

Seedling emergence for winter weeds was converted to cumulative emergence up to *B. carinata* harvest. Similarly, the cumulative seedling emergence for summer weed species was calculated until *B. carinata* harvest and after the *B. carinata* harvest. Data were analyzed with ANOVA using the PROC GLIMMIX procedure in SAS (Statistical Analysis Systems, version 9.4; SAS Institute Inc.). The initial analysis illustrated significant year effect; therefore, data were analyzed separately by year. Data were tested to validate that residuals were random, homogeneous, and followed normality to meet the ANOVA assumptions. Since the data did not violate ANOVA assumptions, transformation was not required. Crop history, weed management, and their interactions were considered as fixed effects, whereas blocks and block*crop history were considered random effects. Means were separated using Fisher's least significant difference test at $p \leq 0.05$.

3 | RESULTS

Unpredicted weather conditions such as heavy rainfall and freezing temperatures can reduce the growth and performance of *B. carinata* as well as the emergence of annual weed species. Intense and frequent rainfall events during November and December 2018 (Table 1) delayed *B. carinata* planting until February 2019 for the 2018–2019 season. The difference in planting dates between the two experimental seasons likely explained the significant interactions between years with most variables ($p < 0.001$), so the data for each year was analyzed and presented separately. Furthermore, there were no interactions between crop history and weed management treatments for any of the studied variables ($0.20 < p < 0.94$; Table 2). Therefore, only the main effects are discussed below.

3.1 | Effect of crop history on weed emergence during *B. carinata* growing season

Lamium amplexicaule emergence was influenced by crop history in 2018–2019 and 2019–2020 ($p < 0.05$; Table 2). Cotton increased *L. amplexicaule* emergence 40% and 50% compared to summer fallow in 2018–2019 and 2019–2020,

TABLE 2 Analysis of variance for the effects of crop history, weed management treatments, and their interactions on winter and summer weed species emergence during the *Brassica carinata* growing season

			Amaranthus hybridus	***Lamium amplexicaule***	***Oenothera laciniata***	***Senna obtusifolia***	***Stellaria media***
Year	**Source of variation**	***df***	***p* value**				
2018–2019	Crop History (CH)	2	0.23	0.01	0.72	0.001	0.37
	Weed Management (WM)	2	0.004	0.02	0.07	0.83	0.01
	CH × WM	4	0.64	0.20	0.29	0.29	0.69
2019–2020	CH	2	0.10	0.01	0.29	0.02	0.001
	WM	2	<0.0001	<0.0001	0.53	<0.0001	0.26
	CH × WM	4	0.50	0.39	0.89	0.31	0.94

Note: Data were combined over the 2018–2019 and 2019–2020 seasons.

Abbreviations: *df*, degrees of freedom; *p* value, probability value.

respectively (Figure 1). Although peanut increased *L. amplexicaule* emergence over 40% compared to summer fallow in 2019–2020, no response to peanut was observed on the emergence in the previous season.

Stellaria media emergence was only affected by the previous crop in 2019–2020, increasing threefold after peanut and fourfold after cotton compared to summer fallow (Figure 1). Unlike the other two winter weed species, crop history did not affect *O. laciniata* emergence (Figure 1; Table 2).

Despite being considered a summer annual weed species, *A. hybridus* emergence was observed during the *B. carinata* growing season from late-February to mid-June and late-November to mid-May in 2018–2019 and 2019–2020 seasons, respectively. In 2018–2019, *A. hybridus* emergence was not affected by the previous crop (Figure 2). Conversely, in

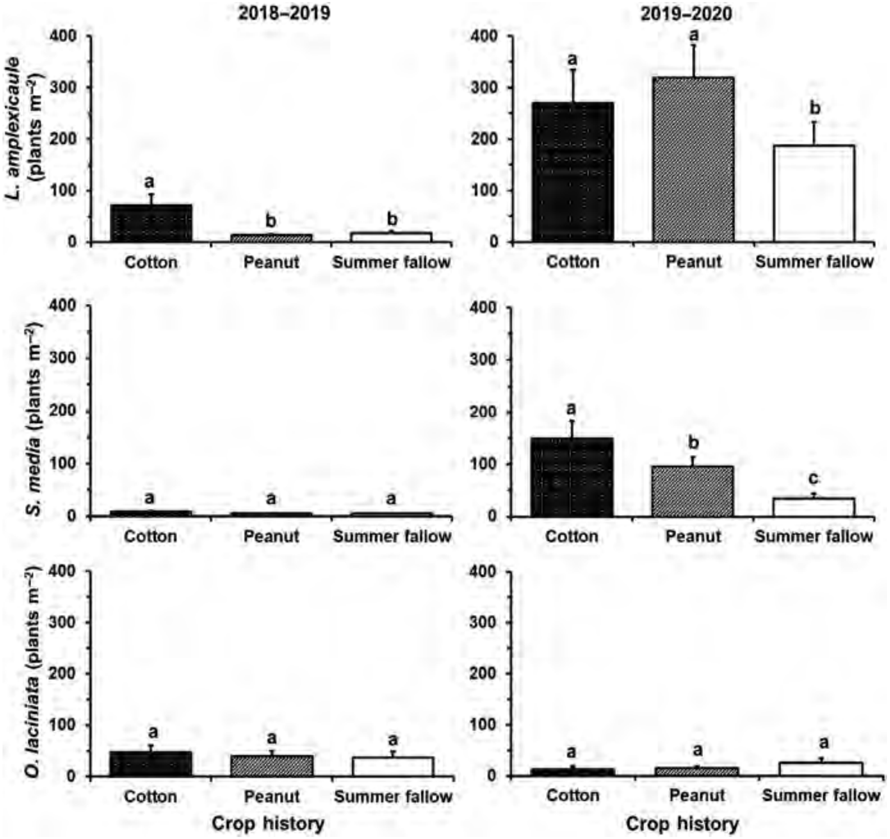

FIGURE 1 Effects of crop history (cotton, peanut, and summer fallow) on *Lamium amplexicaule*, *Stellaria media*, and *Oenothera laciniata* emergence in 2018–2019 and 2019–2020. Error bars represent the standard errors of the means. Treatments with the same letter within year and species are not significantly different ($p \leq 0.05$)

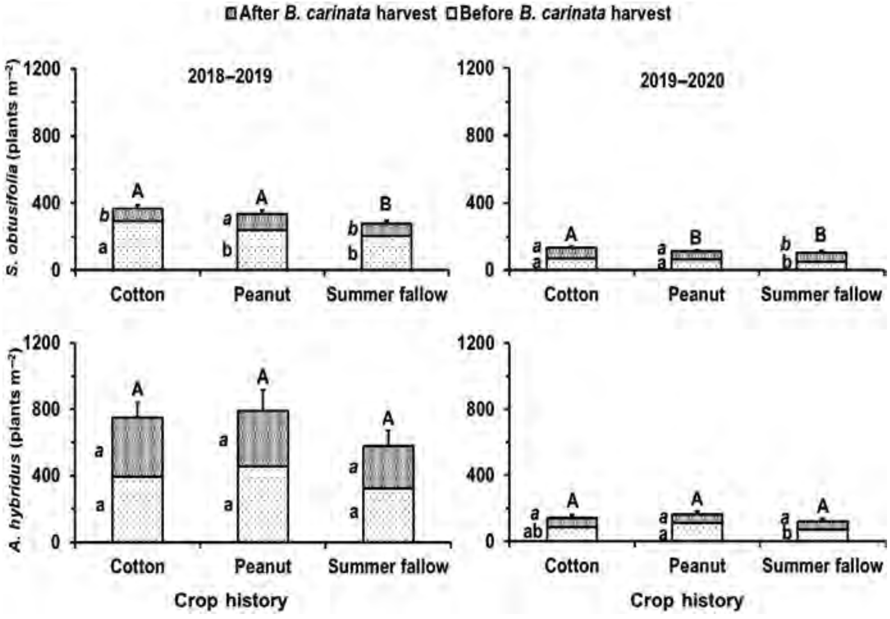

FIGURE 2 Effects of crop history (cotton, peanut, and summer fallow) on *Senna obtusifolia* and *Amaranthus hybridus* emergence before (February–June and November–May) and after (July–September and June–August) *Brassica carinata* harvest in 2018–2019 and 2019–2020. Error bars represent the SEMs. Treatments with the same letter (capitalized at the top of each graphs) within year and species are not significantly different ($p \leq 0.05$). Regular and italicized letters indicate differences between treatments before and *B. carinata* harvest, respectively

2019–2020, *A. hybridus* emergence after peanut increased over 50% compared to summer fallow (Figure 2).

In both years, crop history had a significant effect on *S. obtusifolia* emergence ($0.001 \le p \le 0.02$; Table 2). Interestingly, when cotton was grown the previous season, *S. obtusifolia* emergence during the *B. carinata* growing season was approximately 43% higher than the field left fallow before *B. carinata* planting (Figure 2).

After *B. carinata* harvest, *S. obtusifolia* emergence was at least 23% higher after peanut than the non-crop summer fallow in 2018–2019 (Figure 2). However, crop history did not affect *A. hybridus* emergence in any of the study year.

3.2 | Effect of weed management during *B. carinata* on weed emergence

S-metolachlor applied at planting consistently reduced *L. amplexicaule* population by approximately 80% in both years compared to *B. carinata* plots without the herbicide (Table 2; Figure 3). A similar result was observed in 2018–2019 for *S. media*, but no reduction in the emergence of this weed was observed in 2019–2020.

Oenothera laciniata was less susceptible to *S*-metolachlor than *L. amplexicaule* and *S. media*. The only reduction in *O. laciniata* emergence was observed in 2018–2019 after *S*-metolachlor application and was approximately 46% less compared to the *B. carinata* treatment without herbicide (Figure 3).

In the case of summer weed emergence during the *B. carinata* growing season, in 2018–2019, only *A. hybridus* emergence was reduced 40%–50% when *S*-metolachlor was applied compared to the herbicide-free *B. carinata* and the fallow plots (Figure 4). Conversely, in 2019–2020, although the emergence of summer weeds was less than in 2018–2019, there was a clear trend in which the emergence of both species was reduced as a result of preemergence *S*-metolachlor applications with *B. carinata* ($p < 0.0001$; Table 2). Thus, *S. obtusifolia* and *A. hybridus* populations were reduced in *B. carinata* with *S*-metolachlor by 36% and 89%, respectively, compared to a winter fallow (Figure 4). *Brassica carinata* reduced *A. hybridus* emergence by more than 27% even in the absence of *S*-metolachlor (Figure 4). Likewise, *S. obtusifolia* population was reduced at least 25% in *B. carinata* without *S*-metolachlor compared to the winter fallow (Figure 4). Considering all species studied, the application of *S*-metolachlor reduced weed pressure and the risk of interference with *B. carinata*.

After harvesting *B. carinata*, *A. hybridus* emergence was reduced by >40% with or without *S*-metolachlor

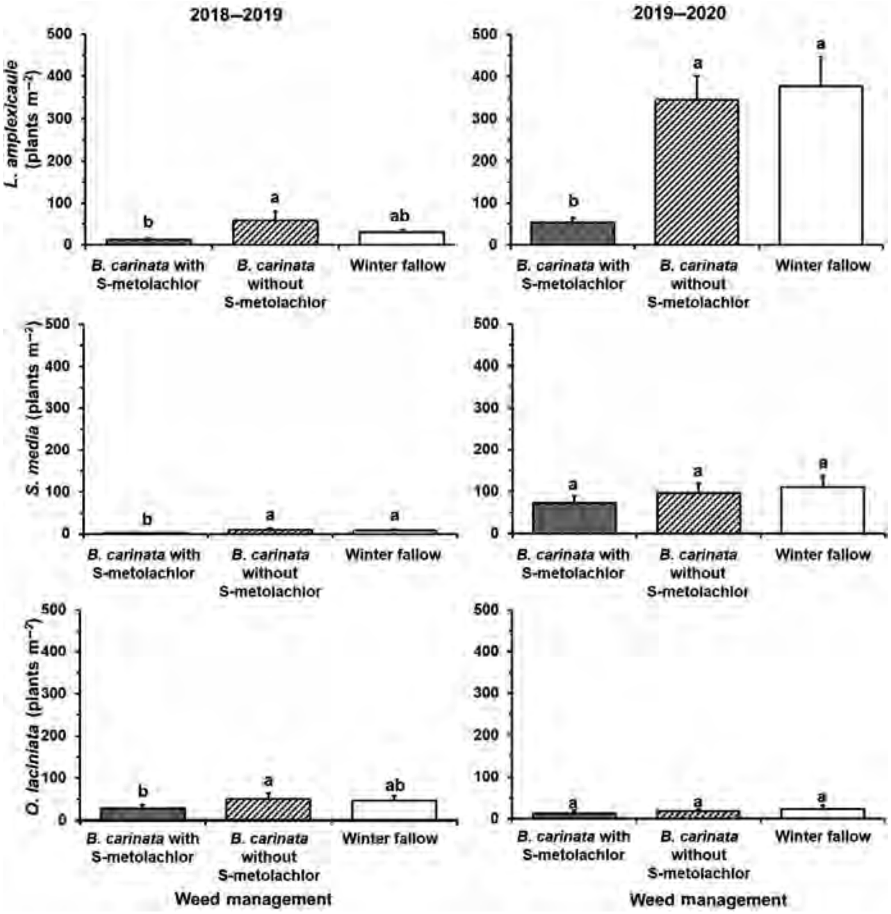

FIGURE 3 Effects of weed management treatments on *Lamium amplexicaule*, *Stellaria media*, and *Oenothera laciniata* emergence in 2018–2019 and 2019–2020. Error bars represent the SEMs. Treatments with the same letter within year and species are not significantly different ($p \le 0.05$)

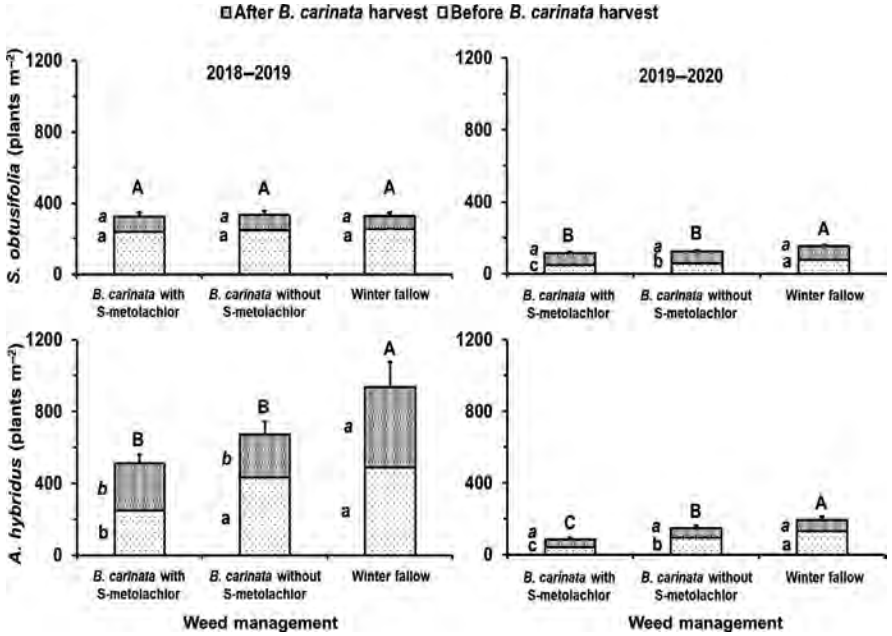

FIGURE 4 Effects of weed management treatments on *Senna obtusifolia* and *Amaranthus hybridus* emergence before (February–June and November–May) and after (July–September and June–August) *Brassica carinata* harvest in 2018–2019 and 2019–2020. Error bars represent the SEMs. Treatments with the same letter within year and species are not significantly different ($p \leq 0.05$). Regular and italicized letters indicate differences between treatments before and *B. carinata* harvest, respectively. Capital letters at the top of each graph represent differences between treatments

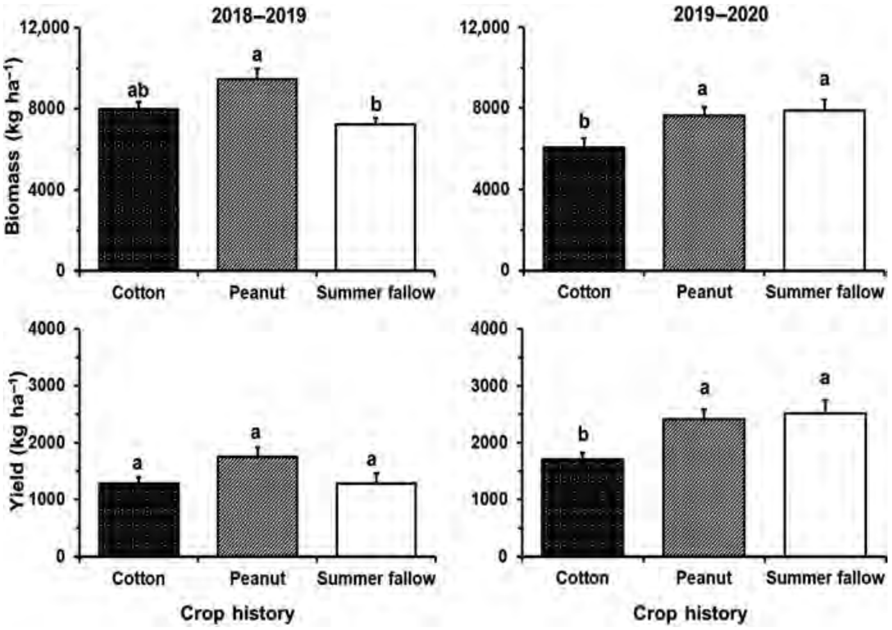

FIGURE 5 Effects of crop history (cotton, peanut, and summer fallow) on *Brassica carinata* biomass and seed yield in 2018–2019 and 2019–2020. Error bars represent the SEMs. Treatments with the same letter within the year are not significantly different ($p \leq 0.05$)

compared to the winter fallow in 2018–2019, while the weed management treatments had no effect during the second season (Figure 4). *S. obtusifolia* emergence was not affected by the weed management treatments in both seasons.

3.3 | Effect of crop history and weed management on *B. carinata* biomass and yield

In general, no clear trend was observed on *B. carinata* biomass production in response to crop history. For example, in 2018–2019, *B. carinata* biomass was higher when grown after peanut (9466 kg ha^{-1}) compared to summer fallow (7233 kg ha^{-1}; Figure 5), but it was not different from cotton. In 2019–2020, *B. carinata* biomass was similar following peanut (7647 kg ha^{-1}) and fallow (7875 kg ha^{-1}), but lower than cotton (6058 kg ha^{-1}; Figure 5). *Brassica carinata* seed yields were similar for all crop history treatments in 2018–2019 (Figure 5; Table 3), whereas seed yield was higher after peanut (2417 kg ha^{-1}) and fallow (2520 kg ha^{-1}) compared to cotton (1710 kg ha^{-1}; Figure 5) in 2019–2020. Interestingly, weed management treatments did not affect *B. carinata* biomass or yield in any of the experimental years ($0.064 < p < 0.52$; Table 3).

TABLE 3 Analysis of variance for the effects of crop history, weed management, and their interactions on *Brassica carinata* biomass and yield

Source of variation	*df*	Biomass 2018–2019	Biomass 2019–2020	Yield 2018–2019	Yield 2019–2020
		p values			
Crop History (CH)	2	0.025	0.037	0.262	0.021
Weed Management (WM)	2	0.064	0.522	0.261	0.379
CH × WM	4	0.528	0.821	0.189	0.896

Note: Data were combined over the 2018–2019 and 2019–2020 experiment year.

Abbreviations: *df*, degrees of freedom; *p* values, probability values.

4 | DISCUSSION

4.1 | Crop history effects on weed emergence during *B. carinata* production

Crop rotations are important from a weed management perspective. Depending on the specific crops used and their durations, crop rotations possess the potential of reducing weed population densities even when herbicides are not applied (Blackshaw et al., 1994; Liebman & Dyck, 1993; Schreiber, 1992). In this study, *B. carinata* grown after cotton resulted in more *L. amplexicaule* emergence in both years and *S. media* emergence in the 2019–2020 season. Positive responses from cotton were detected compared to the summer fallow for *S. obtusifolia* emergence, a summer annual weed species (Figure 2). High levels of soil N have been attributed for promoting weed emergence (Blackshaw et al., 2003; Hans & Johnson, 2002; Qasem, 1992; Supasilapa et al., 1992). This might explain why *L. amplexicaule*, *S. media*, and *S. obtusifolia* emergence were favored after cotton in this experiment (Figures 1 and 2). Common lambsquarters (*Chenopodium album* L.) seed germination was greater after receiving 280 kg ha^{-1} of ammonium nitrate compared to no nitrogen application (Fawcett & Slife, 1978). Thus, the results for higher winter weed emergence after cotton in this study could be associated with the greater nitrate concentration reducing seed dormancy (Fawcett & Slife, 1978; Pons, 1989).

4.2 | Effect of weed management during *B. carinata* season on weed emergence

Brassica carinata did not reduce the winter weed species density compared to winter fallow (Figure 3). Conversely, *S*-metolachlor, a safe preemergence herbicide in *B. carinata* (Leon et al., 2017), successfully reduced weed pressure, allowing us to evaluate weed interference of *B. carinata* by comparing with or without herbicide application.

Considering that *B. carinata* will likely be (at least initially) a secondary crop in the current cotton–peanut rotations in the southeastern U.S., it is critical to minimize production costs and inputs. Even though winter weed populations with *S*-metolachlor were reduced (Figure 3), *B. carinata* seed yield did not differ without this herbicide and with a much higher weed density (Table 3). This is likely due to the canopy structure of *B. carinata*, which is much taller (i.e., over 1.2 m; Seepaul et al., 2019), than the canopy of early emerging winter weeds such as *L. amplexicaule* and *S. media* (i.e., less than 0.35 m; Bryson & DeFelice, 2009). Likewise, the *B. carinata* canopy is fully closed by the time *S. obtusifolia* and *A. hybridus* emergence started, favoring weed suppression and preventing yield reduction. High weed suppressive potential has been reported for other Brassicaceae crops (Al-Khatib et al., 1997; Boydston & Hang, 1995). For example, *B. napus* L. suppressed the growth of *Capsella bursa-pastoris* (L.) Medik., *Setaria viridis* (L.) P. Beauv., and *Bassia scoparia* (L.) A.J.Scott by 76, 25, and 25%, respectively (Al-Khatib et al., 1997). By the time *B. carinata* was harvested, over half of the summer annual weed species populations had emerged but died either due to frost damage or were smothered by *B. carinata* shading (Figures 2 and 4). In a traditional year with early planted summer crops, many of the *S. obtusifolia* and *A. hybridus* seedlings that were eliminated during the *B. carinata* season would likely have been present in the summer crops.

4.3 | Effect of crop history and weed management on *B. carinata* biomass and yield

Weed management treatments had no effect on *B. carinata* yield and biomass for both years (Table 3). It was reported that maintaining row spacing at 0.36 m under weed-free conditions resulted in *B. carinata* seed yield of 2761 kg ha^{-1} when planted in mid-November (Mulvaney et al., 2019). Perhaps if *B. carinata* were planted in mid-November, as in the second year of the current study, a similar yield of 2417 and 2520 kg ha^{-1} could be obtained after summer fallow and peanut, respectively (Figure 5). The low seed yield in 2018–2019 could be the result of the late planting of *B. carinata* and a shorter growing season. Furthermore, although *B. carinata* seed yield without *S*-metolachlor was 2284 kg ha^{-1} for 2019–2020, there was no effect of the weed management treatment on seed yield. This result suggests that winter *B. carinata* could be competitive against winter weeds and provide weed suppression without substantially compromising yield.

4.4 | Implications of *B. carinata* for integrated weed management

Weed population dynamics are expected to vary based on crop history, rotation, and management practices. Research on weed population simulation models has illustrated that the variation of crops in rotations can affect weed populations dynamics over the years (Jordan et al., 1995). After introducing *B. carinata* into the existing crop rotation, not only will there be impacts on the population of winter weeds, including ones that will interfere with *B. carinata*, but also on summer weeds, such as establishment, and timing and duration of the growing season.

Brassica carinata exhibited weed tolerance/suppression when grown without *S*-metolachlor yielding similarly to when *S*-metolachlor was applied to reduce weed populations. Therefore, it seems that weed control, early during the growing season, will suffice to give time to *B. carinata* to reach canopy closure and outcompete weeds, especially those that are late-emerging species. This strategy has the benefit that does not entirely eliminate the emergence and establishment of winter weed species, thus maintaining plant diversity and associated ecosystem services (e.g., providing habitat, food, crop pollination, and pest suppression) in the field without jeopardizing yield goals (Petit et al., 2015).

A significant finding of the present research is that *B. carinata* can decrease densities of some problematic summer weed species in the subsequent crop. The reduction of the seed bank that is germinable at the beginning of the summer cropping season can influence weed management, particularly for low inputs weed control systems (Teasdale et al., 2004). Having a shorter summer season for cash crops after *B. carinata* may not be a feasible option for growers to implement this strategy every year. However, *B. carinata* could be strategically grown once every few years to reduce summer weed seed banks and combine this practice with double cropping with late-planted crops (e.g., soybean or sorghum—*Sorghum bicolor* (L.) Moench) to maintain economic viability. Crop rotation has been a vital component for effective weed control, and most importantly, for the herbicide-resistance management (Beckie, 2011; Chauvel et al., 2001; Owen, 2008). Integrated weed management systems by incorporating *B. carinata* possess the potential to reduce herbicide use (and associated costs) and contribute to more stable weed management in the long term (Swanton & Weise, 1991). Overall, this approach would allow farmers to diversify their crop rotation by including biofuel crops and develop a more robust integrated weed management strategy that will also help for herbicide-resistance management.

5 | CONCLUSION

This research demonstrated that *B. carinata* has the potential to be an alternative winter crop for producing biofuel in the southeast U.S. without increasing weed issues for summer cash crop production. Moreover, the introduction of *B. carinata* into the existing rotations has the added benefit for reducing the densities of problematic weed species of summer cash crops such as cotton, peanut, soybean, and grain sorghum, favoring more robust and resilient integrated weed management strategies in the region.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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