Weed Technology

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Effect of planting pattern and herbicide programs on sicklepod (*Senna obtusifolia* L.) control in peanut

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Research Article

Cite this article: Daramola OS, MacDonald GE, Kanissery RG, Tillman BL, Singh H, Ajani OA, Devkota P (2024) Effect of planting pattern and herbicide programs on sicklepod (*Senna obtusifolia* L.) control in peanut. Weed Technol. **38**(e53), 1–12. doi: 10.1017/wet.2024.64

Received: 12 April 2024
Revised: 24 June 2024
Accepted: 21 July 2024

Associate Editor:
Daniel Stephenson, Louisiana State University Agricultural Center

Nomenclature:
Bentazon; diclosulam; dimethenamid-*P*; fluridone; flumioxazin; imazapic; paraquat; *S*-metolachlor; 2,4-DB; sickelpod; *Senna obtusifolia* L.; peanut; *Arachis hypogaea* L.

Keywords:
Single row; twin-row; flumioxazin; paraquat; imazapic; *S*-metolachlor

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Abstract

Sicklepod is one of the most difficult to control weeds in peanut production in the southeastern United States due to its extended emergence pattern and limited effective herbicides for control. Growers rely on preemergence herbicides as the foundation of their weed control programs; however, postemergence herbicides are often needed for season-long weed control. The objectives of this study were to evaluate the effect of planting pattern and herbicide combinations for sicklepod control in peanut crops. Due to rapid canopy closure, twin-row planting improved late-season sicklepod control by 13% and peanut yield by 5% compared with a single-row pattern. A preemergence application of fluridone, flumioxazin, or fluridone + flumioxazin provided 76% to 89% control of sicklepod 28 d after preemergence. Regardless of the herbicide applied preemergence, paraquat + bentazon + *S*-metolachlor applied early postemergence was required to achieve ≥90% sicklepod control 28 d after early postemergence. All preemergence herbicide treatments followed by (fb) *S*-metolachlor or diclosulam + *S*-metolachlor applied early postemergence provided <90% control 28 d after early postemergence. A mid-postemergence application of imazapic + dimethenamid-*P* + 2,4-DB controlled sicklepod by 67% to 79% prior to peanut harvest, and biomass reduction was unacceptable (<80%), resulting in difficulty in peanut digging. The highest peanut yield was observed when paraquat + bentazon + *S*-metolachlor was applied early postemergence fb imazapic + dimethenamid-*P* + 2,4-DB applied mid-postemergence. Based on the results of this study, a herbicide combination of paraquat + bentazon + *S*-metolachlor is an important early-season tool for controlling sicklepod in peanut crops. The results also showed that a twin-row planting pattern improved late-season sicklepod control but did not reduce herbicide input to protect peanut yield.

Introduction

Peanut is an important economic legume crop in Florida and throughout the southeastern United States. Peanut was planted on 60,841 ha in Florida and 590,841 ha in the United States in 2022 and had a market value of more than US$1 billion (USDA NASS 2023). Peanut has a relatively low canopy and prostate growth habit, making the plant prone to heavy weed infestations from broadleaf, grass, and sedge species (Everman et al. 2008; Webster et al. 2007).

Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.], sicklepod, and tropical spiderwort (*Commelina benghalensis* L.) are among the primary competitors in peanut production in the southeastern United States (Kharel et al. 2022; Stephenson and Brecke 2011; Webster et al. 2007). These weeds interfere with crop growth and reduce yield and harvest efficiency (Kharel et al. 2022; Stephenson and Brecke 2011). A survey conducted in Georgia reported sicklepod as the fifth most challenging of all agricultural pests, including weeds, insects, and diseases (Culpepper et al. 2006). Similar trends found in that report have been reported in other southeastern states, where sicklepod is a troublesome weed in agronomic crop production systems (Daramola et al. 2023a; Sosnoskie et al. 2021). Sicklepod can reduce peanut yield by 22.3 kg ha^{-1} at a density of 1 plant 10 m^{-2} (Hauser et al. 1982). Sicklepod is difficult to control in peanut fields because it has an extended emergence pattern and produces a large number of seeds (>1,600 seeds plant^{-1}) that persist in the soil seedbank (Senseman and Oliver 1993). Additionally, sicklepod and peanut are members of the same plant family (Fabaceae); thus, a limited number of herbicides are selective among these species. Peanut can tolerate many herbicides, but not many can be used on the crop to control sicklepod (Daramola et al. 2023b).

Herbicides are the primary tool for controlling weeds in peanut and are crucial to sustainable peanut production in the United States. Because preemergence herbicides do not provide season-long weed control, successful weed management in peanut often requires using a mixture of herbicides with different modes of action, and combinations of preemergence, early postemergence, and/or late postemergence herbicide treatments with residuals (Chaudhari et al. 2018; Leon et al. 2019). Several postemergence herbicides including acifluorfen, bentazon, paraquat, imazapic, lactofen, and 2,4-DB are available for annual broadleaf weed control in peanut (Daramola et al. 2023b), but no single herbicide can provide a season-long control of sicklepod due to its extended emergence pattern. Weed control could be accomplished by hand-weeding but this is expensive, time-consuming, laborious, and impractical in modern-day farming (Johnson et al. 2012a,b). Mechanical control (cultivation), on the other hand, is limited to early in the season due to the prostrate growth habit of peanut (Boyer et al. 2011). Additionally, cultivation can cause mechanical injury of peanut vines, resulting in increased access for pathogens and soilborne disease incidence (Wilcut et al. 1995). Hence, integrated weed management programs are needed that combine chemical and nonchemical methods.

While herbicides remain important tools for weed control in peanut in the United States, integration of nonchemical control options such as cultural practices that reduce weed competition and enhance crop competitiveness, may provide improved control. The benefits of integrating cultural control methods, such as using cover crops, crop rotation, and tillage; and altering planting dates, planting pattern, row spacing, and crop density have been demonstrated in previous studies (Johnson et al. 2012a,b; Kharel et al. 2022; Stephenson and Brecke 2011). In previous studies, a twin-row planting pattern, as opposed to a single-row pattern, enhanced control of various weed species of peanut including common cocklebur (*Xanthium strumarium* L.) (Brecke and Stephenson 2006), Florida beggarweed (Brecke and Stephenson 2006), eclipta (*Eclipta prostrata*) (Place et al. 2010), *Ipomoea* spp. (Place et al. 2010), and sicklepod (Brecke and Stephenson 2006; Kharel et al. 2022; Lanier et al. 2004a). Although earlier research reported the effects of planting pattern on sicklepod control in peanut, most of those reports used a paraquat-based combination of herbicides (Brecke and Stephenson 2006; Colvin et al. 1985). Limited information exists on the effect of planting pattern in combination with non-paraquat herbicide programs. Although paraquat provides 90% to 100% control of sicklepod (Stephenson and Brecke, 2011), it can cause peanut stunting and foliar injury, and the injury can interact with biotic or abiotic stress, resulting in yield reduction (Brecke et al. 1996). Additionally, paraquat lacks residual activity and can be applied only from peanut hypocotyl emergence until 28 d after emergence (Jordan et al. 2003). Imazapic is one of the most commonly used postemergence herbicides used to control sicklepod in peanut in the southeastern United States (Daramola et al. 2023b; Grey et al. 2003). Imazapic at the recommended use rate of 71 g ai ha^{-1} provides 85% to 95% control of sicklepod (Grey et al. 2003; Wehtje and Brecke 2004; Wehtje et al. 2000). However, crop rotational restrictions must be considered before applying imazapic (Anonymous 2007). Hence, integrated weed management programs that combine herbicides with cultural practices such as planting pattern are needed to improve sicklepod control in peanut. The objective of this study was to determine the effects of peanut planting pattern (single-row or twin-row) and herbicide combinations on sicklepod control, density, and biomass; and peanut injury and yield. We hypothesized that a twin-row planting pattern would improve late-season sicklepod control and reduce herbicide input while maintaining peanut yield.

Materials and Methods

Experimental Site and Design

Field experiments were conducted during the summer of 2022 and 2023 at the West Florida Research and Education Center near Jay, FL (30.776542°N, 87.147662°W, 62 m a.s.l.). The soil at the experimental site was Red Bay fine sandy loam (fine-loamy, kaolinitic, thermic Rhodic Kandiudults) with 2.1% organic matter, pH 5.6. The preceding crop in both years was cotton (*Gossypium hirsutum* L.). The experimental area was tilled using a tractor-mounted moldboard plow to a depth of 20 cm, disked, and leveled before planting in 2022 and 2023. Sicklepod was the predominant weed species in the experimental field in both years. In addition to the natural infestation, sicklepod seeds obtained from Azlin Seed Service (Leland, MS) were spread in the experimental area at a rate of 500 seed m^{-2} (96% germination) in November of both 2021 and 2022 to ensure uniform distribution for observation during the experiments in 2022 and 2023. The growing conditions differed between the 2022 and 2023 growing seasons. Average daily temperature during the growing season in 2022 was comparable with the 16-yr average (2007 to 2023), whereas the cumulative rainfall exceeded the 16-yr average for most of the growing season. In contrast, the cumulative rainfall in 2023 was 229 mm lower than the 16-yr average and the average daily temperature exceeded the 16-yr average during much of the growing season.

The experiment was arranged in a randomized complete block design with a split-plot randomization restriction with four replications. Planting pattern (single-row or twin-row) was assigned as the main-plot factor, whereas herbicide programs were assigned as the subplot factor in a randomized complete block. Plots size was 7.6 m by 3.6 m in both years. Peanut cultivar 'Georgia 06G' (Branch 2007) was planted at 20 seeds m^{-1} on May 1, 2022, and May 5, 2023. Peanut was planted in single rows on 91-cm centers and twin-rows spaced at 18 cm on 91-cm centers. In total, nine herbicide combinations were evaluated: 1) a preemergence application of fluridone (Brake®; SePRO, Carmel, IN) at 0.16 kg ai ha^{-1}; 2) flumioxazin (Valor® SX; Valent U.S.A., Walnut Creek, CA) at 0.06 kg ai ha^{-1}; 3) fluridone at 0.16 + flumioxazin at 0.06 kg ai ha^{-1}. Each preemergence herbicide was followed by (fb) an early postemergence application of paraquat (Gramozone® SL 3.0; Syngenta Crop Protection, LLC, Greensboro, NC) at 0.25 kg ai ha^{-1} + *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection) at 1.33 kg ai ha^{-1} + bentazon (Basagran; BASF Corporation, Research Triangle Park, NC) at 0.33 kg ai ha^{-1}; 4) fluridone at 0.16 kg ai ha^{-1} fb an early postemergence application of diclosulam (Strongarm®; Corteva AgroScience, Indianapolis, IN) at 0.02 kg ai ha^{-1} + *S*-metolachlor at 1.33 kg ai ha^{-1}; 5) flumioxazin at 0.06 kg ai ha^{-1} fb an early application of diclosulam at 0.02 kg a.i. ha^{-1} + *S*-metolachlor at 1.33 kg ai ha^{-1}; 6) fluridone at 0.16 kg ha^{-1} + flumioxazin at 0.06 kg ha^{-1} followed by an early postemergence application of diclosulam at 0.02 kg a.i. ha^{-1} + *S*-metolachlor at 1.33 kg ai ha^{-1}; 7) fluridone at 0.16 kg ai ha^{-1} followed by an early postemergence application of *S*-metolachlor at 1.33 kg ai ha^{-1} alone; 8) flumioxazin at 0.06 kg ai ha^{-1} followed by an early postemergence application of *S*-metolachlor

Table 1. Dates of field activities and treatments in field study evaluating the effects of planting pattern and herbicide programs on sicklepod control in peanut near Jay, FL, in 2022 and 2023.[a,b]

Field activities	2022	2023
Date of planting	May 1	May 5
Date of PRE application	May 1	May 5
Date of emergence	May 9	May 12
Date of EPOST application	June 3	June 6
Date of MPOST application	July 7	July 11
Date of peanut harvest	October 9	October 13

[a]Abbreviations: EPOST, early postemergence; MPOST, mid postemergence; PRE, preemergence.

[b]Sicklepod height and density were 5 cm to 15 cm and 4 to 17 plants m^2, respectively, at the EPOST application, 2 cm to 4 cm and 1 to 5 plants m^2, respectively, at the MPOST application in plots treated with paraquat, and 7 to 14 cm and 7 to 45 plants m^2, respectively, at the MPOST application in plots not treated with paraquat.

at 1.33 kg ai ha^{-1} alone; and 9) fluridone at 0.16 kg ha^{-1} + flumioxazin at 0.06 kg ha^{-1} followed by an early postemergence application of *S*-metolachlor at 1.33 kg ai ha^{-1} alone. All the herbicide programs were followed by a mid-postemergence application of imazapic (Cadre; BASF Corporation) at 0.07 kg ai ha^{-1} + dimethenamid-*P* (Outlook®; BASF Corporation) at 0.02 kg ai ha^{-1} + 2,4-DB (Butyric 200®; Winfield United, Arden Hills, MN) at 0.25 kg a.i. ha^{-1}. A nontreated control was also included for treatment evaluation in both years. Preemergence herbicides were applied the day after planting peanut, early postemergence herbicides were applied 25 d after peanut emergence, and mid-postemergence herbicides were applied on July 7, 2022, and July 11, 2023 (Table 1). Clethodim (Select Max, Valent U.S.A.) was applied at 136 g ai ha^{-1} at 42 d after planting to provide grass weed control. A CO_2-pressurized backpack sprayer with TeeJet TTI11002 nozzles (Spraying Systems Co., Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} spray volume at 4.8 km hr^{-1} was used to spray herbicide treatments in both years. Agronomic practices including fertilizer, fungicide, insecticide, and gypsum application were followed according to the University of Florida Cooperative Extension Services local recommendations (Wright et al. 2016).

Data Collection

Sicklepod control ratings were assessed visually at 28 d after preemergence and 28 d after early postemergence on a scale of 0% to 100% (where 0% is no injury and 100% is complete death of the plant). Sicklepod control following application of mid-postemergence herbicides was assessed prior to peanut harvest using the same scale. Additionally, sicklepod density was recorded 28 d after preemergence, 28 d after early postemergence, and prior to peanut harvest by counting sicklepod plants in two 0.5-m^{-2} quadrats within the two middle rows of each plot. Sicklepod plants within each quadrat were then harvested by clipping the plants at the soil level. Aboveground sicklepod biomass was harvested, dried at 60 C for 7 d, and dry biomass weights were recorded. Sicklepod biomass reduction was determined by comparison with the nontreated control and expressed as a percentage of biomass reduction using the following equation (Wortman 2014):

$$\text{Biomass reduction}(\%) = [(A - B)/A] \times 100 \qquad [1]$$

where A represents the biomass of the nontreated control plot and B represents the biomass of individual herbicide-treated plots.

Peanut plants were visually observed for injury symptoms at 14 and 28 d after preemergence, early postemergence, and mid-postemergence herbicide treatments. Peanut injury ratings were based on a scale of 0% to 100% with 0% representing normal plant growth with no injury symptoms and 100% representing completely dead plants. Injury symptoms observed after a preemergence herbicide application included stunting, irregular leaflet discoloration (when flumioxazin was used), and bleached white tissue (when fluridone was used). Injury symptoms following an early postemergence herbicide application was characterized by stunting, leaf burning, necrosis, and bronzing (with paraquat + *S*-metolachlor + bentazon).

Peanut canopy height and width were measured at 28 d after preemergence, early postemergence, and prior to peanut harvest to evaluate the effect of the treatments on peanut growth. Peanut canopy height and width were measured from four plants in the two middle rows of each plot. A single plant from one of the twin rows was measured. Canopy height was measured from the ground surface to the top of the peanut canopy, whereas canopy width was measured from one side of the peanut canopy to the other side. Peanut optimum harvest timing was determined using the hull and scrape method (Williams and Drexler 1981), and yield was determined at harvest maturity by harvesting the middle two rows of each plot. Peanut plants were dug using a conventional digger-shaker-inverter and were allowed to air-dry in the field for 3 to 5 d. Peanut pod moisture content was measured using a grain moisture meter calibrated for peanuts as recommended by Mulvaney and Devkota (2020), and pod yields were converted to kilograms per hectare (kg ha^{-1}) at 10.5%.

Statistical Analysis

Data were collected on sicklepod control, density, and biomass; and peanut injury, peanut canopy height and width, and peanut yield, and analyzed using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc., Cary, NC). Prior to analysis, all data were tested for homogeneity of error variances. Sicklepod densities and biomass needed square root transformation, and all analyses were performed on the transformed data. An initial analysis was conducted to determine whether the main effect of year or an interaction containing year influenced results. For the initial analysis, year, planting pattern, and herbicide program and their interactions were considered fixed effects, while replication and replication by each fixed effect were considered random effects. When year-by-planting pattern and year-by-herbicide program interactions were significant, 2022 and 2023 data were analyzed separately with planting pattern, herbicide program, and their interaction as fixed effects; and replication and the interaction of replication with all fixed effects as random effects. In the absence of a significant interaction of year with planting pattern or herbicide program, an analysis was performed for the 2 yr combined. For the combined analysis, planting pattern, herbicide program, and their interaction were considered fixed effects; while year, replication nested within year, and their interaction with fixed effects were considered random effects. Means were separated using Tukey's honestly significant difference test at $P < 0.05$. Following treatment means separation, data were back-transformed for the presentation of results.

Results and discussion

Peanut Injury

Year-by-herbicide program interaction was significant for peanut injury 14 and 28 d after preemergence; therefore, data are presented by year. However, this interaction was not significant 14 and 28 d

Table 2. Effect of herbicide programs on peanut injury at 14 and 28 d after preemergence and early postemergence herbicide treatments in field experiments conducted near Jay FL, in 2022 and 2023.[a–f]

Herbicide programs		14 DAPRE		28 DAPRE		14 DAEPOST	28 DAEPOST
		2022	2023	2022	2023		
		%					
PRE	EPOST						
Fluridone	Paraquat + bentazon + *S*-metolachlor	10 b	10 a	2 b	5 a	26 a	13 a
Fluridone	Diclosulam + *S*-metolachlor	10 b	11 a	4 b	5 a	11 bc	7 b
Fluridone	*S*-metolachlor	11 b	11 a	2 b	6 a	5 c	2 c
Flumioxazin	Paraquat + bentazon + *S*-metolachlor	20 a	9 a	10 a	4 a	26 a	10 ab
Flumioxazin	Diclosulam + *S*-metolachlor	18 a	9 a	9 a	4 a	15 b	8 b
Flumioxazin	*S*-metolachlor	18 a	7 a	8 a	4 a	5 c	2 c
Fluridone + flumioxazin	Paraquat + bentazon + *S*-metolachlor	24 a	9 a	14 a	4 a	27 a	12 ab
Fluridone + flumioxazin	Diclosulam + *S*-metolachlor	23 a	9 a	11 a	4 a	14 b	8 b
Fluridone + flumioxazin	*S*-metolachlor	22 a	8 a	12 a	4 a	5 c	2 c
P-value		0.002	0.2	<.001	0.2	<.001	<.001

[a] Abbreviations: DAEPOST, days after postemergence; DAPRE, days after preemergence; EPOST, early postemergence; PRE, preemergence.
[b] Injury ratings were based on visual estimates on a 0% to 100% scale where 0% = no injury and 100% = completely dead plants).
[c] Data on peanut injury 14 and 28 DAEPOST were combined over 2 yr (2022 and 2023).
[d] PRE applications occurred the day after peanut was planted.
[e] EPOST applications occurred 25 d after peanut emergence.
[f] Means (n = 9) within a column followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

after early postemergence; therefore, data were combined across years. Planting pattern and the interaction of planting pattern-by-herbicide program had no effect on peanut injury (data not shown), but herbicide program effect was significant (Table 2). In 2022, flumioxazin alone and fluridone + flumioxazin applied preemergence resulted in at least 2-fold greater injury than fluridone applied alone 14 d after preemergence (Table 2). Although peanut recovered to14% or less injury 28 d after preemergence, the injury from treatments that contained flumioxazin remained twice that observed from fluridone alone. In 2023, there were no differences among herbicide treatments at either 14 d or 28 d after preemergence (Table 2). The greater peanut injury from flumioxazin treatments in 2022 may be due to more precipitation during the first 2 wk after peanut emergence. Previous studies have shown that heavy rain that causes flumioxazin-treated soil to splash on peanut foliage can lead to greater temporary peanut injury (Basinger et al. 2021; Hurdle et al. 2020; Kharel et al. 2022).

Peanut injury after early postemergence treatments was greater following applications of paraquat + bentazon + *S*-metolachlor (<27%) than applications of diclosulam + *S*-metolachlor or *S*-metolachlor alone (<14%) 14 and 28 d after early postemergence (Table 2). By 28 d after early postemergence, peanut injury was <13% for all treatments (Table 2). Similar results were observed in previous studies in which peanut recovered from paraquat injury (Carley et al. 2009; Eason et al. 2020; Knauft et al. 1990; Wehtje et al. 1994). *S*-metolachlor and diclosulam applied postemergence did not cause significant injury to peanut. No visual peanut injury symptom was observed following mid-postemergence applications of imazapic + dimethenamid-*P* + 2,4-DB in 2022 and 2023.

Peanut Canopy Width and Height

The effect of planting pattern on peanut canopy height was not significant throughout the period of observation, but canopy height was influenced by herbicide program (Table 3). Year-by-herbicide program interaction was not significant for peanut canopy width 28 d after early postemergence; therefore, data were combined across both years, but it was significant 28 d after mid-postemergence (Table 4).

Peanut canopy height was reduced by at least 12% following an early postemergence application of paraquat + bentazon + *S*-metolachlor compared with diclosulam + *S*-metolachlor or *S*-metolachlor alone 28 d after early postemergence in both years (Table 3). When evaluated at 28 d after mid-postemergence, corresponding with 12 wk after planting in both years, peanut canopy height following an application of paraquat + bentazon + *S*-metolachlor early postemergence fb imazapic + dimethenamid-*P* + 2,4-DB applied mid-postemergence was at least 5% lower compared with herbicide programs that did not include paraquat + bentazon + *S*-metolachlor. However, the decreased canopy height 28 d after mid-postemergence did not lead to decreased peanut yield. While peanut stunting and canopy reduction is typical of herbicide combinations that contain paraquat, previous studies have shown that peanut recovers when good environmental conditions prevail, and yield is generally not affected if the herbicide is applied before pegging (Carley et al. 2009; Eason et al. 2020; Knauft et al. 1990; Wehtje et al. 1994).

Peanut planted in twin rows achieved full canopy closure earlier than peanut planted in single rows (data not shown). At 28 d after early postemergence, corresponding to 8 wk after planting in both years, and 28 d after mid-postemergence in 2022, peanut canopy width was 6% to 8% greater in twin rows compared with single rows. Seeding rate was similar for both the single-row and twin-row patterns; hence, twin rows produced fewer seeds per linear distance (seeds per meter) with ample space available for enhanced lateral plant growth compared with single rows. Similar results have been reported in at least one previous study (Kharel et al. 2022). At 28 d after mid-postemergence in 2023, peanut planted in twin and single rows had similar canopy width (Table 4). This lack of significant planting pattern effect at 28 d after mid-postemergence in 2023 may be due to reduced precipitation or drought conditions during the mid to late stage of crop growth (July and August) in 2023.

Herbicide programs that included paraquat + bentazon + *S*-metolachlor applied early postemergence resulted in at least 9% reduction in peanut canopy width compared with other preemergence fb early postemergence treatments 28 d after early postemergence. However, peanut plants recovered, and no

Table 3. Effect of planting pattern and herbicide programs on peanut canopy height 28 d after early postemergence, mid-postemergence, and prior to peanut harvest in 2022 and 2023 in field experiments conducted near Jay, FL, in 2022 and 2023.[a–f]

			Canopy height					
			28 DAEPOST		28 DAMPOST		Preharvest	
			cm					
Planting pattern								
Single-row			39	a	53	a	61	a
Twin-row			38	a	53	a	60	a
P-value			0.2		0.3		0.4	
Herbicide programs								
PRE	EPOST	MPOST						
Fluridone	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	42	a	57	a	60	a
Fluridone	Diclosulam + *S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	42	ab	57	a	62	a
Fluridone	*S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	42	ab	56	a	58	a
Flumioxazin	Paraquat + bentazon + *S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	33	c	48	b	61	a
Flumioxazin	Diclosulam + *S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	41	a	54	a	59	a
Flumioxazin	*S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	41	a	54	a	60	a
Fluridone + flumioxazin	Paraquat + bentazon + *S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	32	c	48	b	62	a
Fluridone + flumioxazin	Diclosulam + *S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	39	b	55	a	62	a
Fluridone + flumioxazin	*S*-metolachlor	imazapic + dimethenamid-*P* + 2,4-DB	39	b	54	a	58	a
Nontreated control			32	c	49	b	61	a
P-value			<.001		<.001		0.4	

[a] Abbreviations: DAEPOST, days after postemergence; DAMPOST, days after mid-postemergence; DAPRE, days after preemergence; EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

[b] Data on peanut canopy height were combined for 2022 and 2023.

[c] Means (n = 2, 10) within a column followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

[d] PRE herbicides were applied the day after peanut was planted.

[e] EPOST herbicides were applied 25 d after peanut emergence.

[f] MPOST herbicides were applied 35 d after EPOST application.

reductions were observed 28 d after mid-postemergence in both years (Table 4). Peanut canopy width at 28 d after early postemergence was similar between the herbicide combinations of diclosulam + *S*-metolachlor and *S*-metolachlor alone applied early postemergence. At 28 d after mid-postemergence, all preemergence fb early postemergence fb late postemergence herbicide applications resulted in similar peanut canopy width in 2022, results for which were higher than those of the untreated control (Table 4).

Sicklepod Control, Density, and Biomass Reduction

Year-by-herbicide program interaction was significant for sicklepod control, density, and biomass reduction at 28 d after preemergence and 28 d after early postemergence; therefore, data are presented by year. There were no year by herbicide program interactions at the preharvest evaluation, so data are combined over years. The interaction of planting pattern-by-herbicide program and the main effect of planting pattern for sicklepod control, density, and biomass reduction were not significant at 28 d after preemergence or 28 d after early postemergence in 2022 and 2023; however, the effect of planting pattern was significant prior to peanut harvest, and the subplot effect (herbicide program) was significant throughout the period of observation.

Averaged across herbicides, sicklepod control was 9% greater in the twin-row than the single-row planting pattern prior to peanut harvest (Table 5). Sicklepod density and biomass reduction results were similar to sicklepod control observations. Prior to peanut harvest, sicklepod density was reduced from 15 to 9 plants m^{-2} when single rows are compared to twin rows (Table 6). Similarly, sicklepod biomass was reduced 7% more in the twin-row than in the single-row planting pattern prior to peanut harvest (Table 7). Greater sicklepod control with the twin-row planting pattern observed in this study is attributed mainly to rapid canopy closure, which reduced light reaching the soil surface for late-season weed emergence; this observation is also supported by Buchanan and Hauser (1980). These results agree with those of previous studies that reported better sicklepod control when peanut was seeded in twin-row planting patterns compared with single-row planting patterns due to rapid canopy closure (Brecke and Stephenson 2006; Kharel et al. 2022; Lanier et al. 2004a).

Sicklepod control, density, and biomass reduction were affected by herbicide program throughout the periods of observation in 2022 and 2023. Flumioxazin applied preemergence alone controlled sicklepod by 86% to 88% 28 d after preemergence in 2022 and 2023, respectively; however, control was not improved when flumioxazin was mixed with fluridone (when 86% to 89% control was achieved) (Table 5). Similarly, flumioxazin applied alone or in mixture with fluridone resulted in similar sicklepod density (85% to 90% reduction compared to untreated plants) and biomass reduction (88% to 89%) 28 d after preemergence (Table 6). In previous research, flumioxazin applied preemergence alone controlled sicklepod by 70% to 75% 21 d after treatment (Grey and Wehtje 2005; Willingham et al. 2008), which is lower than the control observed in the current study. Other research has indicated that mixtures of flumioxazin and other residual herbicides such as dimethenamid-*P* and metolachlor did not improve sicklepod control compared with flumioxazin applied alone (Grey et al. 2002).

In 2022, sicklepod control following flumioxazin applied alone and fluridone + flumioxazin applied preemergence (86% to 88% control) were at least 16% to 17% more effective than fluridone when it was used alone (76% to 78% control) 28 d after preemergence (Table 5). In contrast, fluridone applied alone was as effective as flumioxazin or fluridone + flumioxazin in 2023, when all treatments resulted in sicklepod control of 86% to 88%, and a reduction in sicklepod biomass by 85% to 87% 28 d after

Table 4. Effect of planting pattern and herbicide programs on peanut canopy width 28 d after early postemergence and mid-postemergence, and peanut yield in 2022 and 2023 in field experiments conducted near Jay FL, in 2022 and 2023.[a–f]

			Canopy width							
					28 DAMPOST					
			28 DAEPOST		2022		2023		Yield	
Planting pattern			cm						kg ha^{-1}	
Single-row			72	b	86	b	80	a	4,020	b
Twin-row			78	a	91	a	82	a	4,240	a
P-value			0.02		0.001		0.1		0.001	
Herbicide Programs										
PRE	EPOST	MPOST								
Fluridone	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	72	b	88	a	81	a	4,540	ab
Fluridone	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	81	a	88	a	80	a	4,190	d
Fluridone	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	79	a	89	a	81	a	4,120	d
Flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	71	b	89	a	81	a	4,550	ab
Flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	79	a	88	a	82	a	4,240	c
Flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	79	a	88	a	81	a	4,270	c
Fluridone + flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	68	bc	89	a	81	a	4,690	a
Fluridone + flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	79	a	88	a	82	a	4,460	b
Fluridone + flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	78	a	90	a	83	a	4,470	bc
Nontreated control			68	c	83	b	76	b	1,810	e
P-value			<.001		0.02		0.03		<.001	

[a] Abbreviations: DAEPOST, days after postemergence; DAMPOST, days after mid-postemergence; DAPRE, days after preemergence; EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

[b] Data on peanut canopy width 28 DAEPOST and yield were combined for 2022 and 2023.

[c] PRE herbicides were applied the day after peanut was planted.

[d] EPOST herbicides were applied 25 d after peanut emergence.

[e] MPOST herbicides were applied 35 d after EPOST application.

[f] Means (n = 2, 10) within a column followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

Table 5. Effect of herbicide programs on sicklepod control in peanut crops 28 d after preemergence and early postemergence, and prior to harvest in field experiments conducted near Jay, FL, in 2022 and 2023.[a–g]

			28 DAPRE		28 DAEPOST		
			2022	2023	2022	2023	Preharvest
			%				
Planting pattern							
Single-row			83 a	86 a	71 a	88 a	91 b
Twin-row			84 a	87 a	72 a	89 a	99 a
P-value			0.3	0.2	0.3	0.3	<.001
Herbicide programs							
PRE	EPOST	MPOST					
Fluridone	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	76 b	87 a	91 a	99 a	95 a
Fluridone	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	78 b	86 a	64 b	86 b	79 b
Fluridone	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	76 b	86 a	57 c	87 b	77 bc
Flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	88 a	87 a	90 a	97 a	91 a
Flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	86 a	88 a	63 b	86 b	67 d
Flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	87 a	86 a	55 c	86 b	79 b
Fluridone + flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	88 a	87 a	91 a	97 a	94 a
Fluridone + flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	87 a	88 a	69 b	83 b	70 cd
Fluridone + flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	86 a	87 a	68 b	78 b	75 bc
P-value			<.001	<.001	<.001	<.001	<.001

[a] Abbreviations: DAEPOST, days after postemergence; DAPRE, days after preemergence; EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

[b] Visual efficacy/injury was based on a 0% to 100% scale where 0% =no control/no injury and 100% = complete control/plant death.

[c] Preharvest data on sicklepod control were combined for 2022 and 2023.

[d] Means ($n = 2, 9$) within a column followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

[e] PRE herbicides were applied the day after peanut was planted.

[f] EPOST herbicides were applied 25 d after peanut emergence.

[g] MPOST herbicides were applied 35 d after EPOST application.

Table 6. Effect of planting pattern and herbicide programs on sicklepod density in peanut 28 d after preemergence and early postemergence, and prior to harvest in field experiments conducted near Jay, FL, in 2022 and 2023.[a–f]

			28 DAPRE		28 DAEPOST		
			2022	2023	2022	2023	Preharvest
			Plants m^{-2}				
Planting pattern							
Single-row			3 a	5 a	15 a	8 a	15 a
Twin-row			3 a	6 a	16 a	6 a	9 b
P-value			0.3	0.2	0.1	0.2	0.03
Herbicide programs							
PRE	EPOST	MPOST					
Fluridone	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	4 a	3 b	3 d	2 c	1 c
Fluridone	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	4 a	2 b	15 c	6 b	5 c
Fluridone	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	4 a	3 b	24 c	5 b	18 b
Flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	1 b	3 b	4 d	1 c	2 c
Flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	2 b	4 b	17 c	7 b	5 c
Flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	1 b	3 b	18 c	5 b	14 b
Fluridone + flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	2 b	4 b	4 d	2 c	3 c
Fluridone + flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	1 b	4 b	12 c	8 b	5 c
Fluridone + flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	1 b	3 b	16 c	9 b	13 b
Nontreated control			10 c	27 a	40 a	19 a	49 a
P-value			<.001	<.001	<.001	<.001	<.001

[a] Abbreviations: DAEPOST, days after postemergence; DAPRE, days after preemergence; EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

[b] Preharvest data on sicklepod control were combined for 2022 and 2023.

[c] Means ($n = 2, 10$) within a column followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

[d] PRE herbicides were applied the day after peanut was planted.

[e] EPOST herbicides were applied 25 d after peanut emergence.

[f] MPOST herbicides were applied 35 d after EPOST application.

Table 7. Effect of planting pattern and herbicide programs on sicklepod biomass reduction in peanut 28 d after preemergence and early postemergence, and prior to harvest in field experiments conducted near Jay, FL, in 2022 and 2023.[a–g]

			28 DAPRE				28 DAEPOST					
			2022		2023		2022		2023		Pre harvest	
			$g\ m^{-2}$									
Planting pattern												
Single-row			81	a	79	a	15	a	8	a	77	b
Twin-row			84	a	84	a	16	a	6	a	84	a
P-value			0.4		0.2		0.2		0.3		<.001	
Herbicide programs												
PRE	EPOST	MPOST										
Fluridone	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	74	b	72	b	93	a	92	a	95	a
Fluridone	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	70	b	70	b	64	c	68	b	79	b
Fluridone	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	71	b	75	b	44	d	64	b	77	bc
Flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	88	a	89	a	90	a	99	a	91	a
Flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	85	a	88	a	62	c	63	b	67	d
Flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	89	a	86	a	60	c	72	b	79	b
Fluridone + flumioxazin	Paraquat + bentazon + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	88	a	89	a	90	a	99	a	94	a
Fluridone + flumioxazin	Diclosulam + *S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	87	a	84	a	76	b	70	a	70	cd
Fluridone + flumioxazin	*S*-metolachlor	Imazapic + dimethenamid-*P* + 2,4-DB	89	a	87	a	59	c	61	b	75	bc
P-value			<.001		<.001		<.001		<.001		<.001	

[a] Abbreviations: DAEPOST, days after postemergence; DAPRE, days after preemergence; EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

[b] Biomass reduction was calculated by subtracting the dry weight of each treatment from the nontreated control and converting it to a percentage of the nontreated check.

[c] Preharvest data on sicklepod control were combined for 2022 and 2023.

[d] Means (n = 2, 9) within a column followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

[e] PRE herbicides were applied the day after peanut was planted.

[f] EPOST herbicides were applied 25 d after peanut emergence.

[g] MPOST herbicides were applied 35 d after EPOST application.

preemergence (Table 7). To achieve adequate residual weed control, fluridone requires at least 1.3 cm of rain for activation (Anonymous 2023). However, the total amount of rain during the first 2 wk after application in 2022 did not exceed 1.0 cm, compared with 7.0 cm of rain within the first 2 wk after application in 2023. Hence, the reduced effectiveness of fluridone in 2022 may be attributed to the reduced amount of rain needed for activation compared with 2023. Hill et al. (2016) also reported reduced effectiveness of fluridone on Palmer amaranth (*Amaranthus palmeri* L.) in cotton due to inadequate rainfall for activation.

At 28 d after early postemergence in both years and at preharvest, a preemergence fb early postemergence application of residual herbicides *S*-metolachlor or diclosulam + *S*-metolachlor provided less control of sicklepod compared with a preemergence fb early postemergence application of paraquat + bentazon + *S*-metolachlor. Sicklepod control was <70% in 2022 with fluridone, flumioxazin, or fluridone + flumioxazin applied preemergence fb an early postemergence application of *S*-metolachlor or diclosulam + *S*-metolachlor (Table 5). Furthermore, these treatments did not control sicklepod by any more than than 87% 28 d after early postemergence, and control was <79% at preharvest in 2023 due to continued emergence in these heavily infested fields (Table 5). Previous research has emphasized the lack of effective residual herbicides for sicklepod control due primarily to its extended emergence pattern (Grey et al. 2002, 2003; Willingham et al. 2008). Of all the herbicide programs evaluated in this study, only those that included an early postemergence application of paraquat + bentazon + *S*-metolachlor provided >90% sicklepod control 28 d after early postemergence (Table 5).

Sicklepod density and biomass reduction 28 d after early postemergence and preharvest generally reflected the observed sicklepod control. At 28 d after early postemergence and preharvest, sicklepod density in plots that received a preemergence application of fluridone, flumioxazin, or fluridone + flumioxazin each fb paraquat + bentazon + *S*-metolachlor early postemergence was ≤4 plants m^{-2} compared with 5 to 24 plants m^{-2} in plots not treated with paraquat + bentazon + *S*-metolachlor (Table 6). Similarly, treatments of paraquat + bentazon + *S*-metolachlor applied early postemergence provided greater sicklepod biomass reduction (90% to 99%) than other treatments 28 d after early postemergence and at preharvest (Table 7). These results indicate that the residual herbicides evaluated here would not be enough to provide adequate sicklepod control in peanut without a timely application of postemergence herbicides, such as paraquat, similar to findings reported by other researchers (Brecke and Stephenson 2006; Grey et al. 2005).

Peanut Yield

The interaction of year-by-planting pattern and year-by-herbicide program were not significant for peanut yield, so data were averaged for both years (Table 4). The effect of planting pattern and herbicide program were significant, whereas planting pattern-by-herbicide program interaction was not significant (Table 4). Peanut yield was 5% greater with twin-row compared with single-row plantings (Table 4). Several studies have reported yield advantage in twin-row compared with single-row planting under weed-free conditions (Balkcom et al. 2010; Lanier et al. 2004b; Nuti et al. 2008; Tillman et al. 2006). In studies conducted with different herbicide regimes, Brecke and Stephenson (2006) reported 9% yield increase with twin-row compared with single-row planting in 2 of 4 yr using strip tillage, while Kharel et al. (2022) and Lanier et al. (2004a) showed inconsistent yield response with twin-row compared with single-row planting using reduced herbicide input. The results from the current study and reports from the literature suggest that greater peanut yield can be achieved with twin-row than single-row planting when adequate weed management is provided.

All herbicide programs resulted in greater peanut yield compared with the nontreated control (Table 4). Peanut yield was reduced by at least 56% with season-long sicklepod interference. Peanut yield generally reflected the differences observed for sicklepod control, density, and biomass reduction when herbicide programs are compared. All programs (preemergence fb paraquat + bentazon + *S*-metolachlor applied early postemergence fb a mid-postemergence application of imazapic + dimethenamid-*P* + 2,4-DB resulted in peanut yield (4,540 to 4,690 kg ha^{-1}) that was greater than most other herbicide programs (average yield: 4,120 to 4,340 kg ha^{-1}), with the exception of fluridone + flumioxazin applied preemergence fb diclosulam + *S*-metolachlor or *S*-metolachlor applied alone early postemergence fb a mid-postemergence application (average yield: 4,460 to 4,470 kg ha^{-1}) (Table 4). Although peanut treated with paraquat + bentazon + *S*-metolachlor applied early postemergence showed early season canopy width and height reductions, and the yield increase with these treatments indicates that early season canopy width and height reductions are not always indictive of yield loss. Consistent with other research (Carley et al. 2009; Eason et al. 2020; Knauft et al. 1990; Wehtje et al. 1994), results from this study showed that peanut can recover from initial stunting from paraquat with a subsequent increase in yield due to effective weed control. Herbicide programs that contain diclosulam + *S*-metolachlor applied early postemergence increased peanut yield more than programs with early postemergence application of *S*-metolachlor alone (Table 4). This reflects the weed control efficacy and importance of mixing residual herbicides that have different effective sites of action in protecting peanut yield compared with using a single residual herbicide. These results are similar to those reported by Lanier et al. (2004a), when dimethenamid-*P* + diclosulam provided better sicklepod control and greater peanut yield than dimethenamid-*P* alone.

Practical Implications

It is possible to suppress sicklepod with residual herbicides applied preemergence at 28 d after planting, but not as a stand-alone weed management option for peanut. Because of the rapid growth and season-long emergence pattern of sicklepod, it is important to apply herbicides at the early postemergence stage. Regardless of the herbicide applied preemergence (flumioxazin, fluridone, or fluridone + flumioxazin), results of this study showed that an early postemergence application of paraquat + bentazon + *S*-metolachlor was required to provide effective (≥90%) sicklepod control, biomass reduction, and increased peanut yield. Combinations of residual herbicides flumioxazin, fluridone, or fluridone + flumioxazin followed by *S*-metolachlor or diclosulam + *S*-metolachlor provided initial suppression of sicklepod but did not provide adequate sicklepod control later in the growing season. Therefore, residual herbicides applied alone should not be relied on in fields that are heavily infested with sicklepod. Even with overlapping residual herbicide mixtures, it was not possible to maintain a high level of sicklepod control through 28 d after early postemergence without paraquat + bentazon + *S*-metolachlor applied early postemergence. Although a mid-postemergence application of imazapic + dimethenamid-*P* + 2,4-DB improved sicklepod control following preemergence and early postemergence applications of residual herbicides, biomass reduction at peanut harvest was unacceptable (<80%) due to the presence of larger sicklepod plants at the time of mid-postemergence treatment (caused by poor control with the early postemergence application), which resulted in yield reduction and difficulty with peanut digging. Because sicklepod seeds were spread in the experimental area, results with residual herbicides might not match what happens when weed seed is naturally spread throughout the soil for many years. However, the results of this study underscore the importance of a timely postemergence herbicide application for effective sicklepod control and increased harvest efficiency. Although peanut treated with paraquat + bentazon + *S*-metolachlor early postemergence showed early season canopy width and height reductions, this was transient, and no yield reduction was observed.

The importance of twin-row planting is also reaffirmed through this research. Twin-row planting provided greater late-season control of sicklepod with subsequently higher peanut yield than single-row planting due to rapid canopy closure and more efficient use of light and other growth resources that gave peanut a competitive advantage. In addition to other benefits, such as a lower incidence of thrips-transmitted Tomato spotted wilt virus (genus *Tospovirus* in the family Bunyaviridae) (Culbreath and Srinivasan 2011; Tillman et al. 2006), growers can improve sicklepod control and increase peanut yield with twin-row compared with single-row planting. Contrary to our hypothesis, however, the lack of significant planting pattern-by-herbicide program interaction in this study suggest that the use of twin-row planting will not reduce herbicide inputs to protect peanut yield. Therefore, twin-row planting should be considered as a supplement to a comprehensive herbicide program and not a stand-alone option.

Acknowledgment. We thank Dr. Barry Brecke and the field technical support team at West Florida Research and Education Center, Jay, Florida, for their technical support.

Funding. This research is supported by the U.S. Department of Agriculture–National Institute of Food and Agriculture Hatch Project FLAWFC-005843, and by the Florida Peanut Producers Association Checkoff fund G000430-2200-60820000-209-P0177604.

Competing Interests. They authors declare they have no competing interests.

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