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# Competing with the competitors in an endless competition: a systematic review of nonchemical weed management research in peanut (*Arachis hypogea*) in the United States

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**Review**

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## Abstract

Weed interference is a major factor that reduces peanut (*Arachis hypogaea* L.) yield in the United States. Peanut growers rely heavily on herbicides for weed control. Although effective, herbicides are not a complete solution to the complex challenge that weeds present. Therefore, the use of nonchemical weed management options is essential. The literature on weed research in peanut in the past 53 yr in the United States was reviewed to assess the achievements and identify current research gaps and prospects for nonchemical weed management for future research. More than half (79%) of the published studies were from the southeastern United States. Most studies (88%) focused on weed management, while fewer studies (12%) addressed weed distribution, ecology, and competitive mechanisms. Broadleaf weeds were the most frequently studied weed species (60%), whereas only 23% and 19% of the published studies were relevant to grasses and *Cyperus* spp., respectively. Seventy-two percent of the published studies focused on curative measures using herbicides. Nonchemical methods using mechanical (5%) and preventive (13%) measures that influence crop competition and reduce the buildup of the weed seedbank, seedling recruitment, and weed seed production have received less attention. In most studies, the preventive weed management measures provided weed suppression and reduced weed competition but were not effective enough to reduce the need for herbicides to protect peanut yield. Therefore, future research should focus on developing integrated weed management strategies based on multiple preventive measures rather than one preventive measure combined with one or more curative measures. We recommend that research on mechanical weed management should focus on the role of cultivation when integrated with currently available herbicides. For successful weed management with lasting outcomes, the dominant weed communities of specific target locations should be addressed within the context of climate change and emerging constraints rather than focusing on single problematic species.

## Introduction

The United States is the fourth-largest producer of peanut (*Arachis hypogaea* L.) in the world (2,526,000 kg) after China (18,300,000 kg), India (6,300,000 kg), and Nigeria (4,284,000 kg) (USDA-FAS 2023). Peanut is a valuable commodity in the United States, with a total market value of more than US$1 billion (USDA-NASS 2021). From the 1970s to 2021, peanut yield in the United States increased from 2,760 to 4,640 kg ha$^{-1}$ (USDA-NASS 2021), due to advances in agronomic practices, the development of improved cultivars with greater yield potential and disease resistance, and improved weed control with more effective herbicides (Dotray et al. 2012; Holbrook 2019). However, weeds continue to be a major problem in all the peanut-producing regions in the United States despite continuous research efforts made in weed science (Chaudhari et al. 2018; Tubbs 2019).

Weeds are generally considered the most important biotic constraint to crop production (Chauhan 2020). Peanut is a poor early-season competitor due to a relatively short canopy, and it requires a long growing season (140 to 160 d), which results in ample opportunity for weeds to occupy space, compete for growth resources, and reduce productivity (Chaudhari et al. 2018;

Wilcut et al. 1995). Season-long weed interference from combinations of broadleaf and grass weeds was reported to reduce harvest efficiency and peanut yield by 60% to 80% (Everman et al. 2008b; Webster et al. 2007). Depending on the region, weed control with herbicides can cost as much as US$123.50 to US$160.50 ha$^{-1}$ a season, and labor costs average US$24.00 ha$^{-1}$ (Smith and Rabinowitz 2017). Despite the significant financial investment in weed control, weeds still cause considerable economic losses (Webster 2001), which suggests the need for more targeted research to address weed competition and abate yield and economic losses in peanut.

Due to the high cost of hand and mechanical weed control and their damaging effect on the peanut plant, growers currently rely heavily on intensive herbicide programs for profitable peanut production (Boyer et al. 2011). Preemergence control in peanut is achieved mainly with very long-chain fatty acid inhibitors from the chloroacetamide chemical family (e.g., acetochlor, alachlor, dimethenamid-*P*, and *S*-metolachlor) and mitosis inhibitors from the dinitroaniline chemical family (e.g., pendimethalin and trifluralin) (Leon et al. 2019). More recently, the use of the protoporphyrinogen oxidase (PPO) inhibitor flumioxazin for preemergence control and acetolactate synthase (ALS) inhibitors (diclosulam and imazapic) for residual weed control in peanut has increased considerably (Chaudhari et al. 2018). Postemergence broadleaf weed control in peanut is achieved with bentazon and paraquat (photosynthetic inhibitors), acifluorfen and lactofen (PPO inhibitors), 2,4-DB (synthetic auxin), and chlorimuron, diclosulam, imazapic, and imazethapyr (ALS inhibitors), while graminicides such as clethodim and sethoxydim are the major postemergence grass weed herbicides in peanut (Burke et al. 2004; Leon et al. 2019). Although several herbicides are available for weed control in peanut, no single application provides all the required levels of weed control in all situations due to various limitations such as narrow window of application, lack of extended residual activity, and rotational restrictions. Therefore, effective weed management in peanut often requires herbicide mixtures and/or sequential application of preplant-incorporated, preemergence, and/or postemergence herbicides at the right timing and application rates (Chaudhari et al. 2018). However, with the increased incidence of weed resistance to herbicides, including herbicides commonly used in peanut and rotating crops such as corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.], and considering that only one new herbicide mode of action (fluridone) has been introduced in peanut for more than three decades (Anonymous 2019), there is a great cause for concern about the future of weed management in peanut. Most of the postemergence herbicides used in peanut, especially those with both residual and systemic activity, are ALS inhibitors (Berger et al. 2015). These herbicides are more susceptible to resistance selection due to their extended residual activity and active-site mutation (Saari et al. 2018). There are currently 159 weed species resistant to ALS-inhibiting herbicides, some of which seriously threaten peanut production (Berger et al. 2015; Heap 2023). For example, Palmer amaranth (*Amaranthus palmeri* S. Watson) resistance to ALS-inhibiting herbicides was reported in 21 peanut-growing counties in Georgia (Wise et al. 2009), and 97% of the agronomic counties in Florida and North Carolina (Poirier et al. 2014; Sperry et al. 2017). Resistance to ALS-inhibiting herbicides in common ragweed (*Ambrosia artemisiifolia* L.) has also been confirmed in peanut fields across the southeastern United States (Berger et al. 2015; Chandi et al. 2012). While there are more options for alternative weed control with herbicides from other mechanisms of action in corn, cotton, and soybean, only a few alternatives, particularly the PPO-inhibiting herbicides are available in peanut. Resistance to PPO-inhibiting herbicides, however, has recently been reported in soybean (Heap 2023), suggesting that the use of PPO herbicides to manage ALS-resistant weeds in peanut might not be sustainable. Although paraquat remains an important alternative weed control in peanut, it lacks residual activity and is limited to use only within the first 28 d after peanut emergence. It is apparent, therefore, that growers cannot continue to rely on chemical weed control alone.

A previous review on weed competition and management in peanut suggested that an ecologically sustainable and cost-effective weed management approach is required to reduce the high yield and economic losses caused by weed competition and the heavy reliance on herbicides (Wilcut et al. 1995). Similarly, in a more recent review, Leon et al. (2019) highlighted the importance of prevention, avoidance, monitoring, and suppression of weed as parts of an ecologically sustainable weed management program that can help to decrease the weight that herbicides have on overall weed control and reduce the risk of herbicide-resistance evolution. While this indicates the research gap in weed management for peanut-cropping systems, the specific priority areas for research focus in terms of weed species, agronomic practices, and management strategies that could potentially reduce yield loss and increase the profitability of peanut based on current and future challenges have not been emphasized. To identify important areas of research that could reduce the heavy reliance on herbicides and improve future weed management, it is essential to appraise what is known and what opportunities exist to address the current gaps through applied research and the extension of new technologies. Although Wilcut et al. (1995) and Leon et al. (2019) reviewed the effects of weed interference and management in peanut in the United States, a systematic review of existing literature on this subject is still lacking. Therefore, the current paper presents a systematic review of weed management research in peanut in the United States in the last five decades with specific emphasis on nonchemical weed management methods. The objective of this review is to access the progress and achievements in peanut nonchemical weed management research and identify current research gaps and prospects for future research.

This review covers some of the materials discussed in the earlier work by Wilcut et al. (1995) but emphasizes findings since that publication. Also, rather than providing an overview or comprehensive listing of results from weed management research in peanut, we analyzed peanut–weed literature in the United States following two main research priority areas grouped as (1) weed ecology and distribution and (2) weed management. Following Rao et al. (2014), under weed ecology and distribution, we evaluated peanut research focusing on weed distribution, weed interference and competitive mechanism, and the critical period of weed control (CPWC). We categorized weed management research into preventive and curative weed management measures as described by Bastiaans et al. (2008) and Zimdahl (2007). Crop-oriented research focusing on crop competition (e.g., the use of competitive cultivars, optimum seeding rate, row spacing/planting density, planting date, and planting pattern) and other agronomic practices that reduce weed seedbank, weed seedling recruitment, and weed interference (e.g., crop rotation and the use of cover crops) were categorized as preventive weed management. On the other hand, curative weed management includes research focused on practices that lead to the removal or killing of weeds (e.g., cultivation and mechanical weed management).

**Table 1.** Search terms and exclusion criteria used to identify relevant articles in the databases of Scopus, Web of Science, and *Peanut Science* (accessed: July 12, 2022).

| Search terms | Number of sources | | | |
|---|---|---|---|---|
| Language: English only, within the article title, abstract, and key words | Scopus | Web of Science | *Peanut Science* | Total |
| TS = ("weed" OR "weed management" OR "weed control" OR "herbicides" OR "cultural method" OR "mechanical method" OR "biological method" OR "integrated" AND "peanut" OR "*Arachis hypogea*") | 993 | 933 | 245 | 2,171 |
| Exclusion criteria<br>Refined to the United States only; exclude other countries<br>Refined to 1970 to 2022 duration<br>Refined to only research articles; exclude other literature types such as books, book chapters, review articles, and conference proceedings.<br>Refined to only agronomy and agricultural and biological sciences; exclude other subject areas | 202 | 232 | 121 | 555 |

## Systematic Literature Search

The literature search was done using a four-step filtering process.

### Step 1

The databases of Scopus, Web of Science, and *Peanut Science* (journal of the American Peanut Research and Education Society) covering 53 yr (from 1970 to July 2022; accessed July 12, 2022) were searched using predefined search terms (Table 1). *Peanut Science* was included because it is currently not indexed in Scopus or Web of Science but publishes peer-reviewed results of peanut research in the United States.

### Step 2

The total record (2,178 peer-reviewed articles) from the three databases was screened to identify the articles' relevance for the review by refining the search terms based on exclusion criteria (Table 1). This resulted in a refined cohort of 555 peer-reviewed publications.

### Step 3

The refined cohort of 555 peer-reviewed publications from the three databases was exported and combined in Excel, with the year of publication as rows and contents (journal, research focus, weeds studied, study type [field, greenhouse, or laboratory], study location, number of site-years, research methods, and abstract) as columns.

### Step 4

Duplicates (78 peer-reviewed publications) were removed, and the remaining publications (477) were further screened by two independent researchers for their relevance by reviewing the titles and abstracts. This resulted in 273 unique and relevant publications that were subsequently reviewed. Of the 273 publications reviewed, 81 (30%) were relevant to nonchemical weed management, while 192 (72%) were focused on chemical weed management. Because a review of chemical and nonchemical weed management research in peanut for the last five decades (53 yr: 1970 to 2022) in the United States is too broad to be covered extensively in one paper, only the 81 publications that focused on nonchemical weed management are discussed in the "Research Priority Areas" section in the current paper. The remaining 192 publications focused on chemical weed management are covered in the second part of this publication series.

## Weed Research in Peanut-Cropping Systems in the United States

### Geography and Peanut-Growing Regions

More than half of the weed research in peanut (56%) is conducted in the U.S. Southeast (Alabama: 14%; Florida: 13%; and Georgia: 29%) while 23.7% and 19% is conducted in the Virginia–Carolinas (North Carolina, South Carolina, and Virginia) and Southwest (Oklahoma: 3.3%, Texas: 16%) regions, respectively (Figure 1). This level of research corresponds with the importance of peanut in these regions, as about 65%, 17%, and 13% of the total peanut production in the United States is from the Southeast (Alabama, Florida, Georgia, and Mississippi), Southwest, and Virginia–Carolinas regions, respectively (USDA-NASS 2021). Around 85% (231 of 273) of the studies were conducted as individual state trials, with 41% in single sites and 59% in multiple sites. Only 14% of the studies were conducted at multistate levels or in a regionally coordinated manner.

### Study Focus and Methods

Weed research in peanut in the United States focused primarily on weed management (88%). Among the remaining 12% (32 of 273) not focused on weed management, the majority (11%) assessed the effect of weed interference and the CPWC in peanut, while others (1%) presented insights on weed distribution. Seventy-two percent of the studies focused on curative weed management approaches based on chemical weed control with emphasis on optimized herbicide programs. Curative weed management with mechanical options (5%) and preventive management approaches (13%) that influence crop competition, including planting timing, planting pattern, row spacing, and the use of competitive cultivars, have received less attention. Despite the increased advocacy for integrated approaches that combine preventive and curative measures as the best way of keeping weed pressure below thresholds that reduce yields and profits (Swanton et al. 2008), studies on integrated weed management in peanut (8%), although increasing since 2010, remain relatively low (Figure 2).

Most of the weed research in peanut in the United States (83% of the studies) was conducted as on-station field experiments. Other methodologies, such as on-farm researcher-led experiments (3%), combinations of on-station and on-farm studies (6%), field and greenhouse studies (4%), field and laboratory studies (0.4%), field, greenhouse, and laboratory studies (2%), and observational studies such as weed surveys (0.7%), have been used less frequently.

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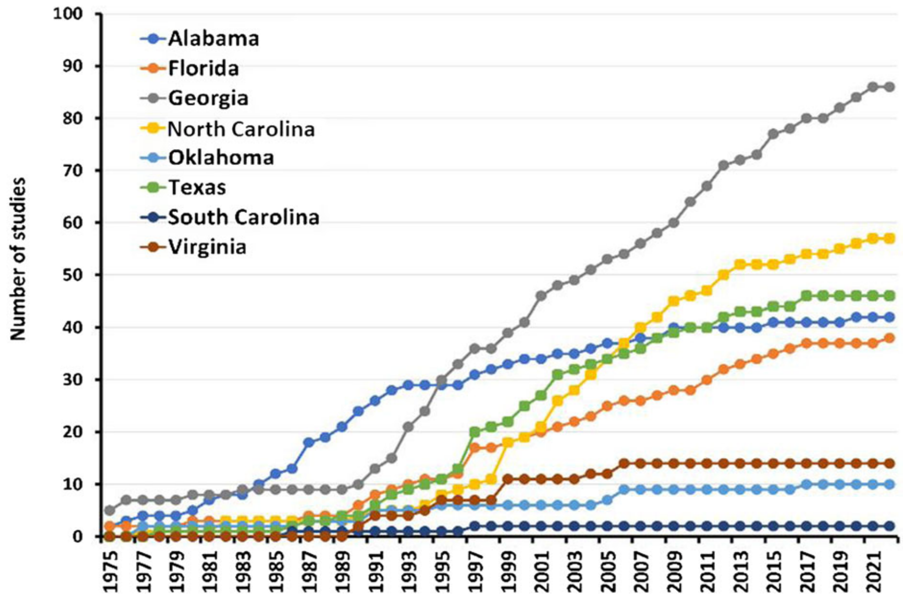


**Figure 1.** The number of weed studies (1971–2022) from the major peanut-producing states in the United States.

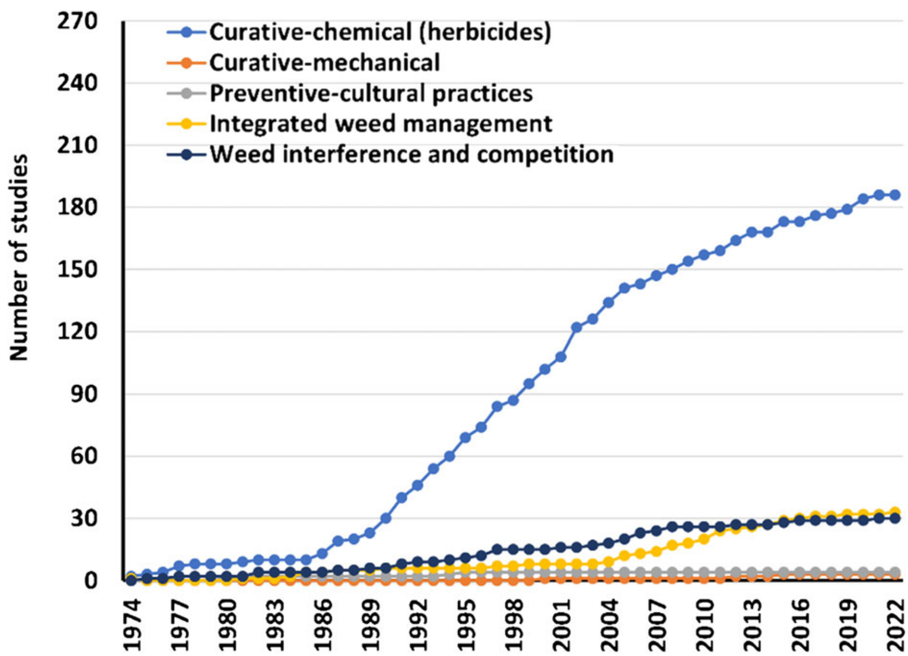


**Figure 2.** The number of weed studies (1971–2022) focusing on different weed control methods in peanut in the United States.

## *Weed Types and Species*

Most of the weed research studies (60%) in peanut-cropping systems in the United States are focused on broadleaf weeds, while only 23% and 19% are relevant to grasses and *Cyperus* spp., respectively (Figure 3A). Broadleaf weeds such as morningglory species (*Ipomoea* spp.) (25%), sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby] (23%), Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.] (21%), pigweed species (*Amaranthus* spp.) (12%), and common lambsquarters (*Chenopodium album* L.) (9%) are the most prominent in the literature (Figure 3B). The greater research attention on these weed species could be explained by their prevalence in peanut fields, as they are ranked among the most common and problematic weeds in peanut in the United States (Cardina and Brecke 1991; Webster and MacDonald 2001; Wilcut et al. 1995).

*Amaranthus* spp. did not receive much attention before the year 2000, unlike other broadleaf weeds such as *D. tortuosum* and *S. obtusifolia*, which have been more frequently studied for many years in peanut. However, the number of studies focused on *Amaranthus* spp. species, particularly *A. palmeri*, increased steeply thereafter (Figure 3B). This can be attributed to the increased awareness of the need for diversified management options for

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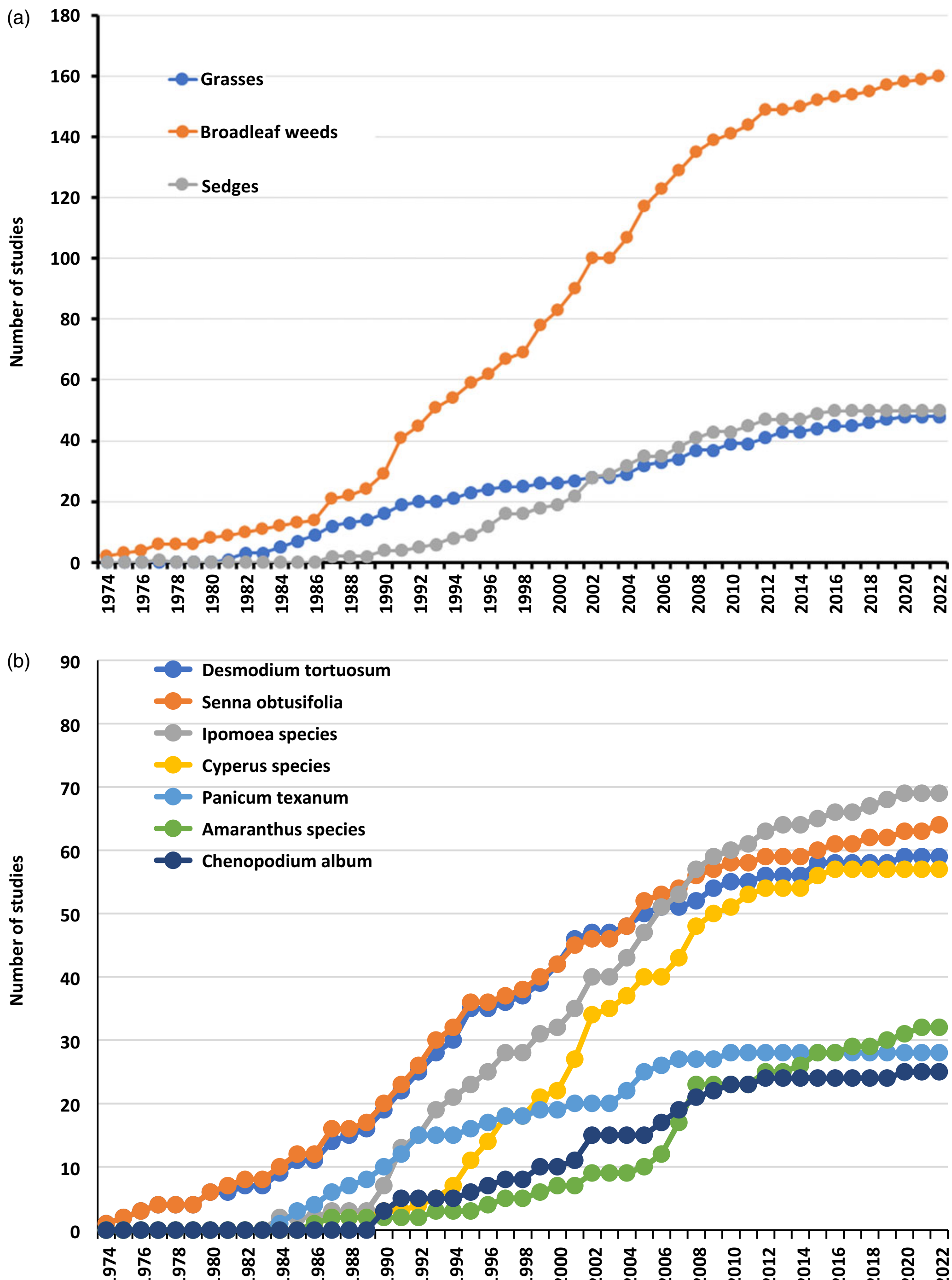


**Figure 3.** The number of weed studies (1971–2022) focusing on a particular weed type or weed species.

*A. palmeri*, which was driven by the evolution of resistance to herbicides commonly used in peanut and rotating crops (Sperry et al. 2017). As discussed earlier, *A. palmeri* biotypes are resistant to ALS-inhibiting herbicides and also dinitroanilines, glyphosate, triazine, and photosystem II- and hydroxyphenylpyruvate dioxygenase-inhibiting herbicides in some parts of the United States (Bond et al. 2006; Culpepper et al. 2006; Heap 2023; Norsworthy et al. 2008; Ward et al. 2013; Wise et al. 2009).

It is noteworthy that other broadleaf weed species such as *A. artemisiifolia*, bristly starbur (*Acanthospermum hispidum* DC.), coffee senna [*Senna occidentalis* (L.) Link], common cocklebur (*Xanthium strumarium* L.), eclipta [*Eclipta prostrata* (L.) L.], horse purslane (*Trianthema portulacastrum* L.), prickly sida (*Sida spinosa* L.), spurred anoda [*Anoda cristata* (L.) Schltdl.], tropic croton (*Croton glandulosus* L.), and wild poinsettia (*Euphorbia heterophylla* L.) were reported in <10% of the weed studies (data not shown). These weed species can be problematic in peanut under certain conditions (Clewis et al. 2001; Grichar 2007; Place et al. 2012; Royal et al. 1997; Walker et al. 1989; Webster and MacDonald 2001), but are not a widespread problem (Webster 2013), which may justify the low research attention they have received.

Only 1.8% (5 out of 273) of the weed studies were focused on tropical spiderwort (*Commelina benghalensis* L.) (data not shown). This level of research is not proportionate to the level of importance of *C. benghalensis* in peanut, as it is identified as one of the most troublesome and difficult weeds to control in peanut in the U.S. Southeast, the major peanut-producing region (Morichetti et al. 2012; Webster et al. 2005). *Commelina benghalensis* is tolerant to many commonly used herbicides, especially glyphosate (Culpepper et al. 2004; Spader and Vidal 2000), which suggests the need for more research studies on diversified options for *C. benghalensis* management in peanut.

The most-studied grass weed species in peanut in the United States are Texas panicum [*Urochloa texana* (Buckley) R. Webster] (10%), large crabgrass [*Digitaria sanguinalis* (L.) Scop.] (6%), goosegrass [*Eleusine indica* (L.) Gaertn.] (3%), broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster] (3%), bermudagrass [*Cynodon dactylon* (L.) Pers.] (2%), and fall panicum [*Dicanthelium dichotomum* (L.) Gould var. *dichotomum*] (1%), while weed research on sedges has mainly focused on yellow nutsedge (*Cyperus esculentus* L.) (19%). Although annual grasses are very competitive, they are not considered a major problem in peanut high-input systems because of the availability of residual herbicides, such as flumioxazin, pendimethalin, and *S*-metolachlor, and postemergence herbicides, such as clethodim, fluazifop-*P*-butyl, and sethoxydim, that can provide effective control of these weed species (Burke et al. 2004; Johnson and Mullinix 2005). This may justify the lower research attention for grasses compared with broadleaf weeds in peanut. However, these weeds are a major problem in organic peanut production (Johnson and Mullinix 2008) and should be considered research priority species. On the other hand, the dominance of weed studies focused on *C. esculentus* compared with individual grass weed species is justified by its allelopathic effect and perennial growth habit, which make it difficult to control (Johnson and Mullinix 2003). In addition, the tubers of *C. esculentus* can be a contamination in the harvested crop. *Cyperus esculentus* can exert great competition and yield reduction through allelopathy, and there are limited herbicide options for its management (Webster and MacDonald 2001; Webster et al. 2005).

## Research Priority Areas

### Weed Ecology and *Distribution*

Only 12% of the published weed research studies on peanut in the United States have focused on weed ecology. The weed ecological research in peanut was conducted mainly on weed distribution, weed interference and competition, and the CPWC.

#### *Weed Distribution*

Despite the acknowledged importance of weed distribution research as a valuable tool to identify the problem weeds of an area, understand weed community diversity, and provide direction for future research efforts (Webster and Coble 1997; Webster 2001), only 1% (3 out of 273) of the weed research studies in peanut in the United States have focused on weed distribution. However, from 1971 to 2013, the Southern Weed Science Society (SWSS), USA, presented an annual weed survey report of the 10 most common and troublesome weeds in major agronomic crops, including peanut. These reports, compiled annually in the proceedings of the SWSS, provide insights into weed distribution and the relative importance of various weed species associated with peanut for each of the participating southern states (Alabama, Arkansas, Florida, Georgia, Mississippi, North Carolina, Oklahoma, South Carolina, and Virginia). Summaries of these regionally coordinated surveys published by Elmore (1984) and Webster and Coble (1997) and a state-specific weed survey from Georgia by Webster and Macdonald (2001) indicated important changes in weed species composition over time in response to production practices. For example, weed surveys conducted in the early 1970s indicated that *X. strumarium* was the most troublesome weed in peanut; however, by the early 1980s and 1990s, it was ranked the seventh most important species (Elmore 1984; Webster and Coble 1997). Similarly, *Cyperus* species were previously identified as the most troublesome weed species in peanut in the southern United States in the early 1980s and 1990s, but their relative importance in peanut decreased thereafter (Elmore 1984; Webster and Coble 1997; Webster and Macdonald 2001). These shifts in weed species composition and the relative importance of weeds associated with peanut were attributed to the introduction of new herbicide chemistries that provided selective control of some troublesome weed species. For instance, *Cyperus* species are shade intolerant and become more established after most grasses and small-seeded broadleaf weeds have been controlled with dinitroaniline herbicides, which do not have activity on *Cyperus* species (Webster and Nichols 2012). The reduction in the relative importance of *Cyperus* species over time may be due to the introduction of newer chemistries like imazethapyr, imazapic, and diclosulam, which have good activity on both *C. esculentus* and purple nutsedge (*Cyperus rotundus* L.) or the increased application of herbicides such as bentazon and metolachlor that can suppress *C. esculentus* growth (Grichar 2002; Webster and Coble 1997).

Some differences were reported in the common and troublesome weed species between the peanut-producing regions in the United States (Elmore 1984; Webster and Coble 1997), even within the same state (Webster and Macdonald 2001), with some species prevalent in one climatological district but absent in another. For example, *C. benghalensis* was ranked as the eighth most troublesome weed in peanut in Georgia but was found only in the southwestern and south-central districts and was listed among the top five species in only eight counties (Webster and Macdonald 2001). This suggests that weed community composition can vary between farms, states, and regions, thus requiring more tailored weed management strategies. However, several weed species such as *D. tortuosum*, *E. indica*, *Ipomoea* spp., *A. palmeri*, *S. obtusifolia*, and *U. texana* are consistently associated with peanut across different environments and have frequently been identified as being among the most troublesome weeds in peanut for many years (Elmore 1984; Webster and Coble 1997; Webster and Macdonald 2001). Their prevalence in peanut-cropping systems is attributed to traits such as hard seed coats, which ensure a persistent seedbank and limits the effectiveness of residual herbicides (e.g., *S. obtusifolia*); large seed size, which enhances germination from deeper soil depth (e.g., *D. tortuosum*, *Ipomoea* spp., and *S. obtusifolia*); prolific seed production, which increases weed population; and rapid growth, which enhances competition (e.g., *A. palmeri* and *S. obtusifolia*) (Lancaster et al. 2005; Webster 2001; Webster and MacDonald 2001; Webster et al. 2005; Wilcut et al. 1995). Also, the evolution of resistance to herbicides commonly used in peanut and in rotating crops has favored the widespread distribution of *A. palmeri* (Poirier et al. 2014). For instance, herbicide-resistant *A. palmeri* was reported as the most troublesome weed in peanut in Georgia and Florida (Berger et al. 2015;

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Webster 2013) and was found to occur throughout the peanut-growing regions in the U.S. Southeast (Wise et al. 2009).

### Weed Interference and Competitive Mechanisms

Peanut–weed interference and weed competitive mechanism studies are important to understand weed dynamics and make appropriate weed management decisions (Jordan et al. 2003; Robinson et al. 2007). Competitive index parameters generated from such studies, along with other factors such as soil moisture status and cost of weed control, have been integrated into computer models and decision aids such as the Herbicide Application Decision Support System (HADSS™) (a trade name registered by North Carolina State University, USA) and computerized economic threshold decision (HERB™) (a trade name registered by North Carolina State University, USA) to accurately predict the level of yield loss at a given weed density and size in order to estimate economic thresholds and devise appropriate weed management strategies (Bennett et al. 2003; Scott et al. 2002; White and Coble 1997). These computer decision models have been used to determine the appropriate herbicide and application rate recommendations, thereby improving the profitability of peanut production while minimizing herbicide inputs and reducing environmental impact (Bennett et al. 2003; Jordan et al. 2003; Scott et al. 2002).

Our systematic review of the literature indicates that 11% of the weed research studies on peanut in the United States focused on assessing the effect of weed interference and the CPWC. These studies showed that weed competition can reduce peanut yield by up to 80% depending on weed species, weed population densities, and the duration of weed interference (Burke et al. 2004; Chamblee et al. 1982; Everman et al. 2008b; York and Coble 1977). Peanut yield decreased with increasing weed density and periods of weed interference, which indicates that weed control is essential throughout much of the growing season (Everman et al. 2008b). Predicted peanut yield loss from season-long weed interference and density-dependent competitive indices (*i* value) that indicate potential weed competitiveness using hyperbolic yield loss model (Cousins et al. 1987) showed that grasses have greater competitiveness and are more detrimental to peanut yield compared with broadleaf weeds and *Cyperus* spp. (Table 2). Season-long interference of grass weed species was reported to reduce peanut yield by 7% to greater than 60% (Everman et al. 2008b; York and Coble 1977). As few as 1.4 *U. platyphylla* plants $m^{-2}$ (Chamblee et al. 1982), 0.1 *D. dichotomum* plants $m^{-2}$ (York and Coble 1977), and 2.2 *U. texana* plants $m^{-2}$ (Johnson and Mullinix 2005) reduced peanut yield by 25%. In contrast, greater densities of *C. esculentus* (68 plants $m^{-2}$) and broadleaf weeds (*D. tortuosum*: 6.2 plants $m^{-2}$; horsenettle [*Solanum carolinense* L.]: 4.2 plants $m^{-2}$; and *S. obtusifolia*: 7.2 plants $m^{-2}$) were required to cause similar yield reduction in peanut (Hackett et al. 1987; Johnson and Mullinix 2003). However, *X. strumarium* (Royal et al. 1997), *A. artemisiifolia* (Clewis et al. 2001), jimsonweed (*Datura stramonium* L.) (Price et al. 2006), *C. glandulosus* (Thomas et al. 2004), *E. heterophylla* (Bridges et al. 1992), *A. palmeri* (Burke et al. 2007), and *A. hispidum* (Walker et al. 1989) are more competitive broadleaf weeds, reducing peanut yield by 25% at much lower densities. *Commelina benghalensis* was also found to be a highly competitive broadleaf weed in peanut, with season-long interference reducing yield by 51% to 100% (Webster et al. 2007).

Although these weed interference studies were conducted using different peanut cultivars under different growth conditions and cultural practices, the values for yield reduction are similar among grass weed species, which is not the case for broadleaf weeds (Table 2). Apart from competition for growth resources, grass weed species generally reduce peanut yield through the production of a fibrous root system that entangles peanut pods during digging, resulting in excessive harvest losses (Johnson and Mullinix 2005). For example, Johnson and Mullinix (2005) observed 836 kg $ha^{-1}$ harvest losses at 2 *U. texana* plants $m^{-1}$ of peanut row. Greater competition of the grass weed species may also be attributed to their $C_4$ metabolism, which confers a higher efficiency in water use, nutrient uptake, and net photosynthesis compared with peanut, which has a $C_3$ pathway of photosynthetic $CO_2$ fixation (Procopio et al. 2004; York and Coble 1977). However, greater variability in peanut yield reduction due to interference among broadleaf weeds (Table 2) may be due to differences in their growth rate, canopy architecture, and shading effects on peanut as influenced by the prevailing growing conditions and cultural practices. Broadleaf weeds that grow very tall and above peanut canopies are generally more competitive and detrimental to peanut yield, because they intercept sunlight at the expense of the crop, leading to reduced phtosynthesis, consequently reducing yield (Barbour et al. 1994; Walker et al. 1989; Webster et al. 2007). For example, *A. hispidum*, with its very dense foliar canopy and greater shading effect on peanut, is at least three times more competitive than *D. tortuosum* and five times more competitive than *S. obtusifolia* (Walker et al. 1989). *Desmodium tortuosum* and *S. obstutifolia* at 1 plant 10 $m^{-2}$ reduced peanut yield by 16 to 30 kg $ha^{-1}$ and 6 to 22 kg $ha^{-1}$, respectively (Hauser et al. 1982), whereas 1 *A. hispidum* plant 7.5 $m^{-1}$ of crop row reduced peanut yield by 75 kg $ha^{-1}$ (Walker et al. 1989). Broadleaf weeds that form a canopy over peanut can also interfere with fungicide deposition and increase canopy humidity, thereby increasing the activity of plant pathogens and the incidence of foliar and soil-borne diseases, causing greater yield reduction (Royal et al. 1997; Webster et al. 2007). In 1 of 2 yr of studies, peanut yield was eliminated (100% yield loss) due to interference by *C. benghalensis* (Webster et al. 2007). The total yield loss was attributed to the inability of applied maintenance fungicide to contact peanut foliage due to interception by *C. benghalensis*, which formed a complete canopy above the peanut. Webster et al. (2007) concluded that the competitive effect of *C. benghalensis* is likely complicated by the activities of plant pathogens. Previous studies have also shown that *C. benghalensis* is an alternate host for several soil-borne pathogens and insects, including aphids (*Aphis* spp.) that transmit peanut rosette virus disease, and nematodes, such as *Meloidogyne*, *Pratylenchus*, and *Paratrichodorus* species that infect peanut (Agostinho et al. 2006; Davis et al. 2006; Desaeger and Rao 2000).

### CPWC in Peanut

The CPWC is the time interval in the crop growth cycle during which the crop must be kept weed-free to prevent unacceptable yield losses (usually losses greater than 2% to 5%, depending on the expected financial gain and cost of weed control) (Knezevic and Datta 2015). Knowledge of the CPWC is essential for identifying the growth stage at which the crop is most vulnerable to weed competition, making appropriate decisions on the timing of weed control, and achieving the efficient use of management practices (Knezevic and Datta 2015). Most of the CPWC studies on peanut in the United States have not focused on a mixed population of weed species, but rather on individual weed species. Although peanut exhibits a clear period of vulnerability to weed competition due to its unique growth habit and

**Table 2.** Competitiveness of weeds found in peanut in the United States based on Cousin et al.'s (1987) hyperbolic yield loss model [$Y = iD/(1 + iD/100)$], where $D$ is the weed density per meter of peanut row, and $i$ is the % yield loss as weed density approaches zero.[a]

| Weed type | Estimated *i* | Predicted yield loss from season-long interference at 1 plant $m^{-1}$ of crop row | Critical period of weed control (CPWC) | References |
|---|---|---|---|---|
| Broadleaf weeds | | | | |
| *Acanthospermum hispidum* DC. | 14.7 | 16% | Between 2 and 6 wk after crop emergence | Walker et al. (1989) |
| *Ambrosia artemisiifolia* L. | 68.3 | 40% | NA | Clewis et al. (2001) |
| *Amaranthus palmeri* S. Watson | 39.0 | 28% | NA | Burke et al. (2007) |
| *Croton glandulosus* L. | 26–61 | 17% | NA | Thomas et al. (2004) |
| Crownbeard [*Verbesina encelioides* (Cav.) Benth. & Hook. f. ex A. Gray] | NA | 16% | Weed removal by or before 4 wk after crop emergence | Farris et al. (2005) |
| *Commelina benghalensis* L. | NA | NA | Between 3 to 7 wk after crop emergence | Webster et al. (2007) |
| *Desmodium tortuosum* (Sw.) DC. | NA | 25% at 2.5 plants $m^{-1}$ | Weed-free maintenance for 4 to 6 wk after emergence | Cardina and Brecke (1991); Hauser et al. (1975) |
| *Datura stramonium* L. | 10.7 | 40% | NA | Price et al. (2006) |
| *Euphorbia heterophylla* L. | NA | 17% | Weed-free maintenance for 8 to 10 wk after crop emergence | Bridges et al. (1992) |
| *Senna obtusifolia* (L.) Irwin & Barneby | NA | 25% at 2.5 plants $m^{-1}$ | Weed-free maintenance for 4 to 6 wk after emergence | Hauser et al. (1975) |
| *Solanum carolinense* L. | 20.6 | 14% | Between 2 to 6 or 8 wk after crop emergence | Hackett et al. (1987) |
| *Xanthium strumarium* L. | 149.5 | 70% | Between 2 and 12 wk after crop emergence | Royal et al. (1997) |
| Grasses | | | | |
| *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster | 3.2 | 25% | Between 2 and 6 wk after crop emergence | Chamblee et al. (1982) |
| *Eleusine indica* (L.) Gaertn. | NA | 19% | NA | McCarty and Coble (1983) |
| *Dichanthelium dichotomum* (L.) Gould var. *dichotomum* | 22.7 | 25% at 0.2 plant $m^{-1}$ | Between 2 and 8 wk after crop emergence | York and Coble (1977) |
| *Urochloa texana* (Buckley) R. Webster | NA | 12.5% | Not later than 9 to 10 wk after crop emergence | Johnson and Mullinix (2005) |
| Sedges | | | | |
| *Cyperus esculentus* L. | NA | 25% at 68 plants $m^{-1}$ | NA | Johnson and Mullinix (2003) |

[a]NA, not available in the literature.

canopy architecture, studies indicate that the duration of the CPWC in peanut varies by weed species (Table 2).

Depending on the weed community, peanut requires a weed-free period beginning from 2 to 3 wk until 6 to 12 wk after crop emergence to avoid unacceptable yield loss (Everman et al. 2008b; Wilcut et al. 1994). When the weed community was composed of a mixed population of annual grasses and broadleaf weeds, the CPWC lasted approximately 5 wk, from 3.1 to 7.5 wk after crop emergence (Everman et al. 2008b). Similarly, when the weed community was predominantly a mixed population of broadleaf weeds, the CPWC lasted approximately 5 wk (from 2.6 to 8 wk after crop emergence) but began earlier and ended later than the CPWC in peanut infested with a mixed population of annual grasses and broadleaf weeds (Everman et al. 2008a). The earlier start of the CPWC for broadleaf weeds illustrates the need for timely broadleaf weed control early in the crop life cycle to avoid yield loss. If not controlled, broadleaf weed species such as *A. artemisiifolia*, *A. hispidum*, *X. strumarium* (Royal et al. 1997), *A. palmeri*, *D. tortusum*, and *S. obtusifolia* that emerge at or before peanut emergence can outgrow the crop and effectively compete for nutrients, water, and light, thus causing yield losses (Burke et al. 2007; Walker et al. 1989). For example, broadleaf weeds such as *A. hispidum* and *X. strumarium* reduced yield by 4% and 8%, respectively, when allowed to compete with peanut for 2 wk after planting (Royal et al. 1997; Walker et al. 1989). *Amaranthus palmeri* that emerged with peanut produced an approximately 10-fold greater number of seeds compared with *A. palmeri* that emerged 3 wk later, with heavier seed production leading to greater weed problems and yield reduction in subsequent cropping seasons (Mahoney et al. 2021).

In a study investigating the CPWC for individual broadleaf weeds including *D. tortuosum* and *S. obtusifolia*, Hauser et al. (1982) observed the greatest yield when peanut was kept weed-free for 4 wk after crop emergence. For *A. hispidum* (Walker et al. 1989) and *S. carolinense* (Hackett et al. 1987), the CPWC was between 2 and 6 wk after peanut emergence. However, when peanut was grown in competition with *X. strumarium*, a highly competitive broadleaf weed, Royal et al. (1997) found that the CPWC extended from 2 to 12 wk after crop emergence, which was 4 wk longer than the CPWC observed for a mixed population of less competitive broadleaf weeds reported in a later study by Everman et al. (2008a). This indicates that broadleaf weeds can affect peanut yields for an extended period or throughout much of the growing season, depending on the competitiveness of the dominant species.

In peanut infested with a mixed population of annual grasses including *B. platyphyla*, *D. sanguinalis*, *E. indica*, and *U. texana*, the CPWC occurred between 4.3 and 9 wk after crop emergence, beginning and ending later than the CPWC for peanut infested with a mixed population of broadleaf weeds or grasses and broadleaf weeds combined (Everman et al. 2008a). However, when

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peanut was grown in competition with *U. platyphyla* or *D. dichotomum* in single species-specific studies, the end of the CPWC was at least 2 wk earlier (Chamblee et al. 1982; York and Coble 1977). The variability in the CPWC among individual weed species reflects the differences in the competitive abilities of the weed species. This variability may also be due to the differences in the methodology used to achieve weed-free periods in different studies. CPWC studies in peanut in the United States have utilized hand weeding or hoeing (Bridges et al. 1992; Hauser et al. 1975; Webster et al. 2007; York and Coble 1977), herbicides (Everman et al. 2008a, 2008b), and the combination of hand weeding and herbicides (Farris et al. 2005; Price et al. 2006) to maintain weed-free periods. Hand hoeing or herbicide application at different intervals or peanut growth stages may impact the CPWC intervals. While hand weeding will immediately terminate weed competition, weeds treated with herbicides, on the other hand, may continue to interfere with peanut for several days after treatment (Ferrell et al. 2003; Webster et al. 2007). Therefore, the herbicide mode of action is an important consideration in applying the CPWC intervals for weed management in peanut. Although weeds that emerge before or after the CPWC would not directly impact crop yield, if not controlled, they can reduce harvest efficiency by interfering with peanut digging and also increase the weed seedbank, which can make weed management more problematic in subsequent growing seasons (Burke et al. 2004; Johnson and Mullinix 2003; Mahoney et al. 2021). Hence season-long weed control is often required to maximize peanut yield.

## Weed Management

### Preventive Weed Management

One of the first steps in achieving effective weed management is to prevent weed establishment, because it is difficult to control weeds once they are established (Chauhan et al. 2012). Preventive weed management involves the use of different measures that reduce the buildup of the weed seedbank, weed seedling recruitment, weed interference, and weed seed production (Chauhan et al. 2012). It is often considered an easier, less costly, and environmentally friendly weed management option compared with curative options, especially for problematic weeds under the circumstances of limited herbicide options and herbicide resistance (Bajwa et al. 2017; Chauhan et al. 2012). However, the literature on weed management in peanut in the United States includes only a few examples of weed management programs centered on preventive measures. Apart from preventive weed management practices used in combination with curative measures, only about 3% of the published weed research studies in peanut in the United States have focused mainly on the impact of preventive measures on weed management: crop rotation (Johnson et al. 2001; Leon et al. 2015; Tiwari et al. 2021), stale seedbed (Johnson and Mullinix 1995, 2000), cover crops (Aulakh et al. 2015; Dobrow et al. 2011; Johnson et al. 2010; Lassiter et al. 2011; Price et al. 2007), row spacing (Johnson et al. 2005; Stephenson and Brecke 2011), planting pattern (Besler et al. 2008; Brecke and Stephenson 2006; Colvin et al. 1985; Grichar et al. 1994; Kharel et al. 2022), planting date (Kharel et al. 2022; Linker and Coble 1990), and the use of competitive cultivars (Fiebig et al. 1991; Leon et al. 2016; Place et al. 2010, 2012). These are examples of weed-preventive measures that have been studied in peanut in the United States, and these measures were mainly tested in combination with curative measures, particularly chemical weed control.

### Crop Rotation

Crop rotation is considered an essential component of an effective weed management program. In the United States, peanut is commonly rotated with crops such as corn, cotton, grain sorghum [*Sorghum bicolor* (L.) Moench. ssp. *bicolor*], wheat (*Triticum aestivum* L.), and sometimes soybean (Johnson and Mullinix 1997; Jordan et al. 2008; Leon et al. 2015). Nematodes and soil-borne diseases can quickly become an economic problem when peanut is grown in consecutive years, whereas rotating peanut with these crops can improve weed control and reduce the buildup of pests and pathogens that can negatively impact peanut yield (Warren and Coble 1999). For instance, *C. esculentus* population densities and tubers were reduced with peanut–corn and peanut–cotton rotations compared with fallow (Johnson and Mullinix 1997). Similarly, shoots and tubers of *C. rotundus* were effectively managed with imazapic with 20% and 7% yield increase in a 3-yr corn and peanut rotation sequence (corn–peanut–corn) compared with peanut grown in consecutive (peanut–peanut–peanut) or alternate years (peanut–corn–peanut), respectively (Warren and Coble 1999). Additionally, rotating peanut with other crops allows effective rotation of herbicides or herbicide modes of action, which can improve weed management (Jordan et al. 2008). For example, *A. artemisiifolia*, *E. prostrata*, and *S. obtusifolia* can be difficult to control in peanut but can be relatively well controlled in glyphosate-resistant crops, such as corn, cotton, and soybean. Furthermore, diversification of crop rotations can be an essential tool for improving weed management (Owen 2008). Evidence from peanut in the United States for this idea is limited. Diversified crop rotations as a weed-preventive measure have only been tested by Leon et al. (2015) in north Florida and more recently by Tiwari et al. (2021) in west Florida. Leon et al. (2015) reported that adding bahiagrass (*Paspalum notatum* Flueggé), a perennial, to the predominant peanut–cotton rotation system of Florida growers modified the structure of the weed community and increased weed species evenness and richness, thereby favoring weed species diversity. Results from their 13-yr rotation study showed that the bahiagrass–bahiagrass–peanut–cotton rotation system had more diverse and dense weed seedbanks and a higher weed frequency than the conventional peanut–cotton–cotton rotation system (Leon et al. 2015). However, they concluded that adding bahiagrass to the rotation system did not affect weed management in peanut, because the increased weed community with this rotation system was transient and only limited to the first phase of bahiagrass. Thereafter, the weed seedbank structure and density decreased and were similar to the peanut phase, which was suggested to be due to increased seed-predatory activity that possibly resulted from the greater ground cover provided by bahiagrass (Leon et al. 2015).

Tiwari et al. (2021) evaluated the effect of winter carinata (*Brassica carinata* A. Braun)—a recently introduced nonedible winter biofuel crop in the southeastern United States—on summer weed population dynamics in peanut. In that study, winter carinata grown in winter reduced the emergence of smooth pigweed (*Amaranthus hybridus* L.) and *S. obtusifolia* by greater than 27% and 25%, respectively, without preemergence herbicide application. With or without preemergence application of *S*-metolachlor, greater than 40% reduction in *A. hybridus* emergence was observed after winter carinata harvest compared with winter fallow (Tiwari et al. 2021). This indicates that winter carinata has the potential to

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enhance integrated weed management strategies in peanut at the rotational level by reducing summer weed seedbanks.

### Stale Seedbed and Tillage

The use of stale seedbed tillage is a valuable way to reduce weed pressure, improve weed management, and possibly reduce herbicide inputs (Chauhan et al. 2012). In this practice, soil disturbance through tillage is used to stimulate weed seed germination several days, weeks, or months before planting a crop, and emerged weed seedlings are killed using shallow tillage or a nonselective herbicide such as paraquat or glyphosate (Johnson and Mullinix 2000). This practice can provide a weed-free environment for crop emergence and growth early in the growing season, thereby enhancing crop competition with late-emerging weeds (Chauhan et al. 2012). In peanut, stale seedbed with shallow tillage of 7.6-cm depth using a power tiller three times at 2-wk intervals was found very effective, resulting in lower densities of weed species such as *D. tortuosum*, *U. texana*, and *C. esculentus* compared with conventional tillage (23-cm deep) or glyphosate (Johnson and Mullinix 1995). In another study, however, Johnson and Mullinix (2000) demonstrated that stale seedbeds with shallow tillage did not improve weed control compared with a non-tilled control.

### Cover Crops

Although peanut production in the United States is mostly in conventional tillage, interest in the conservation-tillage system has increased dramatically in recent years due to its economic and environmental benefits (Price et al. 2007). The conservation-tillage system leaves at least 30% of residue cover on the soil surface after planting (SSSA 2020). In conservation-tillage systems, cover crop residues or mulch present on the soil surface protects soil resources before planting peanut and can serve as a preventive weed management measure to provide weed suppression through reduced light transmittance to the soil surface, allelopathy, or direct physical suppression (Lassiter et al. 2011; Price et al. 2007). Several cover crops, including black oat (*Avena strigosa* Schreb.), cereal rye (*Secale cereale* L.), Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], oats (*Avena sativa* L.), triticale (×*Triticosecale* Wittm. ex A. Camus [*Secale* × *Triticum*]), and winter wheat are easy to establish and can provide high amounts of biomass for weed suppression in peanut (Lassiter et al. 2011; Price et al. 2007), but challenges with pegging, digging, and inverting peanut vines have limited the use of this approach for weed management in peanut (Leon et al. 2019). Furthermore, even when the cover crop provides high residues, weed suppression is inadequate without other supplementary control measures such as herbicide input. A 4-yr study conducted by Price et al. (2007) in Alabama demonstrated that winter cover crops such as black oat, cereal rye, and wheat were not effective in controlling weeds without a herbicide program in a high-residue conservation-tillage peanut production system. Similarly, studies conducted in Georgia showed that strip tillage with the use of cereal rye provided only moderate control of annual grasses, including southern crabgrass [*Digitaria ciliaris* (Retz.) Koeler] and *U. texana* in the absence of herbicide input (Johnson et al. 2010). However, high-residue cover crops, including cereal rye, Italian ryegrass, oats, triticale, and wheat, tested in combination with herbicide programs provided greater weed control and yield advantage relative to no cover (Aulakh et al. 2015; Dobrow et al. 2011; Lassiter et al. 2011). When the cover crop does not produce adequate biomass to provide a dense layer of residue on the ground for weed suppression, the benefits of this weed-preventive measure are limited, and a comprehensive herbicide program will be required for effective weed management (Dobrow et al. 2011; Johnson et al. 2010).

### Row Spacing, Seeding Rate, and Planting Pattern

One of the most effective approaches to preventive weed management is the use of agronomic practices such as row spacing, seeding rate, and planting pattern to minimize weed interference and enhance crop competitiveness with weeds (Bajwa et al. 2017). Because of the prostrate and initial slow growth habit of peanut, most weeds that establish before peanut plants will overtop and outcompete the crop, reducing harvest efficiency and yield (Burke et al. 2004). Therefore, cultural practices that enhance uniform stand establishment, rapid growth, increased nutrient uptake, elevated plant height, greater dry matter production, rapid canopy closure, greater light interception, and shading of weeds in the understory (below the crop canopy) are important to increase peanut competitiveness against weeds (Burke et al. 2004, 2007; Johnson et al. 2005). The use of narrow row spacing to increase the rate of canopy closure and the competitive ability of peanut has proved highly beneficial in terms of weed suppression and yield improvement in many studies (Brecke and Stephenson 2006; Buchanan and Hauser 1980; Hauser and Buchanan 1981; Johnson et al. 2005; Stephenson and Brecke 2011). For instance, due to rapid canopy closure, late-season *D. tortuosum* and *S. obtusifolia* biomass was reduced by 28% and 18%, respectively, when peanut was planted at 41-cm row spacing compared with 81-cm row spacing (Buchanan and Hauser 1980). Additionally, the yield benefit for the 41-cm row spacing was about 50% due to better weed suppression and favorable conditions for crop growth that increased yield (Buchanan and Hauser 1980). Similarly, a reduction in row spacing from 81.2 to 20.3 cm decreased *S. obtusifolia* density and increased peanut yield by up to 15% in studies conducted on two soil types in Alabama and Georgia (Hauser and Buchanan 1981). Also, a 4-yr study conducted in Florida showed that narrow (38-cm) row spacing provided greater browntop millet [*Brachiaria ramosa* (L.) Stapf] and *C. benghalensis* control than wide (76-cm) row spacing but did not influence control of pitted morningglory (*Ipomoea lacunosa* L.) or *S. obtusifolia* (Stephenson and Brecke 2011). However, Johnson et al. (2005) found that peanut planted in 30-cm rows had greater midseason control of *S. obtusifolia* and a 25% decrease in total weed density compared with peanut planted in 91-cm rows. Johnson et al. (2005) also reported a 12% increase in peanut yield under the narrow- versus the wide-row peanut system (Stephenson and Brecke 2011). Despite the improved weed control and proven yield increase, peanut seeded in narrow-row patterns is not common, because increased crop canopy commonly associated with narrow row spacing and increased plant population can serve to create and maintain a humid subcanopy environment that can serve to enhance occurrence and severity of diseases such as stem rot (*Sclerotium rolfsii* Sacc.) (Wehtje et al. 1994).

Numerous studies have reported the superior weed suppressive ability of peanut using twin rows as a weed-preventive measure compared with single rows (Brecke and Stephenson 2006; Colvin et al. 1985; Grichar et al. 1994; Kharel et al. 2022; Wehtje et al. 1984). The benefits of twin-row spacing are attributed mainly to rapid canopy cover and more efficient use of light and water that give peanut a competitive advantage against weeds (Brecke and Stephenson 2006; Johnson et al. 2005; Kharel et al. 2022; Place et al.

2010). In a recent study, Kharel et al. (2022) reported that twin rows spaced 18 or 23 cm apart on 91-cm centers achieved canopy closure 2 wk earlier, resulting in greater *S. obtusifolia* suppression and an 18% increase in yield compared with single rows spaced 76 cm apart. Similarly, *S. obtusifolia* control was 9% higher and yield 10% to 43% higher when peanut was seeded in the twin-row planting pattern (rows spaced 18 cm apart on 91-cm centers) compared with peanut planted in the single-row planting pattern (single rows on 91-cm centers) under different herbicide treatments (Lanier et al. 2004). In another study, twin rows spaced 18 cm apart on 91-cm centers reduced competition from *D. sanguinalis* and *U. texana*, resulting in greater peanut yield (Wehtje et al. 1984). The twin-row planting pattern has also been reported to provide greater late-season control of *C. esculentus* (Grichar et al. 1994), *D. tortuosum* (Brecke and Stephenson 2006; Colvin et al. 1985), *E. prostrata* (Place et al. 2010), *Ipomoea* spp. (Place et al. 2010), *S. obtusifolia* (Brecke and Stephenson 2006; Colvin et al. 1985; Lanier et al. 2004), *U. texana* (Colvin et al. 1985), tumbleweed (*Salsola tragus* L.), and *X. strumarium* (Brecke and Stephenson 2006) compared with the single-row planting pattern in peanut. However, not all cultivars benefit equally from the twin-row planting pattern. Jordan et al. (2010) showed that a bunch-type growing habit cultivar responded more positively to twin-row planting than a cultivar with a prostrate growth habit. Also, apart from weed suppression, yield benefits from twin-row planting from different studies have been inconsistent. Colvin et al. (1985) and Kharel et al. (2022) reported greater peanut yield in twin rows compared with single rows. In a similar study, Grichar et al. (1994) found no yield benefit with twin-row spacing compared with single-row spacing. Although *S. obtusifolia* control was greater when peanut was planted in twin rows in both conventional- and conservation-tillage systems, consistent yield increase with twin rows was only observed in conservation tillage (Brecke and Stephenson 2006).

The use of twin-row planting patterns can improve weed control and reduce the incidence of tomato spotted wilt of peanut (Johnson et al. 2005), but most of the studies reported that the increase in weed control from a twin-row planting pattern was not sufficient to reduce or eliminate the need for herbicides to protect yield (Brecke and Stephenson 2006; Colvin et al. 1985; Lanier et al. 2004; Place et al. 2010). This suggests that twin-row spacing can only be used as a supplement to a comprehensive weed control program and should not be considered a stand-alone weed management option. Additionally, peanut seed is one of the most costly inputs in peanut production. Increasing the seeding rate in twin rows to enhance weed suppression will further increase the cost of production, as the seeding rate is 10% to 20% greater in narrow rows compared with wide rows (Smith and Smith 2011). Furthermore, increasing plant population with the use of a twin-row pattern can increase the incidence of stem rot disease (Wehtje et al. 1994). Hence, reaching a balance between disease prevention, improved weed control, and increased yield must be a central goal when choosing peanut planting patterns.

### Planting Date

Planting date can have a huge impact on weed management in peanut by affecting weed seed germination, weed growth rate, and crop vegetative growth (Linker and Coble 1990). Peanut planting dates in the United States range between mid-April and late June (Linker and Coble 1990; Kharel et al. 2022). During this period, weeds have a well-defined period of emergence determined by soil moisture content and soil temperature (Egley and Paul 1986; Stoller and Wax 1973). Therefore, peanut planting date can be manipulated as a weed-preventive measure in such a way that the ecological conditions for weed seed germination are not met during the planting timing. The peak of weed emergence and prolonged competition can also be avoided through a well-planned planting date (Kharel et al. 2022). Furthermore, the planting date can be adjusted to facilitate faster growth, which can result in rapid canopy closure, increased crop competitiveness, and greater weed suppression (Kharel et al. 2022). Gardner and Auma (1989) showed that peanut planted earlier in May had greater leaf area index, canopy light interception, and total dry matter than peanut planted late in June, suggesting that planting date can be optimized to enhance the competitive ability of peanut. However, the effect of planting date on weed suppression in peanut can vary depending on environmental conditions and prevailing weed species (Kharel et al. 2022; Linker and Coble 1990). For example, in the first year of a 2-yr study, Kharel et al. (2022) reported that *S. obtusifolia* biomass was reduced in peanut planted in early May compared with mid-May and early-June planting dates. In the second year of the same study, however, delayed planting resulted in reduced *S. obtusifolia* density compared with mid- or early-May planting dates (Kharel et al. 2022). This inconsistency was attributed to the environmental conditions, which were favorable for longer periods of weed infestation and enhanced *S. obtusifolia* growth with early planting in one year and late planting in the other (Kharel et al. 2022). In addition to the direct effect on weed growth, planting date can affect the efficacy and intensity of herbicide use in peanut. Wehtje et al. (1986) reported greater herbicide efficacy for the control of *U. texana* in early-planted peanut compared with late-planted peanut. Hauser et al. (1977) also showed that early-planted peanut required reduced herbicide input for weed control compared with late-planted peanut.

### Competitive Cultivars

Competitive crop cultivars play an important role in effective weed management, because they offer some level of weed suppression and are better able to acquire growth resources such as light, nutrients, water, and space (Leon et al. 2016). Despite its short stature compared with other row crops, when grown at the right planting density and arrangement, peanut can form a dense canopy that limits light transmittance to the soil surface, thereby reducing weed seed germination and suppressing weed growth. Peanut cultivars can differ in their weed suppressive ability due to differences in growth habits, plant morphology, canopy architecture, and efficiency of light interception (Fiebig et al. 1991; Leon et al. 2016; Place et al. 2012). However, only a few studies have been conducted in the United States to test the weed competitive ability of peanut cultivars. Fiebig et al. (1991) observed differences in the response of four peanut genotypes to *X. strumarium* competition that were mostly associated with differences in growth habits and canopy architecture. *Xanthium strumarium* at distances of 0 to 25 cm from peanut reduced yields 50% for the cultivars 'NC7' and 30, 26, and 13% for the Florida breeding lines 'BL-10', 'BL-8', and 'F8143B', respectively (Fiebig et al. 1991). Similarly, Hackett et al. (1987) reported that the tall Spanish peanut cultivar 'Pronto' was more competitive and exhibited greater tolerance for *S. carolinense* interference compared with the runner-type cultivar 'Florunner.' Although these studies were conducted using what are now obsolete cultivars, the results indicate that there is potential for developing peanut cultivars with improved competitive ability against weeds. Subsequent studies conducted with other cultivars, however, showed that the morphological response to weed interference was similar among the cultivars despite the variation in growth habit and canopy architecture (Leon et al. 2016; Place et al. 2010, 2012). Place et al. (2012) compared the response to weed interference among eight Virginia market-type genotypes, including 'NC 10C', 'NC-V 11', 'NC 12C', 'Phillips', 'VA 98R', and breeding lines 'N99027L', 'N01013T', and 'N02020J' and found no clear differences despite variations in canopy coverage among the genotypes. In another study, Place et al. (2010) observed that the difference in peanut cultivar VA 98R, with runner growth habit, and NC 12C, with excessive vine growth, and an intermediate (between a runner and bunch type growth) had only minor effects on weed control. Leon et al. (2016) also showed that the differences in growth habits among peanut cultivars 'Bailey', with an erect and tall canopy height, 'Georgia-06G', with a semi-bunch and intermediate height, and advanced breeding line 'UFT312', with very prostrate growth and short canopy height, had no effect on weed suppression and weed tolerance. Furthermore, peanut cultivars with early maturity that may allow earlier harvest have not been effective. Increased weed tolerance in peanut in previous studies was attributed to the allocation of more photosynthate resources to vegetative growth than to reproductive growth, which may result in delayed maturity and potentially lower yield (Fiebig et al. 1991). Therefore, breeding efforts to increase weed suppression and competitiveness in peanut must be pursued with the goal of identifying lines that better balance the translocation of photoassimilates over vegetative growth and developing cultivars that allow earlier harvest with increased weed tolerance and high yield potential. Such cultivars could help reduce reliance on chemical weed control and serve as a viable component of integrated weed management.

## Curative—Mechanical Weed Management

Mechanical weed management involves the use of tillage or hand tools to cut, remove, or disrupt weed growth without inflicting any harm to the crop (Johnson et al. 2012b). Mechanical weed control is simple and effective and does not leave chemical residues on the crop, which makes it the major weed control method in organic systems. However, mechanical weed control is complicated by limitations of equipment design, operation, and cost (Johnson et al. 2012b; Johnson and Davis 2015). Mechanical weed control in peanut in the United States is achieved mainly with the use of interrow cultivation implements such as a tine weeder, sweep cultivator, and brush hoe (Johnson et al. 2012b; Wann and Tubbs 2014). Weed control using these implements is achieved by cutting, shredding, tearing, and burying weeds (Wann et al. 2011). The tine weeder is made of a series of spring-steel rods arranged in multiple rows that displaces weed seedlings using the high-speed vibratory action of the tines (Johnson and Luo 2019). The sweep cultivator control weeds using uniquely shaped blades that cut weeds by slicing under the soil surface between the interrow space (Johnson et al. 2012b). The brush hoe, on the other hand, is made of a series of rotating stiff brushes that scours the seedbed between the crop rows and a rear-steering linkage that keeps the brushes close to the crop row (Colquhoun and Bellinder 1997; Johnson et al. 2012b).

Cultivation has been used as a method of weed control in peanut for many years, particularly in organic and low-input systems (Johnson et al. 2012a, 2012b; Johnson and Davis 2015; Russo and Webber 2012) and in combination with herbicides as a component of integrated weed management system in conventional peanut production (Colvin et al. 1985; Johnson and Luo 2019; Wilcut et al. 1987). Although the morphology of the peanut plant limits the intensity and duration of cultivation, several studies reported effective control of annual grasses and small-seeded broadleaf weeds with repeated cultivation after weed seed germination, but before full seedling emergence, particularly in organic peanut (Johnson et al. 2012a, 2012b, 2013; Johnson and Luo 2019; Wann et al. 2011). In a recent study, cultivation with the tine weeder improved the control of smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb] by 76% to 95% when used as a supplement to preemergence applications of ethalfluralin or *S*-metolachlor and the control of annual grasses by 54% to 75% when used as a supplement to postemergence application of imazapic in conventional peanut production (Johnson and Luo 2019). Similarly, earlier studies conducted in conventional peanut production showed that timely cultivation improved the overall management of troublesome weed species, including *A. hispidum*, *D. tortuosum*, *D. sanguinalis*, *S. obtusifolia*, and *U. texana*, by controlling escapes at low cost when used as a supplement to herbicides (Bridges et al. 1984; Colvin et al. 1985; Wilcut et al. 1987). However, these studies indicated that peanut was vulnerable to injury from cultivation and increased incidence of stem rot disease caused by soil movement onto the peanut crown. Contrary to the report of earlier studies, Johnson et al. (2018) showed that intensive cultivation with the tine weeder did not consistently affect the incidence of stem rot in organic peanut. However, peanut crops' tolerance to cultivation and the weed control effectiveness of a tine weeder or sweep cultivator is dependent on the timing and frequency of cultivation (Johnson et al. 2012a, 2013; Johnson and Davis 2015).

Greater control of *D. ciliaris*, *J. tamnifolia*, and *U. texana* was observed when the cultivation regime with tine weeder and brush hoe began at peanut "cracking" or vegetative emergence (VE) stage compared with 1 or 2 wk after the VE stage (Johnson et al. 2012b). In the same study, Johnson et al. (2012b) reported greater weed control and maximum peanut yield with sequential cultivation at VE and 1 wk after VE compared with cultivations at VE and 2 wk after VE or cultivations at VE, 1, and 2 wk after VE stages. Also, tine and sweep cultivation combined at least once a week for a duration of 4 or 5 wk provided greater control of annual grasses and Florida pusley (*Richardia scabra* L.) and improved peanut yield compared with cultivation of 3-wk duration (Wann et al. 2011). Also, weekly tine cultivation for a 5-wk duration combined with two sweep cultivations at 2 and 5 wk after planting effectively controlled crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.], *D. ciliaris*, *J. tamnifolia*, *R. scabra*, and *Amaranthus* spp. and reduced the hand-weeding time requirement by more than 38% compared with no tine cultivation (Wann and Tubbs 2014). In another study, the control of *D. aegyptium*, *D. ciliaris*, *D. tortuosum*, *I. lacunosa*, *J. tamnifolia*, and *S. obtusifolia* was similar with tine-weeder cultivation of 6- and 8-wk duration (Johnson et al. 2012a)

The effectiveness of weed control using cultivation can also vary depending on the weed species composition (Johnson and Luo 2019; Wann et al. 2011; Wann and Tubbs 2014). Available literature suggests that annual grasses are likely to have a greater response to cultivation than dicot weeds. Also, cultivation is reported to be of primary benefit in controlling annual but not perennial weed species (Wilcut et al. 1994). Studies have shown that the vegetative structures of perennial broadleaf, grass, and sedge weeds such as rhizomes and stolons are spread by cultivation, which exacerbates weed proliferation (Bridges et al. 1984; Wilcut et al. 1994). Additionally, while cultivation can provide effective weed control between peanut crop rows, in-row weed control remains problematic, because cultivation implements are unable to control weeds in or close to peanut rows, where weed competition effect can be more deleterious (Johnson and Mullinix 2008; Johnson et al. 2013; Wann et al. 2011). Several research attempts to improve in-row weed control with cultivation implements, however, have proven ineffective or at best provided only marginal effectiveness. Johnson et al. (2012a) evaluated the potential of cultural practices that facilitate early canopy closure in improving in-row weed control with the cultivation of organic peanut. In this study, the benefit of reduced seeding rates and twin-row spacing in improving weed control with tine cultivation or brush hoe was inconsistent and varied among weed species. While *D. aegyptium* control with cultivation was better in twin rows than in wide rows, *D. ciliaris* control was not affected. Also, *D. tortuosum* and *I. lacunosa* control with cultivation was improved in wide rows compared with twin rows, but *S. obtusifolia* control was not affected (Johnson et al. 2012b). Weed control with cultivation was more effective with a narrow-row pattern using 20 to 26 seeds $m^{-1}$ in each row compared with the recommended seeding rate (10 to 13 seeds $m^{-1}$ in each row) (Johnson et al. 2012b). In studies evaluating the effect of the direction of cultivation along the crop row on in-row weed control in organic peanut, Johnson and Davis (2015) demonstrated that cultivation with a tine weeder and sweep cultivator perpendicular to the row direction did not improve in-row weed control compared with cultivation in the same direction as crop rows. Similarly, in other attempts, remedial weed control, such as applications of corn gluten meal and broadcast propane flaming, and herbicides derived from natural products, such as clove oil and citric plus acetic acid, failed to improve in-row weed control with sweep cultivation in organic peanut (Johnson and Mullinix 2008; Johnson et al. 2013).

Mowing is another curative mechanical weed management practice in peanut reported in the literature. Mowing was a common weed control practice in agronomic crops in the past but was abandoned as more effective herbicides became available for weed control (Wehtje et al. 1999). The few available results on the benefit of mowing as a mechanical weed management practice in peanut are inconsistent. Wehtje et al. (1999) demonstrated that mowing was beneficial to peanut yield and net return but was of no benefit as a weed control supplement to herbicides or cultivation. However, Grey and Bridges (2005) reported that mowing *D. tortuosum* at 63 d after crop emergence was as effective as chlorimuron applied either at 49 or 63 d after emergence.

## Synthesis and Future Perspectives

Weed competition is one of the most important biotic constraints to peanut production in the United States, and as such has received great research attention. Peanut presents several unique features that justify targeted investments in weed research. First, peanut has a prostrate growth habit and a relatively shallow canopy. Second, peanut requires a long growing season for development and maturity. Third, peanut fruit develops underground on pegs that originate from the stem that grows parallel to the soil. These unique features can be considered drivers for research and development endeavors.

The prostrate growth habit and relatively shallow canopy of peanut allow weeds to be more competitive, particularly early in the growing season. The long growing season requirement of peanut allows more time for weed competition, making weed management essential throughout much of the growing season. Further, the pattern of fruit development of peanut implies that growers cannot use cultivation as a weed management practice late in the growing season, and therefore weed management is overwhelmingly achieved with herbicides. Based on our systematic review of the literature, 72% of the research addressing weed problems in peanut in the United States is focused on curative weed management with the use of herbicides. While this may be justified by the unique features of peanut that necessitate weed control for much of the growing season and restrict cultivation to an early-season control option, the evolution of herbicide-resistant weeds due to the heavy reliance on herbicides in high-input systems threatens the sustainability of weed management in peanut. On the other hand, the increasing cost of labor and limited mechanical control alternatives in low-input systems remains a big challenge. Unfortunately, preventive nonchemical weed management strategies that can enhance the competitiveness of peanut against weeds (e.g., identification of competitive cultivars and use of narrow or twin-row spacing) and reduce weed interference and the buildup of the weed seedbank (e.g., crop rotation and cover crop) have received less attention (only 13% of the weed management research on peanut in the United States). These strategies should be marked as high-priority areas for future research, as growers may likely be forced to incorporate nonchemical weed management strategies into their production systems.

The available research studies on preventive weed management strategies have generated tangible solutions for weed management, including crop rotation and the use of narrow or twin-row spacing, stale seedbed tillage, high-residue cover crops, and early planting, that reduced weed competition in peanut. Although these solutions were not effective enough to eliminate or reduce the need for herbicides to protect yield in most studies, they provided significant weed suppression, and management strategies based on agroecology (e.g., crop rotation and the use of cover crop) should ideally reduce the long-term weed seedbank replenishment, seedling recruitment, and consequent weed pressure in subsequent growing seasons. These preventive weed management strategies should be expanded in future research in terms of diversification of crop rotation and cover crop management (e.g., species selection, timing, and method of planting and terminating cover crops). More importantly, because single preventive measures have proven ineffective in reducing herbicide input for weed management, more attention should be given to the integrated use of compatible multiple preventive weed management strategies in future research. Perhaps this would help to reduce the need for herbicide inputs without compromising peanut yield. In the literature on weed management in peanut in the United States, there are currently only a few tangible examples of integrated weed management strategies that are based on multiple preventive measures. Most preventive measures were tested in combination with curative measures, particularly herbicides.

While cultivar resistance has been effective for disease management in peanut, tolerance of weed interference has not been effective. Although earlier studies conducted with what are now obsolete cultivars showed that there is potential to develop peanut cultivars with increased competitiveness through the improvement of certain vegetative traits, breeding efforts to develop such cultivars have not been pursued. Further, only a few studies have been conducted to test the weed competitive ability of currently available peanut cultivars. Future research should therefore aim at identifying weed-tolerant cultivars while breeding efforts should be pursued to develop weed-tolerant cultivars with high yield potential. Such cultivars could help reduce reliance on chemical weed control and serve as a viable component of integrated weed management.

We identified a research gap regarding the use of cultivation in the conventional peanut production system. While cultivation has been used extensively in organic peanut production, this option has not been well exploited in the conventional peanut production system, particularly as a component of integrated weed management. Cultivation integrated with herbicides (e.g., benefin, chloramben, dinoseb, naptalam, and vernolate) provided effective weed control in earlier studies. However, most of these herbicides are no longer commercially available or used in peanut. Research is needed to determine the value of cultivation when integrated with currently available herbicides. Perhaps this would broaden the options available for integrated weed management, particularly for herbicide-resistant weeds.

With respect to the timing of weed management, significant progress has been made to identify the CPWC for numerous weed species in peanut. Depending on the weed community, peanut require a weed-free period beginning from 2 to 3 wk until 6 to 12 wk after crop emergence to avoid unacceptable yield loss. However, there is a dearth of information on the CPWC for some important weed species (e.g., *A. artemisiifolia*, *A. palmeri*, *C. esculentus*, *C. glandulous*, *D. stramonium*, and *E. indica*) in peanut. Research on the influence of production practices (e.g., planting pattern, row spacing, cover crops, residual herbicides) on the CPWC in peanut is also scant. Additionally, most of the CPWC studies on peanut in the United States have not focused on a mixed population of weed species but on individual weed species. Although it is important to prioritize individual weed species of economic importance (e.g., *A. palmeri*, *C. benghalensis*, and *S. obtusifolia*) based on the severity of competition or difficulty of control, successful weed management with lasting outcomes and wider relevance will be better achieved by identifying and addressing dominant weed communities in specific target locations, in light of the diversity and dynamics of the weed communities. This will require more research efforts on weed distribution and ecological requirements of the weed communities, areas that currently have received the least attention (only 1% of the weed research studies in peanut in the United States). Finally, future weed management research in peanut should be considered within the context of climate change and emerging constraints, such as water shortages, drought, and flooding, and the effects of rising temperatures and increased $CO_2$ concentration on peanut–weed interactions and weed management.

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