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Running title: Cereal rye termination in peanut

Implications of cereal rye cover crop termination timing and residue management on Palmer amaranth (*Amaranthus palmeri*) and sicklepod (*Senna obtusifolia*) control in peanut

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Abstract

Weed management in peanut primarily relies on intensive herbicide programs. Integrating cereal rye as a cover crop may reduce herbicide input without compromising weed control. Field experiments were conducted to evaluate cereal rye termination management and herbicide programs in peanut. Main plot treatments included a winter fallow control and four cereal rye termination scenarios: (1) early termination 28 days before peanut planting (DBP) with residue rolled flat, (2) early termination 28 DBP with residue left standing, (3) late termination 14 DBP with residue rolled flat, or (4) late termination 14 DBP with residue left standing. Sub-plot treatments consisted of four herbicide programs: (1) preemergence (PRE) plus early postemergence (EPOST) plus mid-postemergence (MPOST) herbicides; (2) PRE plus MPOST herbicides; (3) EPOST plus MPOST herbicides; and (4) a nontreated control. Early cereal rye termination (28 DBP), whether rolled or standing, reduced Palmer amaranth density by 36 to 48% without PRE herbicides and by 36 to 50% when PRE herbicides (fluridone or flumioxazin) were applied. Sicklepod density was unaffected by early termination. In contrast, late termination reduced sicklepod density by 47 to 50% and Palmer amaranth density by 64–86% relative to the winter fallow control at 28 days after PRE application. Across all treatments, cereal rye reduced Palmer amaranth and sicklepod biomass by 63 to 67% and 63 to 65%, respectively, 28 days after MPOST herbicide application. However, standing cereal rye residue reduced peanut yield compared to rolled residue and the winter fallow. Late-terminated, rolled cereal rye residue combined with reduced herbicide programs (PRE plus MPOST or EPOST plus MPOST) provided weed control and yield comparable to the intensive herbicide program (PRE plus EPOST plus MPOST) in winter fallow control. Based on these findings, late-terminated, rolled cereal rye has the potential to reduce herbicide input while maintaining peanut yield and effective weed suppression.

Nomenclature: Acifluorfen; bentazon; diclosulam; dimethenamid-P; fluridone; flumioxazin; imazapic; paraquat; Premix bentazon-acifluorfen; *S*-metolachlor; 2,4-DB; Palmer amaranth; *Amaranthus palmeri* S. Watson.; sicklepod; *Senna obtusifolia* (L.) H.S. Irwin & Barneby; cereal rye; *Secale cereale* L.; peanut; *Arachis hypogaea* L.

Keywords: Rolled cereal rye residue; standing cereal rye residue; winter fallow; weed control; paraquat; imazapic.

Introduction

Palmer amaranth and sicklepod are among the most challenging to control and economically damaging weed species in peanut production systems across the southeastern US (Daramola et al. 2023a; Everman et al. 2008). These species compete aggressively with peanut growth, leading to significant reductions in yield and harvest operation efficiency (Daramola et al. 2024a; Johnson and Luo et al. 2019). Their management in peanut is particularly challenging due to their high seed production, prolonged emergence periods, and the limited availability of effective herbicide options (Everman et al. 2008; Mahoney et al. 2021). As of 2024, there are 131 confirmed cases of herbicide resistance across 12 different weed species in the United States (Heap 2024). Among these, Palmer amaranth is regarded as one of the most difficult to manage in peanut systems, having evolved resistance to nine different herbicide sites of action (Heap 2024). Controlling sicklepod is also challenging, as it belongs to the same plant family as peanut, limiting the availability of selective herbicide options.

Historically, peanut growers in the United States have relied on intensive tillage systems to establish residue-free seedbeds (Price et al. 2007). However, rising production costs and growing concerns about soil health have sparked interest in conservation tillage practices that minimize soil disturbance (Godsey et al. 2011). Although conservation tillage offers soil and environmental benefits, it often leads to greater dependence on herbicides for weed management due to limited mechanical options, thereby increasing the risk for the development of herbicide-resistant weeds (Dentzman and Burke 2021; Van Deynze et al. 2022). Furthermore, the growing prevalence of herbicide-resistant weeds has imposed significant challenges on conservation tillage systems, leading to poor weed management and a resurgence in tillage (Beckie 2014; Kumar et al. 2020; Price et al. 2011).

In the past two decades, the use of cover crops to diversify cropping and weed management systems has grown steadily and become more popular in the southeastern United States (Deines et al. 2023). Between 2012 and 2017, the cover-cropped area in the United States increased by 50%, from approximately 4 million ha to 6 million ha, with projections estimating expansion to 40 million hectares in 2025 (Hamilton et al. 2017). Fall-planted cover crops have been shown to benefit agronomic cropping systems by improving soil quality and water infiltration, reducing nutrient leaching, increasing soil organic matter, conserving soil moisture, sequestering organic carbon, and providing early-season weed suppression (Essman et al. 2020;

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Silva and Bagavathiannan 2022). Cereal rye is the predominant winter cover crop among growers in the southeastern United States due to its winter hardiness and potential for high biomass production (SARE, 2012; Silva and Bagavathiannan 2022). The weed-suppressive effects of cereal rye are primarily attributed to the release of allelochemicals and the physical barrier created by its residue biomass, which inhibits weed seed germination and growth by modifying the quality and intensity of light reaching the soil surface (Blackshaw et al. 2001; Teasdale and Mohler 2000). However, the level of weed suppression from cereal rye residue has been shown to vary with management practices and geographic location (Silva and Bagavathiannan, 2022; Osipitan et al. 2018).

Management practices related to the establishment and termination of cereal rye are important for optimizing biomass production and weed suppression, with termination timing exerting the greatest influence (Boselli et al. 2021; Mirsky et al. 2017). For example, Mirsky et al. (2017) demonstrated that termination timing has a stronger influence on cereal rye biomass accumulation than planting date. Specifically, delaying termination by just 10 days increased biomass by an average of 2,000 kg ha^{-1}, whereas achieving a similar increase required planting the cover crop 45 days earlier. Delayed cereal rye termination has been shown to provide superior weed suppression relative to early termination in several row crops, including corn (Balkcom et al. 2015; Carrera et al. 2004, DeSimini et al. 2020), cotton (Price et al. 2016; Saini et al. 2008; Wiggins et al. 2016, 2017), and soybean (Essman et al. 2023; Nunes et al. 2023; Palhano et al. 2018; Wiggins et al. 2017). Additionally, integrating herbicides with rye termination has shown promise for improving weed control (Carrera et al. 2004; Price et al. 2016; Nunes et al. 2023). However, to our knowledge, no published research has examined the combined effects of cereal rye termination timing and herbicide programs on weed management in peanut. Existing studies in peanut have focused on a single termination timing (Aulakh et al. 2015; Dobrow et al. 2011; Lassiter et al. 2011; Price et al. 2007). While delayed termination can enhance biomass accumulation and weed suppression, excessive residue may hinder peanut stand establishment, increase interception of residual herbicides, and potentially reduce their efficacy (Nunes et al. 2023). Furthermore, residue management techniques such as the use of roller-crimper to flatten desiccated cereal rye into a surface mulch or planting directly into standing residue may also influence weed suppression and peanut crop response. Standing residue can reduce soil erosion and moisture loss but may obstruct planting equipment (Torbert et al. 2007).

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In contrast, rolled cereal rye forms a uniform mulch that enhances weed suppression but may increase pre-emergence herbicide interception, reduce soil evaporation, and lower soil strength compared to standing residue (Ashford and Reeves 2003; Kornecki et al. 2009). Therefore, a balance must be achieved between maximizing cereal rye biomass for weed suppression and managing surface residue to minimize negative impacts on peanut production. The objective of this study was to evaluate the interactions among cereal rye termination timing, residue management strategy, and herbicide program intensity on weed control in peanut.

Materials and Methods

Description of experimental site

Field experiments were conducted during the 2022–2023 and 2023–2024 growing seasons at the West Florida Research and Education Center, Jay, FL (30.776542° N, 87.147662° W; 62 m elevation), using separate fields each year. The study site was left as a natural weedy fallow, with no chemical or tillage weed control, for one year prior to trial initiation each season. Soil at the site was classified as a Red Bay Fine sandy loam with 2.1% organic matter and a pH of 5.6. Sicklepod was the dominant weed species present in both years. To ensure consistent weed pressure, sicklepod and Palmer amaranth seeds collected from a previous study in 2021 were broadcast at rates of 300 seeds m^{-2} and 500 seeds m^{-2}, respectively, in mid-November of each year.

Experimental design and treatments

The experiment was arranged in a randomized complete block design with a split-plot layout and four replications. Each sub-plot measured 3.6 × 9.1 m, and each main plot consisted of four sub-plots, resulting in a total main plot size of 14.4 × 9.1 m. The main plot treatments were the combination of cereal rye termination timing and residue management which included: (i) early termination 28 d before peanut planting (DBP) with cereal rye residue left standing; (ii) early termination 28 DBP with cereal rye residue rolled flat; (iii) late termination 14 DBP with cereal rye residue left standing; (iv) late termination 14 d DBP with cereal rye residue rolled flat; and (v) no-till control without cereal rye cover crop. The sub-plot treatments were herbicide program intensity (Table 1), which comprised four treatments: (i) an intensive program including preemergence (PRE), early postemergence (EPOST), and mid-postemergence (MPOST) applications; (ii) a reduced program excluding PRE herbicides; (iii) a reduced program excluding

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EPOST herbicides; and (iv) a non-treated control. Herbicides were applied at 1, 30, and 60 days after peanut planting (DAP) for PRE, EPOST, and MPOST timings, respectively (Table 2).

Crop management

Prior to cereal rye planting, paraquat (Gramoxone SL 2.0®, 1.1 kg ai ha^{-1}; Syngenta Crop Protection, Greensboro, NC) was applied to control emerged vegetation. Cereal rye (cv. Wrens Abruzzi) was sown as a winter cover crop in mid-November preceding each trial using a no-till drill (Great Plains 1206 NT; Salina, KS) at a rate of 65 kg ha^{-1}, with 2.6-cm seeding depth and 19-cm row spacing. Cereal rye was terminated at either 28 days before peanut planting (early termination) or 14 days before planting (late termination) using glyphosate (Roundup PowerMAX®, Bayer Crop Science, St. Louis, MO) applied at 1 kg ae ha^{-1} plus ammonium sulfate at 1.1 kg ae ha^{-1} for each timing. At early and late termination, cereal rye growth corresponded to Zadoks stages Z51 and Z61, representing heading to mid-anthesis (Zadoks et al. 1974). Desiccated cereal rye in the rolled treatment plots was flattened in a single pass using a 10.5-ft (4-row) tractor-mounted roller-crimper (I&J Manufacturing LLC, Gordonville, PA) 1 day before peanut planting, oriented in the same direction as planting. Peanut cultivar Georgia 12-Y was planted in single rows spaced 91 cm apart at 154 kg ha^{-1} using a John Deere 1720 Max Emerge no-till planter (Deere & Company, Moline, IL), on May 15, 2023, and May 1, 2024. Herbicide treatments were applied in spray solution at 140 L ha^{-1} using a CO_2-pressurized backpack sprayer (Spraying Systems Co., Wheaton, IL). All treatments were applied with a 3.6-m boom fitted with eight TeeJet® TTI11002 nozzles at an application speed of 4.8 km h^{-1}.

Data collection

Data were collected on cereal rye biomass, weed control, and peanut yield. Prior to chemical termination, aboveground cereal rye biomass was collected from two 0.5 m^2 quadrats randomly placed within each plot by clipping cereal rye at the soil surface to assess the effect of termination timing on biomass production. Harvested samples were oven-dried at 60°C for 72 h to quantify dry biomass and reported as dry weight in kg ha^{-1}. Weed density and biomass were evaluated at three growth stages corresponding to 28 days after each herbicide application: 28 days after the PRE application (early season), 28 days after the EPOST application (mid-season), and 28 days after the MPOST application (late season). Weed density was determined by counting the number of emerged weeds from two randomly positioned 0.5 m^2 quadrats located

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between the middle rows of each plot. Plants within each quadrat were cut at ground level for sampling and placed in a dryer set at 60 C for 72 h, after which their dry weight was measured and recorded. Peanut plants were dug using a conventional digger-shaker-inverter and allowed to air-dry in the field for 3 to 5 d; cereal rye biomass did not interfere with digging or harvesting operations. Peanut yield, reported in kg ha^{-1} was adjusted to a standard moisture level of 10.5%, following the procedure of Mulvaney and Devkota (2020).

Statistical analysis

The data were analyzed using the GLIMMIX procedure in SAS 9.4 (SAS Institute, 2012). Preliminary analyses considered all response variables with year included as a fixed effect. The explanatory variables included year, timing of termination, residue management strategies, and herbicide treatments. Interactions between year and treatment were assessed. If significant ($P < 0.05$), results were reported separately for 2023 and 2024; otherwise, data across both years were pooled for further analysis. In the combined analysis, termination timing and residue management (main plot factor), herbicide program (sub-plot factor), and their interactions, were treated as fixed effects. To account for the split-plot design, year, replications (blocks) nested within year, and main plots nested within replications within year were specified as random effects. Prior to conducting ANOVA, datasets were evaluated for homogeneity of error variance. Square-root transformations were applied as necessary to improve normality and model fit. Treatment means were separated using Tukey's Honest Significant Difference test at $P \leq 0.05$. Where appropriate, data were back-transformed for reporting purposes.

Results and Discussion

Cereal rye biomass production

Cereal rye biomass production differed across years and termination timings. In 2023, biomass production ranged from 6,400 to 7,350 kg ha^{-1}, which was higher than in 2024 (6,080 to 6,800 kg ha^{-1}; Figure 1). Delaying termination from 28 to 14 DPP increased cereal rye biomass by 15% in 2023 and 12% in 2024, with growth advancing from Z51 (beginning of heading) to Z61 (anthesis), a stage at which biomass accumulation is generally near its seasonal maximum. These increases were likely driven by greater growing degree day (GDD) accumulation between planting and termination in 2023 (GDD 2437 to 2710) compared to 2024 (GDD 2066 to 2319; Table 3), with late termination providing an additional 342 to 391 GDDs compared to early termination in both years. Accumulated GDD is a major factor influencing biomass production,

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and delayed termination has been shown to enhance heat unit accumulation and cereal rye biomass production (Essman et al. 2023; Ficks et al. 2023; Haramoto and Pearce 2019; Mirsky et al. 2011). For each 10-d increase, Mirsky et al. (2011) observed an approximate gain of 2,000 kg ha^{-1} in cereal rye biomass. Previous studies have indicated that biomass levels exceeding 5,000 kg ha^{-1} are typically required for effective weed suppression (Norsworthy et al. 2018; Nichols et al. 2020). In the current study, regardless of termination timing, cereal rye biomass production surpassed this threshold.

Early-season weed density

Treatment-by-year interactions were not significant ($P = 0.1$) for early-season Palmer amaranth density; therefore, data were combined across years for analysis. A significant interaction was observed between cereal rye termination management and PRE herbicide treatments for Palmer amaranth ($P < 0.001$) and sicklepod density ($P < 0.001$) at 28 days after PRE application (Table 4). Palmer amaranth density was reduced by 30% to 85% in plots with cereal rye cover crop compared to winter fallow, supporting previous findings that cereal rye can provide effective early-season suppression of Palmer amaranth (Hodgekiss et al. 2021; Nunes et al. 2023; Price et al. 2016; Wells et al. 2013; Vollmer et al. 2020). The high level of suppression observed in this study is likely due to high cereal rye biomass accumulation. Wells et al. (2013) reported approximately 75% Palmer amaranth control with only about 4,500 kg ha^{-1} of cereal rye biomass. In this study, cereal rye biomass production exceeded that threshold regardless of termination timing (Figure 1). However, no significant difference in Palmer amaranth density was observed between standing and rolled cereal rye residue, indicating that weed suppression was not solely due to physical mulch cover, but may also involve altered light conditions and microenvironmental factors from standing cereal rye residue (Menalled et al. 2022; Silva and Baumann 2023).

Late cereal rye termination, whether rolled or left standing, resulted in greater reductions in Palmer amaranth density compared to early termination (Table 4). Early cereal rye termination (28 DBP), whether rolled or standing, reduced Palmer amaranth density by 36–48% without PRE herbicides. In contrast, late termination reduced Palmer amaranth density by 64–70% without PRE herbicides relative to the winter fallow control at 28 days after PRE application. The greater suppression of Palmer amaranth with late cereal rye termination is attributed to greater biomass

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accumulation at the later termination timing (Figure 1), which was more resistant to decomposition and likely created a more effective long lasting physical barrier that inhibited germination, emergence, and establishment of Palmer amaranth. This result is consistent with previous research in other cropping systems. For instance, Hodgskiss et al. (2021) reported that cereal rye terminated at or after soybean planting accumulated 40% more biomass and enhanced suppression of waterhemp [*Amaranthus tuberculatus* (Moq.)], compared to cereal rye terminated before planting. Similarly, Vollmer et al. (2020) found that cereal rye terminated 10 days prior to soybean planting improved Palmer amaranth control by 6% compared to termination 20 days prior to planting.

Palmer amaranth density under late cereal rye termination without PRE herbicide application (11 plants m^{-2}) was comparable to that observed in winter fallow plots treated with PRE herbicides (13 plants m^{-2}; Table 4). Hence, in addition to a greater Palmer amaranth suppression compared with early termination, late termination of cereal rye was as effective as PRE application of fluridone or flumioxazin in suppressing Palmer amaranth in this study. Nunes et al. (2023) similarly observed that cereal rye cover provided effective early-season suppression of *Amaranthus* spp. similar to flumioxazin and pyroxasulfone in soybean. Likewise, Cornelius and Bradley (2017) reported that cereal rye residue provided a similar level of waterhemp suppression compared to PRE application of sulfentrazone. Therefore, our results support previous research demonstrating the effectiveness of cereal rye residue in managing Palmer amaranth. However, weed suppression by cereal rye is closely linked to biomass accumulation and ground cover, both of which are highly variable and influenced by climatic conditions and management practices (Silva and Bagavathiannan 2022). Under low biomass production conditions (e.g., 2,500 kg ha^{-1}), cereal rye has been shown to provide insufficient suppression of Palmer amaranth in peanut systems (Dobrow et al. 2011). Furthermore, not all weed species respond uniformly to cereal rye-based suppression (Lowry and Brainard 2019; Teasdale et al. 1991). Therefore, cereal rye should be viewed as a component of an integrated weed management approach rather than a stand-alone alternative to PRE herbicides for early-season weed suppression.

Differences in sicklepod density between cereal rye termination timings (early vs. late) were observed only in the absence of PRE herbicide application (Table 4). Without PRE herbicides, sicklepod density was 47% to 50% lower in the late termination treatments, whether

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cereal rye was rolled or left standing, compared to winter fallow. Sicklepod density did not differ between early cereal rye termination treatments (rolled or left standing) and the winter-fallow control in the absence of PRE herbicides. Only when cereal rye termination was delayed until 14 DPP did biomass accumulation become sufficient to reduce sicklepod density compared to the winter fallow control without PRE herbicides. The lack of suppression with early termination may be attributed to the ability of large-seeded weed species such as sicklepod to emerge through mulch layers, as well as their reduced light requirement for germination (Mirsky et al. 2011; Pittman et al. 2020). Previous studies have shown that the need for light to trigger germination decreases as seed mass increases (Milberg et al. 2000), which may explain the minimal impact of cereal rye residue on sicklepod. Our findings are consistent with previous research indicating that large-seeded weeds are generally less affected by cover crop residue (Pittman et al. 2019; Vollmer et al. 2020).

No significant differences in sicklepod density were observed among cereal rye termination treatments and winter fallow when PRE herbicides, either fluridone or flumioxazin were applied. This suggest that cereal rye residue presence did not compromise early-season residual control of sicklepod. Although cover crop mulch has the potential to intercept herbicide sprays, this effect appeared negligible in this study, likely due to sufficient rainfall following herbicide application. Rainfall of at least 9 mm occurred within 1 to 4 d after PRE treatment in both years, which may have facilitated herbicide activation and movement into the soil. This suggests that, under adequate post-application rainfall conditions, PRE herbicides applied in the presence of cereal rye residue can remain effective in reducing weed density. Nunes et al. (2023) similarly reported that the presence of cereal rye residue did not impact the early-season efficacy of flumioxazin or pyroxasulfone in soybeans, even though the concentrations of herbicides were reduced in the soil. Haramoto and Pearce (2019) also found that the effectiveness of sulfentrazone plus carfentrazone-ethyl, was not negatively affected by the presence of cover crop residues.

Mid-season weed density

As with early-season weed control, year-by-treatment interactions were not significant ($P = 0.3$) for mid-season assessments; therefore, data were pooled across both years. A significant interaction ($P < 0.001$) between cereal rye termination management and herbicide program was

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observed for mid-season weed density (Table 5). In the absence of cereal rye residue, the combination of PRE and EPOST herbicides reduced Palmer amaranth and sicklepod densities by 75% and 70%, respectively, compared to the EPOST-only program. However, when cereal rye residue was present, no significant differences in weed density were detected among herbicide programs, regardless of termination management. These results suggest that in systems utilizing a cereal rye cover crop, a more intensive herbicide program may not be necessary to achieve effective mid-season suppression of Palmer amaranth and sicklepod. The cereal rye mulch appeared to provide suppression comparable to that of PRE herbicides prior to EPOST application, highlighting the additive benefit of cereal rye cover crop in integrated weed management system. These results further support the potential of cereal rye cover crop to complement, or in some cases replace the weed suppression achieved with PRE herbicides, depending on weed seedbank density.

The PRE-only herbicide program resulted in 4 to 7 more Palmer amaranth plants m^{-2} and 4 to 10 more sicklepod plants m^{-2} compared to the PRE plus EPOST treatment, across cereal rye termination management treatments. These results indicate that cereal rye residue alone is insufficient to eliminate the need for EPOST herbicides to achieve optimal weed suppression. While cereal rye residue can provide effective early-season control, its gradual degradation allows later-emerging weed cohorts to establish (Mirsky et al. 2011). This finding is consistent with previous studies demonstrating that cereal rye residue alone rarely provides season-long weed suppression (Osipitan et al. 2018; Schramski et al. 2021), highlighting the importance of timely EPOST herbicide applications. In cereal rye-based systems, the use of EPOST-only herbicides alone reduced sicklepod density by 57% to 71% compared to cereal rye systems treated only with PRE herbicides. Under late cereal rye termination conditions, rolled cereal rye reduced sicklepod density by 43% more than standing rye when only PRE herbicides were used, likely due to reduction in light and physical barrier.

Late-season weed density and biomass

Interactions between year and treatments were not significant for late-season Palmer amaranth and sicklepod densities or biomass ($P > 0.05$); therefore, data were pooled across years. No significant interaction was observed between cereal rye termination management and herbicide program for either species ($P > 0.05$). At 28 d after MPOST herbicide application, the

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presence of cereal rye residue did not significantly affect sicklepod density (P = 0.1), regardless of termination management (Table 6). In contrast, Palmer amaranth density was 40% to 53% lower in treatments that included cereal rye compared to the winter fallow control. The lack of cereal rye residue effect on late-season sicklepod density may be attributed to the progressive decomposition of cereal rye mulch over the season and the ability of sicklepod to emerge through decomposing residue. Unlike Palmer amaranth, large-seeded weed species such as sicklepod (seed weight: 23–28 mg) possess sufficient seed reserves to produce elongated shoots capable of penetrating dense mulch layers (Clay and Griffin 2000; Leishman and Westoby 1994). Despite differences in density responses, both Palmer amaranth and sicklepod exhibited significantly reduced biomass in cereal rye treatments compared with the winter fallow control (Table 6). Across herbicide programs, treatments that included cereal rye reduced late-season Palmer amaranth biomass by 63–67% and sicklepod biomass by 63–65% compared with programs without rye. These results align with those of Pittman et al. (2019), who reported that cereal rye cover crop with 7,671 kg ha^{-1} of biomass reduced horseweed [*Conyza canadensis* (L.) Cronquist] biomass by 50% at soybean harvest. However, they contrast with findings by Price et al. (2007), where cereal rye biomass of 6,550 kg ha^{-1} did not persist long enough to significantly reduce weed biomass later in the season in a high-residue conservation-tillage peanut production system.

At 28 days after MPOST herbicide application, Palmer amaranth and sicklepod densities and biomass did not differ between the PRE + EPOST + MPOST program and the EPOST + MPOST program (Table 1). Both of these herbicide programs provided at least 43% and 44% greater reductions in Palmer amaranth and sicklepod densities, respectively, compared to the PRE (flumioxazin) + MPOST (acifluorfen + dimethenamid-*P* + 2,4-DB) program. Similarly, the PRE + EPOST + MPOST and EPOST + MPOST programs reduced Palmer amaranth and sicklepod biomass by at least 36% and 15%, respectively, relative to the PRE + MPOST program (Table 6). These results indicate that residual herbicides alone are insufficient to maximize control of Palmer amaranth and sicklepod in peanut systems. Due to the rapid growth and prolonged emergence periods of these weed species, timely EPOST applications are critical to target small, susceptible weed cohorts, regardless of the presence of a cereal rye cover crop.

Peanut yield

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Peanut yield was significantly affected by cereal rye termination management (P = 0.03), herbicide program (P = 0.01), and their interaction (P < 0.001). In the absence of herbicide application, standing cereal rye residue reduced yield by 14% to 17% compared to the winter fallow control, regardless of termination timing. In contrast, rolled cereal rye residue increased yield by 15% to 23% relative to the untreated winter fallow control (Table 7). These yield gains are likely attributable to reductions in weed density and biomass, along with the well-documented agronomic benefits of rolled cereal rye residue, such as improved water infiltration, decreased soil moisture loss through evaporation, and enhanced soil quality (Scavo et al. 2020; Silva and Bagavathiannan 2022). Across all termination timings and herbicide programs, there was a consistent trend of reduced yield in the standing cereal rye residue treatments. Standing cereal rye residue decreased yield by 8% to 33% relative to rolled cereal rye and winter fallow control, for both early and late termination timings. The reduced yield observed in the standing cereal rye treatments may be attributed to increased peanut plant height (data not shown) or etiolation, potentially induced by shading from the standing cereal rye residue. This response could have led to reduced flower retention and lower belowground resource acquisition (Barbour et al. 1994). Similar findings have been reported previously, where shading-induced etiolation in peanut reduced light-use efficiency, pod formation, and yield (Adjhahossou et al. 2008; Stirling et al. 1990).

Regardless of cereal rye residue management (rolled or standing), peanut yield did not differ between early and late cereal rye termination timing when an intensive herbicide program (PRE + EPOST + MPOST) was used. However, under reduced herbicide input (either PRE + MPOST or EPOST + MPOST), late-terminated cereal rye residue resulted in 9% to 27% higher peanut yields than early termination (Table 7). Notably, when cereal rye was terminated late and rolled flat, yield under the reduced herbicide program (EPOST + MPOST; 4,373 kg ha^{-1}) was comparable to the highest-yielding treatments that included intensive herbicide input with rolled cereal rye residue or winter fallow control (4,225 to 4,406 kg ha^{-1}). These results suggest that late-terminated, rolled cereal rye can supplement weed management and reduce reliance on PRE herbicides in peanut production without compromising yield. Nonetheless, PRE herbicides remain essential for consistent *Amaranthus* management, particularly given the limited and resistance-prone POST options available in peanut production. The observed yield improvements are likely due to the synergistic effects of greater cereal rye biomass at late termination and

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timely application of EPOST and MPOST herbicides, which provided weed control levels similar to those achieved with intensive herbicide programs. These findings are most relevant to peanut production in the southern U.S., where herbicide options are limited and longer seasons allow greater rye biomass accumulation. In contrast, cropping systems such as corn and soybean have broader herbicide options and, in cooler northern regions, less cover crop biomass.

Regardless of termination management, treatments receiving reduced herbicide input (PRE + MPOST) produced 8% to 42% lower peanut yields compared to the highest-yielding treatments that included intensive herbicide input. This underscores the critical role of EPOST herbicide applications in maximizing peanut yield, regardless of the presence of cereal rye cover crop. Since cereal rye residue did not persist throughout the season, treatments lacking EPOST had higher mid- and late-season weed densities and biomass, likely contributing to the observed yield losses. Although MPOST herbicide application improved late-season weed control, it is probable that crop suffered irrevocable yield losses due to weed competition during the critical weed-free period of 3 to 8 weeks after crop emergence.

Practical implications

This study affirms the value of cereal rye cover crops for early-season weed suppression in peanut production systems. The results suggest that rolled cereal rye with sufficient biomass accumulation can help reduce reliance herbicides without compromising peanut yield. However, the effectiveness of cereal rye residue for weed suppression is species-specific: while early cereal rye termination at 14 DPP suppressed Palmer amaranth, it did not adequately suppress sicklepod. Based on the rapid growth and extended emergence window of sicklepod, late termination of cereal rye is necessary to ensure adequate biomass for effective early-season suppression in the absence of PRE herbicides. However, cereal rye cover crop should not be considered a stand-alone replacement for PRE herbicides but rather a complementary tool within an integrated weed management strategy.

Beyond weed suppression, high-biomass cereal rye residue also has implications for peanut establishment and harvest. Standing residue reduced yields, likely due to interference with seedling emergence and early growth, whereas rolling the biomass at termination improved establishment and yield outcomes. Importantly, when managed properly, rolled rye residue did not interfere with digging or inversion at harvest, indicating compatibility with conventional peanut harvesting practices. When cereal rye was terminated late and rolled flat, a reduced-input

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herbicide program (EPOST + MPOST) resulted in yields comparable to those achieved with intensive herbicide programs (PRE + EPOST + MPOST) in the absence of cereal rye residue. This indicates potential to reduce herbicide inputs when cereal rye cover crops are properly managed. However, effective mid- and late-season weed control and consequently high yields could not be achieved without EPOST applications, regardless of cereal rye presence. The rapid growth and season-long emergence of Palmer amaranth and sicklepod underscore the critical role of timely EPOST herbicide programs. In conclusion, cereal rye cover crops can effectively complement or partially substitute PRE herbicides depending on weed seedbank density, but they do not eliminate the need for EPOST applications. Based on our results, we recommend terminating cereal rye cover crop 14 DPP and rolling the residue to optimize weed suppression and peanut yield. Timely EPOST applications should remain a priority in any herbicide program, with or without a cereal rye cover crop.

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Competing Interest

No competing interests have been declared.

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Table 1. Herbicide program evaluated on the effects of cereal rye termination timing, residue management and herbicide programs on weed control in no-till peanut at Jay FL, from 2022 to 2024.

	Application timing		
Herbicide program	Preemergence	Early postemergence	Mid-postemergence
Intensive herbicide program	Fluridone[a]	Paraquat[b] + *S*-metolachlor[c] + bentazon[d]	Imazapic[e] + dimethenamid-*P*[f] + 2,4-DB[g]
Reduced herbicide program 1	Non	Imazapic + dimethenamid-*P* + 2,4-DB	Premix bentazon-acifluorfen[h] + *S*-metolachlor + 2,4-DB
Reduced herbicide program 2	Flumioxazin[i]	Non	Acifluorfen + dimethenamid-*P* + 2,4-DB

[a]Brake®; SePRO, Carmel, IN (0.16 kg ai ha^{-1})

[b]Gramoxone® SL 3.0; Syngenta Crop Protection, LLC, Greensboro, NC (0.25 kg ai ha^{-1})

[c]Dual Magnum®; Syngenta, Crop Protection, LLC, Greensboro (1.33 kg ai ha^{-1})

[d]Basagran®; Winfield Solutions, Research Triangle Park, NC (0.33 kg ai ha^{-1})

[e]Cadre®; BASF, Corporation, Durham, NC (0.07 kg ai ha^{-1})

[f]Outlook®; BASF, Corporation, Durham, NC (0.02 kg ai ha^{-1})

[g]Butyric 200®; Winfield Solutions, Research Triangle Park, NC (0.25 kg ai ha^{-1})

[h]Storm®; United Phosphorus Inc., King of Prussia, PA (0.25 kg ai ha^{-1})

[i]Valor® SX; Valent U.S.A. Corporation, Walnut Creek, CA (0.06 kg ai ha^{-1})

[j]Ultra Blazer®; United Phosphorus Inc., King of Prussia, PA (0.25 kg ai ha^{-1})

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Table 2. Dates of field activities and treatments in study evaluating the effects of cereal rye termination timing, residue management and herbicide programs on weed control in no-till peanut at Jay FL, from 2022 to 2024.

Field activities	2022-2023	2023-2024
Cereal rye cover crop planting	Nov 17, 2022	Nov 12, 2023
Early termination of cereal rye	April 13, 2023	April 3, 2024
Late termination of cereal rye	May 1, 2023	April 18, 2024
Peanut planting	May 15, 2023	May 1, 2024
Preemergence herbicide application	May 16, 2023	May 2, 2024
Early-season weed/peanut data collection	June 13, 2023	May 30, 2024
Early postemergence herbicide application	June 14, 2023	May 31, 2024
Mid-season weed/peanut data collection	July 12, 2023	June 28, 2024
Mid-postemergence herbicide application	July 23, 2023	July 10, 2024
Late-season weed/peanut data collection	Aug 20, 2023	Aug 7, 2024
Peanut harvesting	Oct 18, 2023	Oct 22, 2024

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Table 3: Weather conditions at West Florida Research and Education Center, Jay FL, during the experiment period in 2022-2024[a]

	Precipitation			Average air temperature			Average soil temperature (5-cm depth)			Growing degree day (GDD)[b]		
	2022/ 2023	2023/ 2024	16 yr avg.	2022/ 2023	2023/ 2024	16 yr avg.	2022/ 2023	2023/ 2024	16 yr avg.	2022/ 2023	2023/ 2024	16 yr avg.
	———mm———			———C———			———C———					
Nov	75	104	81	17	15	13	16	14	14	358	306	405
Dec	121	130	164	14	11	12	12	12	13	254	215	385
Jan	184	167	119	14	10	9	14	9	12	289	165	328
Feb	259	202	115	16	13	12	16	17	18	340	256	460
Mar	135	150	99	18	17	15	17	15	19	412	387	459
April	126	105	132	19	20	19	20	18	21	460	468	562
May	108	241	135	23	23	23	23	19	23	597	522	755
Jun	343	165	202	25	27	26	26	28	27	599	598	551
Jul	84	102	212	27	28	27	27	29	28	611	675	636
Aug	42	51	149	28	28	27	29	39	29	621	731	691
Sep	149	175	125	24	26	24	25	28	25	632	728	672
Oct	30	38	122	19	21	21	19	23	18	584	642	585

[a]Weather data from 2007 to 2023 at West Florida Research and Education Center, Jay FL recorded from the Florida Automatic Weather Network. [b]GDD, growing degree days, base 4.4 C (Mirsky et al. 2011) calculated from seeding to termination date.

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Table 4. Effect of cereal rye termination management and herbicide program interaction on weed density at 28 d after preemergence herbicide application, averaged over 2 years in field experiments conducted near Jay Fl, in 2023 and 2024.

Cereal rye termination (residue management)	Herbicide programs	Palmer amaranth		Sicklepod	
		Plants m^{-2}			
Early-terminated, rolled cereal rye	Floridone	7 (4.4)	f	11 (3.3)	c
	Flumioxazin	7 (3.9)	f	13 (2.2)	bc
	Nontreated	17 (7.8)	bc	30 (3.8)	a
Early-terminated, standing cereal rye	Floridone	7 (5.6)	f	12 (4.0)	bc
	Flumioxazin	9 (4.8)	ef	12 (3.3)	bc
	Nontreated	21 (5.9)	b	28 (4.9)	a
Late-terminated, rolled cereal rye	Floridone	3 (4.8)	g	12 (3.7)	bc
	Flumioxazin	2 (3.3)	g	8 (4.8)	c
	Nontreated	12 (2.9)	de	16 (3.9)	bc
Late-terminated, standing cereal rye	Floridone	3 (6.0)	g	13 (2.2)	bc
	Flumioxazin	2 (6.0)	g	10 (3.8)	c
	Nontreated	10 (4.8)	def	17 (5.8)	b
Winter fallow control	Floridone	14 (3.3)	cd	10 (4.9)	c
	Flumioxazin	14 (8.9)	cd	9 (2.1)	c
	Nontreated	33 (8.6)	a	32 (3.3)	a
P value		$P < 0.001$		$P < 0.001$	

[a]Means within a column followed by a different letter are significantly different at $\alpha \leq 0.05$. Standard errors are presented in parentheses

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Table 5. Effect of cereal rye termination management and herbicide program interaction on mid-season weed density at 28 d after early postemergence herbicide application, averaged over 2 years in field experiments conducted near Jay Fl, in 2023 and 2024.

Cereal rye termination (residue management)	Herbicide programs	Palmer amaranth		Sicklepod	
		plants m^{-2}			
Early-terminated, rolled cereal rye	PRE plus EPOST	2 (0.3)	e	7 (2.2)	e
	PRE-only	7 (2.2)	cd	14 (4.3)	cd
	EPOST-only	4 (1.2)	de	6 (2.1)	e
	Nontreated	17 (2.9)	b	22 (3.8)	b
Early-terminated, standing cereal rye	PRE plus EPOST	2 (0.3)	e	8 (1.8)	e
	PRE-only	9 (2.2)	c	14 (3.3)	cd
	EPOST-only	3 (0.2)	e	7 (2.9)	e
	Nontreated	21 (3.3)	b	21 (2.8)	b
Late-terminated, rolled cereal rye	PRE plus EPOST	1 (0.1)	e	4 (0.7)	e
	PRE-only	5 (1.1)	cde	11 (2.2)	d
	EPOST-only	4 (1.0)	de	4 (0.8)	e
	Nontreated	18 (4.4)	b	24 (2.1)	b
Late-terminated, standing cereal rye	PRE plus EPOST	1 (0.1)	e	5 (2.2)	e
	PRE-only	5 (1.8)	cde	14 (4.8)	b
	EPOST-only	4 (0.9)	de	4 (0.2)	e
	Nontreated	19 (2.1)	b	23 (2.8)	b
Winter fallow control	PRE plus EPOST	5 (1.1)	cde	7 (3.1)	e

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	PRE-only	9 (1.8)	c	17 (7.9)	cd
	EPOST-only	20 (2.9)	b	23 (6.8)	b
	Nontreated	39 (4.9)	a	37 (4.4)	a
P-value		P < 0.001		P < 0.001	

[a]Means within a column followed by a different letter are significantly different at $\alpha \leq 0.05$. Standard errors are presented in parentheses [b]PRE plus EPOST- preemergence application of fluridone followed by early postemergence application of paraquat plus *S*-metolachlor plus bentazon at 30 d after planting [c]PRE-only- preemergence application of flumioxazin

[d]EPOST- early postemergence application of imazapic plus dimethenamid-P plus 2,4-DB at 30 d after planting

Table 6. Effect of cereal rye termination management and herbicide programs on late-season weed density and biomass in peanut at 28 d after mid-postemergence herbicide application[a], averaged over 2 years in field experiments conducted near Jay Fl, in 2023 and 2024.

Cereal rye termination (residue management)	Weed density				Weed biomass			
	Palmer amaranth		Sicklepod		Palmer amaranth		Sicklepod	
	Plants m^{-2}				g m^{-2}			
Early-terminated, rolled cereal rye	7 (3.5)	b	12 (3.4)		77 (5.6)	b	48 (1.7)	b
Early-terminated, standing cereal rye	9 (2.0)	b	13 (2.3)		72 (6.7)	b	48 (1.9)	b
Late-terminated, rolled cereal rye	7 (2.8)	b	11 (2.0)		69 (10.4)	b	48 (2.6)	b
Late-terminated, standing cereal rye	7 (4.5)	b	12 (5.6)		77 (12.9)	b	53 (7.9)	b
Winter fallow control	15 (1.2)	a	19 (4.5)		207 (23.2)	a	200 (12.4)	a
P-value	0.002		0.1		P < 0.001		P < 0.001	
Herbicide program								
PRE plus EPOST plus MPOST[b]	2 (0.6)	c	7 (2.2)	c	36 (1.7)	c	46 (1.4)	c
PRE plus MPOST[c]	9 (0.7)	b	17 (2.4)	b	55 (3.7)	b	81 (4.9)	b
EPOST plus MPOST[d]	3 (1.0)	c	5 (3.3)	c	32 (3.6)	c	50 (2.3)	c
Nontreated	21 (1.7)	a	25 (3.7)	a	282 (19.3)	a	134 (12.3)	a
P-value	0.001		0.003		P < 0.001		P < 0.001	

[a]Means within a column followed by a different letter are significantly different at $\alpha \leq 0.05$. Standard errors are presented in parentheses [b]PRE plus EPOST plus MPOST- preemergence application of fluridone followed by early postemergence application of paraquat + *S*-metolachlor + bentazon at 30 d after planting followed by MPOST application of imazapic + dimethenamid-*P* + 2,4-DB at 60 d after planting. [c]PRE plus MPOST- preemergence application of flumioxazin followed by mid-postemergence application of Acifluorfen + dimethenamid-*P* + 2,4-DB at 60 d after planting. [d]EPOST- early postemergence application of imazapic + dimethenamid-P + 2,4-DB

Table 7. Effect of cereal rye termination management and herbicide programs interaction on peanut yield[a] in field experiments conducted near Jay Fl, in 2023 and 2024.

Cereal rye termination (residue management)	Herbicide programs	Yield (Kg ha^{-1})	
Early-terminated, rolled cereal rye	PRE plus EPOST plus MPOST[b]	4,316 (28.0)	a
	PRE plus MPOST[c]	3,426 (56.2)	c
	EPOST plus MPOST[d]	3,804 (73.2)	b
	Nontreated	2,974 (58.4)	e
Early-terminated, standing cereal rye	PRE plus EPOST plus MPOST	3,900 (65.5)	b
	PRE plus MPOST	2,561 (43.7)	f
	EPOST plus MPOST	3,210 (196.3)	cd
	Nontreated	2,058 (354.0)	h
Late-terminated, rolled cereal rye	PRE plus EPOST plus MPOST	4,225 (131.7)	a
	PRE plus MPOST	3,880 (91.0)	b
	EPOST plus MPOST	4,373 (56.7)	a
	Nontreated	3,027 (91.0)	de
Late-terminated, standing cereal rye	PRE plus EPOST plus MPOST	3,877 (76.3)	b
	PRE plus MPOST	3,530 (65.3)	c
	EPOST plus MPOST	3,528 (67.9)	c
	Nontreated	2,139 (98.3)	h
Winter fallow control	PRE plus EPOST plus MPOST	4,406 (129.6)	a
	PRE plus MPOST	3,850 (87.4)	b
	EPOST plus MPOST	3,946 (68.7)	b

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	Nontreated	2,492 (98.3)	f
P-value		P < 0.001	

[a]Means within a column followed by a different letter are significantly different at α ≤ 0.05. Standard errors are presented in parentheses

[b]PRE plus EPOST plus MPOST- preemergence application of fluridone followed by early postemergence application of paraquat + *S*-metolachlor + bentazon at 30 d after planting followed by MPOST application of imazapic + dimethenamid-*P* + 2,4-DB at 60 d after planting. [c]PRE plus MPOST- preemergence application of flumioxazin followed by mid-postemergence application of Acifluorfen + dimethenamid-*P* + 2,4-DB at 60 d after planting. [d]EPOST- early postemergence application of imazapic + dimethenamid-P + 2,4-DB at 30 d after planting followed by mid-postemergence application of premix bentazon + acifluorfen + S-metolachlor + 2,4-DB at 60 d after planting.

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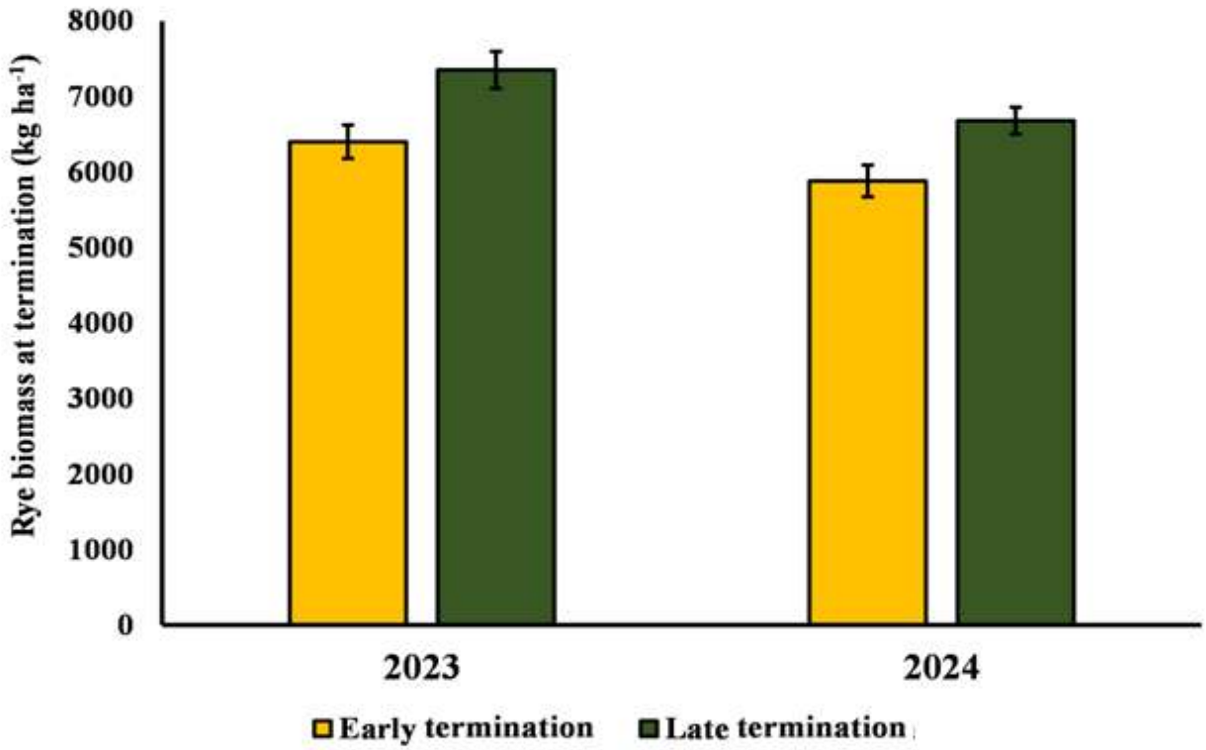

Figure 1. Effect of termination timing on cereal rye biomass production in field experiments conducted near Jay Fl, in 2023 and 2024.

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