

ORIGINAL ARTICLE

Crop Management

Crop rotation and herbicide program effects on Palmer amaranth and common ragweed population growth rate

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Abstract

The success of weed management decisions must be assessed not only in the short-term within season but also in the long-term over several seasons. This study investigated the effects of crop rotation and herbicide program structure on the population growth rates of Palmer amaranth (*Amaranthus palmeri* S. Watson) and common ragweed (*Ambrosia artemisiifolia* L.). A field experiment was conducted over a 3-year period in North Carolina to compare cotton (*Gossypium hirsutum* L.)–sweetpotato [*Ipomoea batatas* (L.) Lam.]–soybean [*Glycine max* (L.) Merr.], cotton–peanut (*Arachis hypogaea* L.)–soybean, cotton–tobacco (*Nicotiana tabacum* L.)–soybean, and cotton–soybean–soybean rotations and preemergence and postemergence herbicide application timings. Results showed that preemergence herbicide application in the soybean phase of the rotation reduced Palmer amaranth populations 79%. However, the preemergence herbicides were only effective at reducing weed populations for the current season, not beyond. Common ragweed population growth rate was highest after the first 2 years ($\lambda = 1.63$) of the cotton–tobacco–soybean rotation. Preemergence herbicides were effective in reducing common ragweed populations, particularly in rotations with cotton–sweetpotato and cotton–peanut. Soybean yields were similar across rotations ranging from 62 bu/ac to 68 bu/ac. Annual use of preemergence herbicides was essential to reduce Palmer amaranth populations. For common ragweed, the effectiveness of preemergence herbicides to mitigate population growth was reduced when poorly competitive crops were part of the rotation.

Plain Language Summary

The efficacy and durability of weed control programs must be assessed over several years. This includes detecting whether weed populations are increasing or decreasing. For most species, those trends are influenced by crop rotation and

Abbreviations: CPWC, critical period for weed control; IWM, integrated weed management.

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herbicide programs. The present study evaluated how rotations including cotton, peanut, sweetpotato, tobacco, and soybean combined with herbicide programs affect the growth of Palmer amaranth and common ragweed populations over 3 years. The results demonstrated that preemergence herbicides must be applied every year to ensure decreasing Palmer amaranth and common ragweed populations. Rotations including tobacco were the most likely to result in increased trends of the populations of both species. The cotton–sweetpotato–soybean rotation was the most effective to decrease weed populations consistently.

1 | INTRODUCTION

Integrated weed management (IWM) is a systems approach, which integrates different methods of weed control. If implemented systematically, the combination of methods results in more effective weed control than any of those methods alone (Swanton & Weise, 1991). This approach provides crops with a competitive advantage over weeds, helping to prevent yield losses (Swanton & Murphy, 1996). The use of these methods varies depending on the weed species, weather conditions, soil characteristics, crop management practices, financial limitations, and the expectations of growers of acceptable levels of variability of yields and financial returns (Gunsolus & Buhler, 1999). Among management decisions involved in IWM, crop rotation is one of the most important components (Doucet et al., 1999; Swanton & Weise, 1991). The effectiveness of incorporating rotation in an IWM program relies on generating diverse patterns of resource competition, herbicide programs, and mechanical damage. This creates an unstable and often hostile environment, ultimately diminishing the reproductive capacity of weeds (Gaba et al., 2014; MacLaren et al., 2021; Weisberger et al., 2019).

Another key component of effective IWM programs is the use of preemergence and postemergence herbicides (Swanton et al., 2008). The use of postemergence herbicides is crucial to prevent yield losses, when they are applied during the critical period for weed control (CPWC) (Knezevic et al., 2002). Control failures during this period will not only cause yield reductions but also will likely increase weed populations. Furthermore, postemergence herbicides applied after the CPWC are useful to reduce the reproduction of weeds escaping control. Usually, late emerging weeds produce less biomass and are less competitive than early emerging ones; thus, they represent a lower risk of yield loss (Hock et al., 2006; Puricelli et al., 2002). However, an effective long term weed management program must consider the seeds produced by weeds emerging late in the season (Bagavathiannan & Norsworthy, 2012; Walker & Oliver, 2008), which will contribute to maintaining or increasing weed populations (Grundy, 2003).

Preemergence herbicides are very important early in the season to prevent the establishment of weeds emerging with

the crop until the CPWC to avoid yield losses (Knezevic et al., 2002). Additionally, preemergence herbicides play a key role in reducing the number of seeds in the seedbank, as late emerging plants produce fewer seeds than early emerging plants (Oreja, Stempels, & de la Fuente, 2023; Puricelli et al., 2002). The application of a specific preemergence herbicide may affect the weed community composition by removing competitors and favoring not only the crop but also other weeds (Grundy et al., 2011).

Palmer amaranth (*Amaranthus palmeri* S. Watson) and common ragweed (*Ambrosia artemisiifolia* L.) are among the most common and troublesome weeds in dicotyledonous crops, such as cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], fruits, and vegetables in North Carolina (Van Wychen, 2022). Several biological and physiological characteristics make these species highly competitive weeds (Brandes & Nitzsche, 2006; Ward et al., 2013) including evolved herbicide resistance (Heap, 2024). They are among the most important causes of yield losses in several crops such as corn (*Zea mays* L.), cotton, peanut (*Arachis hypogaea* L.), sorghum [*Sorghum bicolor* (L.) Moench], and soybean (Clewis et al., 2001; Hall et al., 2021; Harrison et al., 2001; Ward et al., 2013).

Most studies evaluating the management of problematic weed species focus on immediate effects in a single season, measuring outcomes such as the reduction of plant numbers, biomass reductions, or crop yield losses. Nonetheless, IWM programs must include long-term goals focused on tracking changes in population density over time. Therefore, the objectives of this work were to determine the effects of crop rotation, preemergence, and postemergence herbicide sequences on the population growth rates of Palmer amaranth and common ragweed.

2 | MATERIALS AND METHODS

2.1 | Experimental site

During 2016, 2017, and 2018, two experiments were conducted in separate fields (Field 1 and Field 2) in North

Carolina at the Upper Coastal Plain Research Station near Rocky Mount (35.897° N, −77.675° W). The soil was an Aycok very fine sandy loam (fine silty, siliceous, subactive, thermic Typic Paleudult), and fields were naturally infested with Palmer amaranth and common ragweed. Cotton was planted in the first year with DP1646 (Monsanto Co.) on May 20, into conventional-tillage plots that were 12-rows (3-ft row spacing) wide and 50-ft long. Crop and pest management practices were based on North Carolina Cooperative Extension recommendations for cotton (Edmisten et al., 2018).

The experimental design was a randomized complete block with four replications arranged, as a split-plot within each field. However, fields were considered in the ANOVA model as fixed factor. For this reason, the data was first analyzed as a split-split-plot design using the following model:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + \beta\gamma_{jk} + \delta_l + \beta\delta_{jl} + \gamma\delta_{kl} + \beta\gamma\delta_{jkl} + \alpha\beta\gamma\delta_{ijkl} + \rho_{ijkl} + \epsilon_{ijkl}$$

where Y_{ijkl} is the response for each variable; μ is the overall mean; α_i is the i th response to the field effect; β_j is the j th response to the crop rotation effect; $\alpha\beta_{ij}$ is the main plot error for the field and crop rotation random interaction; γ_k is the k th response to preemergence herbicide application sequence; $\beta\gamma_{jk}$ is the interactive effect between crop rotation and preemergence herbicide sequence; δ_l is the l th response to postemergence herbicide application; $\beta\delta_{jl}$ is the interactive effect between crop rotation and postemergence herbicide application; $\gamma\delta_{kl}$ is the interactive effect between preemergence sequence and postemergence herbicide; $\beta\gamma\delta_{jkl}$ is the interactive effect between crop rotation, preemergence herbicide sequence, and postemergence herbicide application; $\alpha\beta\gamma\delta_{ijkl}$ is the subplot error for the field and herbicide treatment random interactions; $\alpha\beta\gamma\delta_{ijkl}$ is the interaction of field, crop rotation, and herbicide effects; ρ_{ijkl} is the random effect of block within field; and ϵ_{ijkl} is the residual error. If the analysis of this full model indicated that the $\beta\gamma\delta_{jkl}$, $\beta\gamma\delta_{jkl}$, and $\beta\gamma\delta_{jkl}$ were not significant ($p > 0.05$), the main effects and their interactions were removed from the full model. In those cases, the results are presented using the simplified ANOVA model.

Preemergence herbicide sequences were based on the year(s) in which they were implemented during the crop rotation. Because herbicides differed among the crops in rotation (Tables 1 and 2), the sequences were described considering whether preemergence herbicides were present (P) or absent (N) each year. Thus, the treatments were applications on year one only (PNN), two only (NPN), three only (NNP), one and two (PPN), one and three (PNP), two and three (NPP), all years (PPP), and a nontreated control (NNN). Postemergence herbicide treatments were with

TABLE 1 Crops, rotation year, and herbicide treatments.

Crop	Rotation year	Preemergence herbicides	Postemergence herbicides
Cotton	First	Acetochlor + fomesafen + diuron	Glufosinate
Tobacco	Second	Clomazone	Sulfentrazone
Sweetpotato		S-metholachlor	Flumioxazin
Peanut		S-metholachlor	Flumioxazin
Soybean		Fomesafen	Clethodim
Soybean	Third	Fomesafen	Clethodim

and without application of the corresponding herbicide program for each crop. Herbicide programs were designed to control Palmer amaranth and common ragweed populations resistant to glyphosate and acetolactate synthase-inhibiting herbicides. Preemergence herbicides were applied the same day of planting and postemergence applications were done 4 weeks after planting. Herbicides were applied using a CO₂-pressurized backpack sprayer equipped with flat-fan nozzles (AIXR 11002 TeeJet Air Induction XR flat-spray nozzles, TeeJet Technologies) spaced 18 inches and calibrated to deliver 15 gal per acre at 31 psi. Adequate rainfall for herbicide activation occurred within 10 days after preemergence application (from 0.83 inches to 2.15 inches). Plots planted with cotton in the first year were subsequently planted in early May with ‘Covington’ sweetpotato (Yencho et al., 2008), ‘Bailey’ peanut (Isleib et al., 2011), ‘NC 196’ tobacco (NCCIA, 2023), and ‘Credenz 7007LL’ soybean (BASF Corporation) in the second year, and all with soybean in the third year in early May. Crop and pest management practices were based on recommendations from the North Carolina Cooperative Extension (Brown et al., 2023; Drake-Stowe et al., 2022; Jordan et al., 2023).

2.2 | Data collection and analysis

Palmer amaranth and common ragweed seedling density were determined 3 weeks after planting and 1 week after postemergence herbicide application using a 1-ft by 1-ft frame thrown randomly three times within each plot. This sampling timing was chosen to ensure that quantification of weed population changes was done to capture weed pressure within the CPWC each year. Weed population growth rate, lambda (λ), was estimated as:

$$\lambda = \sqrt[n_{t+1}/n_t]{n_t} \quad (1)$$

Where t is the number of seasons, n_t is the number of emerged seedlings in the quadrats from the seedbank 3 weeks before planting, at the beginning of the experiment before the first-

TABLE 2 Herbicide active ingredient, trade name, formulation application rate, and manufacturer.

Herbicides	Trade name	Formulation concentration (lb ai/gal)	Rate (fl oz/acre)	Manufacturer
Acetochlor	Warrant	3	48	Monsanto Co. St. Louis, MO
Fomesafen	Reflex	2	24	Syngenta Crop Protection, LLC. Greensboro, NC
Glufosinate	Liberty 280SL	2.34	29	Bayer CropScience, LP, Research Triangle Park, NC
Diuron	Direx 4L	4	32	Makhteshim Agan North America, Inc. Raleigh, NC
Clomazone	Command	4	32	FMC Corporation, Mobile, Alabama
S-metholachlor	Dual Magnum	7.62	21	Syngenta Crop Protection, LLC. Greensboro, NC
Sulfentrazone	Spartan 4F	4	12	FMC Corporation, Mobile, Alabama
Flumioxazin	Valor SX	4	2	Valent U.S.A Corp., Memphis, Tennessee
Clethodim	Select 2EC	2	16	Valent U.S.A Corp., Memphis, Tennessee

year crop planting, and $n_{(t+1)}$ is the total number of seedlings emerged 1 week after the postemergence application. For Palmer amaranth, all 3 years of the rotation were considered ($t = 3$ years), but for common ragweed, only the first 2 years of the rotation were considered because in the last year of the rotation ($t = 2$ years), with soybean, no plants were detected in the four rotations. At the end of the rotation, soybean yield was quantified.

Data were analyzed with the statistical language R (Version 4.3.1). Lambda values for Palmer amaranth and common ragweed were analyzed using the aforementioned experimental design with repeated measures to account for the non-independence of observations within each experimental unit across time. Tukey's multiple comparison test was used to determine differences between treatments at the 1% significance level. When necessary, data were square-root transformed or, in the case of percentages, square-root-arcsine transformed (Bartlett, 1947) to meet ANOVA assumptions. In some cases where transformations were insufficient to achieve homogeneity of variance, data were analyzed using the generalized least squares (GLS) method, which corrects for heterogeneity of variances. Regarding the population growth rates of common ragweed, the rotation cotton–soybean, in which no weeds were present, was not included in the analysis.

3 | RESULTS

3.1 | Population growth rate of Palmer amaranth

The rate of change of Palmer amaranth populations did not differ among rotations ($p = 0.17$) or whether or not glufosinate was applied ($p = 0.17$). The population growth rate of Palmer amaranth was higher in Field 2 ($\lambda = 0.55$) than in Field 1 ($\lambda = 0.44$) ($p = 0.017$). Regarding the use of preemergence herbicides, all treatments that included a preemergence appli-

cation in the last year of the rotation (i.e., soybean) exhibited a lower population growth rate ($\lambda = 0.21$) than treatments without this application ($\lambda = 1.01$). This was observed regardless of whether preemergence herbicides were applied in one or two of the preceding years of the (Figure 1). This result must be interpreted carefully because it is likely that the dramatic reduction in λ was because of the preemergence treatment in the soybean phase when the last weed count was done. Therefore, the magnitude of the change in λ might be an over-estimation. Nonetheless, the fact that stopping preemergence herbicide use maintained population growth rates clearly indicated that this practice must be implemented every year to reduce the seed bank.

The application of preemergence herbicides resulted in a crucial tool to reduce population growth rates of Palmer amaranth compared with those treatments without application in the current season ($\lambda = 1.01$ vs $\lambda = 0.21$ on average). This could be due to its high fecundity allowing a few escaped individuals to replenish the seedbank. A single plant growing for the entire season can produce between 22,327 seeds when growing with corn, and 323,856 seeds when growing with cotton or peanut (Mahoney et al., 2023). In addition, in the region where the experiment was conducted, Palmer amaranth can emerge from the end of April until October (Reinhardt Piskackova et al., 2021). Thus, seedlings can emerge within the crop canopy, and if not controlled, they can produce seeds and replenish the seedbank. Lastly, after 36 months, Palmer amaranth seeds can still have 15% of viability when buried at 4 inches (Sosnoskie et al., 2013), which creates a seedbank that requires strategies to manage weeds across multiple years (Sebastian et al., 2017).

The presence of viable seeds in the seedbank from previous seasons, acting as a buffer to short term changes in response to recent control (Schwartz-Lazaro & Copes, 2019), could be the reason for the lack of differences among crop rotations in Palmer amaranth population growth rate. Depending on the seedbank density, a different crop in a 3-year rotation may

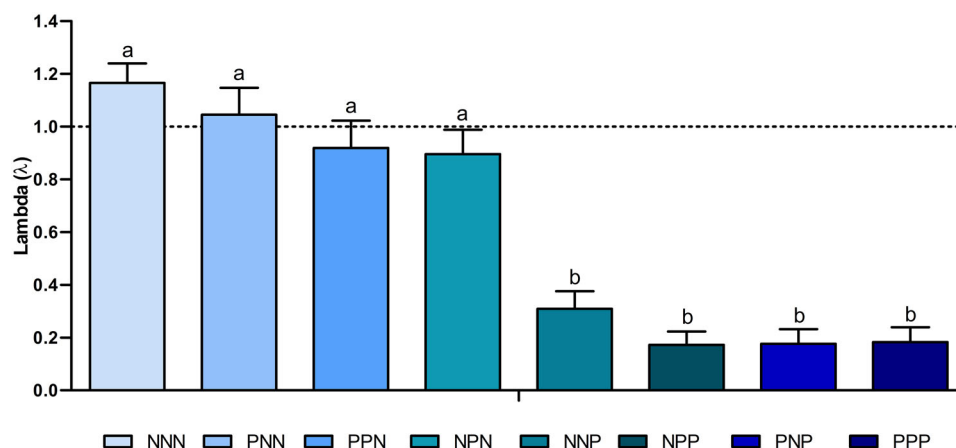


FIGURE 1 Palmer amaranth population growth rate (λ) between 2016 and 2018 for different combinations of preemergence herbicides applied only in the first year (PNN), in the second year (NPN), in the third year (NNP), in the first 2 years (PPN), in the last 2 years (NPP), in the 3 years (PPP) and a nontreated control (NNN). Means with the same letter, on each field, were not statistically different for each year, according to Tukey's HSD ($p = 0.05$). Errors bars represent standard error of the mean. Horizontal dashed line represents population stability ($\lambda = 1.0$).

not be enough to cause detectable changes in the population. On the other hand, the lack of response to glufosinate postemergence herbicides could be due to the short window of action to control this weed (Barnett et al., 2013; Reinhardt Piskackova et al., 2021). Usually, a single application of glufosinate is not enough to achieve a successful control on this species (Hoffner et al., 2012). Palmer amaranth surviving glufosinate will remain fecund and add a significant number of seeds to the seedbank (2400 to 22,000 seeds per plant; Jones et al., 2022).

3.2 | Population growth rate of common ragweed

No plants were observed in the cotton–soybean rotation treatments; therefore, common ragweed populations decreased at very high rates from the initiation to the end of the study. This result must be considered with caution because the lack of detection does not mean that the seedbank of this weed was depleted. It is likely that when the density of the populations reached very low levels, the sampling approach used was not sensitive enough to adequately detect and quantify population density.

Two different interactions were observed between rotation and field, and between rotation and preemergence herbicides; therefore, these interactions were analyzed separately. No differences ($p = 0.389$) were observed between treatments with ($\lambda = 0.78$) or without ($\lambda = 0.74$) postemergence herbicide application. Regarding the interaction between rotation and field, no differences were observed among rotations in Field 1. Conversely, in Field 2, the rotation cotton–tobacco–soybean had the highest population growth rate ($\lambda = 2.3$), which means that common ragweed population will double every rotation

cycle. The rotation cotton–peanut–soybean ($\lambda = 1.1$) resulted in a stable population indicating that the management was sufficient to prevent density increase but not strong enough to decrease the common ragweed seedbank. However, the rotation cotton–sweetpotato–soybean ($\lambda = 0.5$) halved population density every rotation cycle (Figure 2).

In the rotation cotton–peanut–soybean, a positive population growth rate ($\lambda = 1.57$) was observed when preemergence herbicides were not applied during the peanut phase. However, when preemergence herbicides were applied, common ragweed populations decreased rapidly ($\lambda = 0.15$) (Figure 3). In the rotation cotton–sweetpotato–soybean, a higher population growth rate ($\lambda = 1.03$) was observed in the treatment without the application of preemergence herbicides during the 2 years of the rotation compared with treatments where preemergence herbicides were applied ($\lambda = 0.40$). Finally, for the cotton–tobacco–soybean rotation, no differences among treatments were observed (Figure 3).

Despite common ragweed being very competitive in soybean, causing significant yield losses (Cowbrough et al., 2003), low weed density values and a delayed emergence of the weed compared to the crop may reduce the weed's competition ability and seed production. According to Simard and Benoit (2012), plants emerging later than soybean and growing with the crop produced 90% fewer seeds than those growing on bare soil.

Tobacco was the least competitive crop to include in a 3-year rotation with cotton and soybean (Figure 3). Despite the lack of differences in Field 1, the crop had the highest common ragweed population rates in both fields, and in all cases populations will increase approximately 50% to 100% per rotation. Tobacco is not a good weed suppressor due to its wide row spacing. The limited canopy closure throughout the

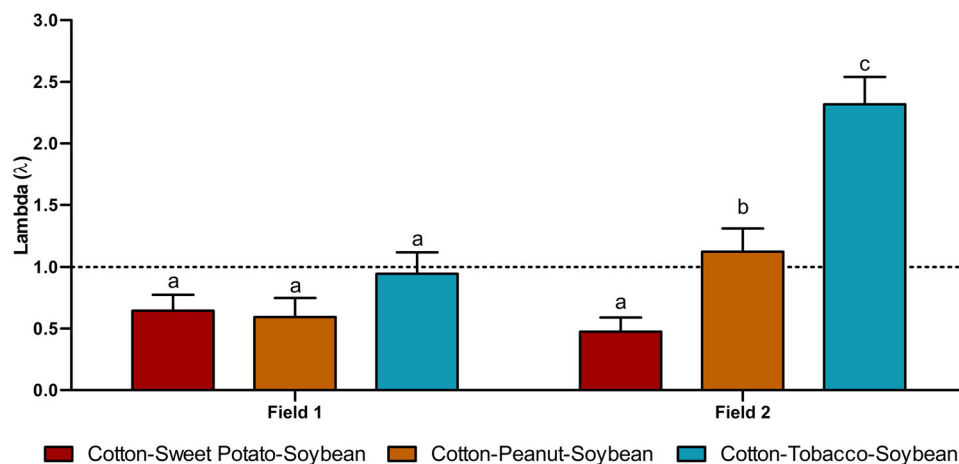


FIGURE 2 Common ragweed population growth rate (λ) in Field 1 and Field 2 between 2016 and 2017 for different rotations cotton-peanut-soybean, cotton-sweetpotato-soybean and cotton-tobacco-soybean. Means with the same letter within field, were not statistically different according to Tukey's HSD ($p = 0.05$). Errors bars represent standard error of the mean. Horizontal dashed line represents population stability ($\lambda = 1$).

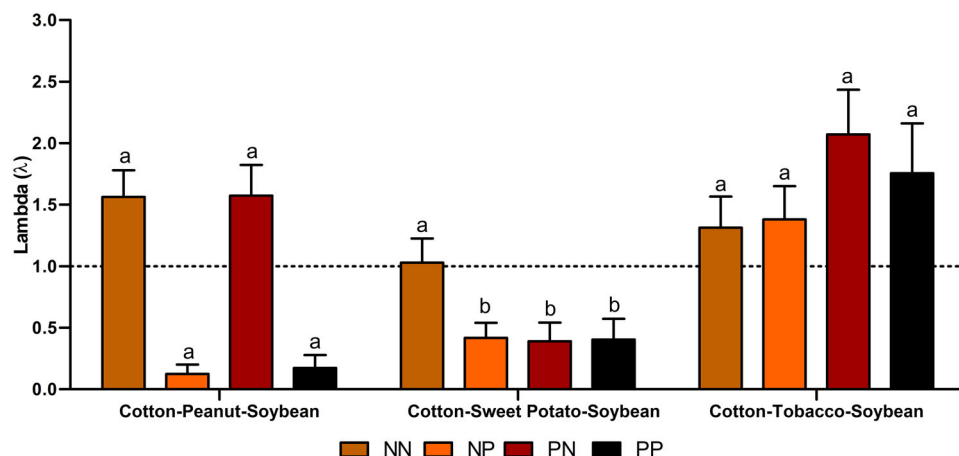


FIGURE 3 Common ragweed population growth rate (λ) between 2016 and 2017 for different combinations of rotations cotton-peanut-soybean, cotton-sweetpotato-soybean and cotton-tobacco-soybean and preemergence herbicides applied only in the first year (PN), in the second year (NP), both years (PP) and never (NN). Means with the same letter, on each rotation, were not statistically different according to Tukey's HSD ($p = 0.05$). Errors bars represent standard error of the mean. Horizontal dashed line represents population stability ($\lambda = 1$).

growing season makes this crop highly dependent on the use of herbicides for effective control, especially between 4 and 9 weeks after planting at the topping stage (Ian et al., 2013). It seems that the use of preemergence herbicides, even in the last season, was not enough to reduce the population growth rate of common ragweed in the rotation with tobacco.

In the rotations containing peanut and sweetpotato, the use of preemergence herbicides reduced common ragweed population growth, highlighting the benefits of combining the use of crops with full canopy closure and herbicide-based control. However, unlike sweetpotato, the population growth rate in peanut in Field 2 was increasing. Peanut weed suppressive ability is lower than other crops, such as corn, soybean, and

cotton (Leon et al., 2016; Oreja, Hare, et al., 2023). Compared to crops such as corn and soybean, peanut has a more prostrate growth and a relatively slower growth rate, thus taking longer to achieve full canopy closure (Mahoney et al., 2021; Misbahulmunir et al., 1989). These traits make this crop a poorer competitor with species such as common ragweed and Palmer amaranth.

The different responses between Fields 1 and 2 could be attributed to variations in the initial seedbank sizes or distinct rotation histories that may have influenced the results. A larger seedbank in Field 2, or a different history of rotations less effective at suppressing common ragweed, might explain the higher population growth rates observed. These factors

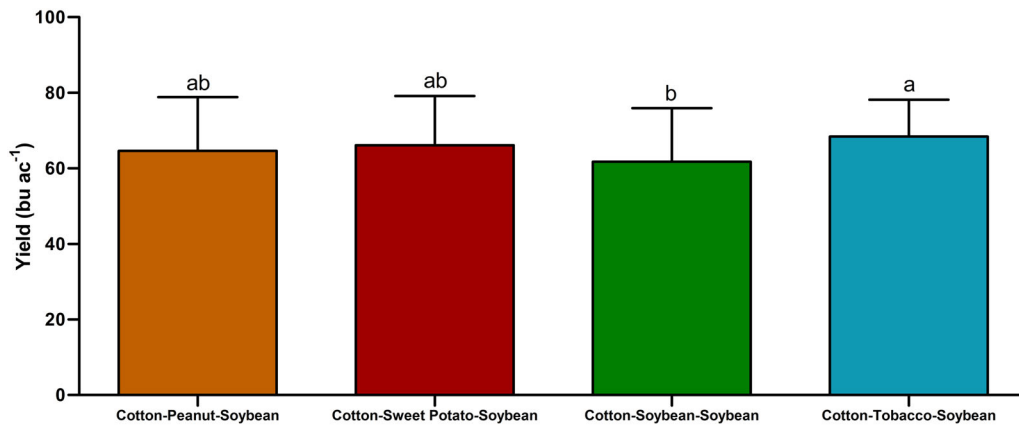


FIGURE 4 Soybean yield in the last year of the rotation, for different rotations cotton–peanut–soybean, cotton–sweetpotato–soybean, cotton–soybean–soybean and cotton–tobacco–soybean. Means with the same letter, on each field, were not statistically different according to Tukey’s HSD ($p = 0.05$). Errors bars represent standard error of the mean.

likely contributed to the increased resilience and reproduction of the weed in Field 2 compared to Field 1.

3.3 | Soybean yield in the last year of the rotation

Regarding soybean yield the last year of the rotation, there were differences between fields ($p < 0.001$), postemergence herbicide applications ($p = 0.036$), and rotations ($p < 0.001$). However, no effects were observed for preemergence herbicides ($p = 0.78$). Furthermore, none of interactions were significant ($p = 0.18$ – 0.92). Soybean yield was higher in Field 1 (71 bu/ac) than in Field 2 (60 bu/ac). The application of a postemergence herbicide in the soybean phase increased yield by 3 bu/ac compared with the treatment without this application (61.3 bu/ac vs 58.2 bu/ac, respectively). Lastly, when averaged across fields, the only difference in soybean yield among rotations was between cotton–tobacco–soybean (68 bu/ac) and cotton–soybean–soybean (62 bu/ac) (Figure 4). It is interesting that weed population growth rates varied in response to the different factors evaluated, but soybean yield did not follow the same pattern. There are several possible potential explanations. First, the efficacy of the weed control in the soybean phase was very high and masked the changes in weed density. This is unlikely because there were no differences between treatments with and without preemergence herbicide applications in the soybean phase. Another alternative is that legacy effect of weed control in the previous two crops resulted in seedbanks that were at densities with limited effect on yield when escapes occurred. A third explanation is that based on the original seedbank density, more than a single rotation cycle is needed to allow population growth rates to change weed pressure to levels that would more clearly impact soybean yield.

3.4 | Practical implications

An integrated weed management program focused on reducing the populations of Palmer amaranth and common ragweed weeds in the long-term must consider the adoption of crop rotation along with herbicide use. The use of preemergence herbicides annually was a critical practice to ensure the constant and progressive decrease of Palmer amaranth populations. Regarding common ragweed, special attention must be paid to rotations including tobacco because this crop allows increases in the populations of this weed to levels that may nullify gains in control in previous crops. Sweetpotato and peanut are good crops to be included in the rotation to reduce weed pressure, but they must be accompanied by preemergence herbicides to avoid population increases.

AUTHOR CONTRIBUTIONS

Fernando H. Oreja: Data curation; formal analysis; visualization; writing—original draft. **Denis J. Mahoney:** Data curation; investigation; writing—review and editing. **David L. Jordan:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; writing—review and editing. **Katie M. Jennings:** Investigation; resources; writing—review and editing. **Matthew Vann:** Investigation; resources; writing—review and editing. **Ramon G. Leon:** Formal analysis; methodology; supervision; validation; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing financial interests or personal relationships which could influence this work.

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