Weed Science

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Weed community differences in row crops with varying input levels in Ghana

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Research Article

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Abstract

Peanut (*Arachis hypogaea* L.) and maize (*Zea mays* L.) are essential crops for Ghana's economy and food security, but weed infestation poses a significant threat to their cultivation. Crop rotations influence weed communities, but little is known about these processes in peanut-cropping systems in West Africa. This study investigated the impact of different crop rotations and input levels on weed communities in Ghana over 3 yr. Results showed that low inputs (absence of herbicide and fertilization) favored species richness, while higher input levels (weed control with herbicides and fertilizer use) reduced it. Diversity and evenness were also affected by inputs, with varying patterns across locations and seasons. Weed population growth rates (λ) varied significantly by location and treatment; all management programs resulted in increasing weed populations. Principal component analysis revealed distinct associations between weed species and crop management. The majority of weed species exhibited a generalist behavior and did not associate with a particular management. However, billygoat weed (*Ageratum conyzoides* L.) and Benghal dayflower (*Commelina benghalensis* L.) were positively associated with high-input systems, while purple nutsedge (*Cyperus rotundus* L.) exhibited strong associations with low and medium inputs. The weed–crop rotation dynamics described here demonstrate how management drives the selection of weed species that are more pervasive and interfere with important food crops in Ghanaian agriculture.

Introduction

Peanut (syn.: groundnut; *Arachis hypogaea* L.) and maize (*Zea mays* L.) are very important crops for Ghana's economy, nutrition, and food security. Their cultivation, postharvest handling, and processing serve as a source of income and employment to many smallholder farmers, processors, retailers, and other workers in the value chain. In Ghana, more than 70% of farmers in the three northern regions and transitional zones cultivate peanuts (Owusu-Adjei et al. 2017). Apart from serving as an important source of energy in animal fodder, peanut haulms help improve soil structure and fertility. While the kernels are eaten raw, boiled, or roasted, they are also a major ingredient for the preparation of most ready-to-use supplementary food and therapeutic food to combat malnutrition (Manary and Callaghan-Gillespie 2018). The kernels are also processed into peanut flour and confectionary. Maize also accounts for over half of the total cereal production in Ghana (Kankam-Boadu et al. 2018; Manary and Callaghan-Gillespie 2018). More than 15% of the maize produced in the country is utilized as animal feed (mostly for poultry and fish), and the demand for maize keeps increasing (Kankam-Boadu et al. 2018; Koffi et al. 2020; Wongnaa et al. 2018). Weeds are important pests in peanut and maize fields in Ghana, causing yield losses of between 50% and 80% in peanut fields in West Africa (Dzomeku et al. 2009).

Among the biological factors reducing yield, weeds are the most important in most extensive crops (Oerke 2006). Farmers from sub-Saharan Africa (SSA) considered weeds the most

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Table 1. Annual rainfall and average annual mean, minimum and maximum temperatures for locations in Ghana

Location	Year	Total rainfall	Mean temperature	Minimum temperature	Maximum temperature
		mm	C		
Kumasi	2019	1,538	24.0	21.5	27.7
	2020	1,255	24.1	21.5	28.0
	2021	1,666	23.9	21.7	27.5
Tamale	2019	998	29.5	24.3	34.6
	2020	1,418	28.9	23.6	34.3
	2021	991	29.1	23.8	34.5
Wa	2020	n.a.[a]	27.8	33.1	22.4
	2021	n.a.[a]	28.1	33.5	22.6

[a]n.a., on-site data not available, but historical records are 879 mm yr^{-1}.

important constraint for crop production (Adesina et al. 1994; Ogwuike et al. 2014). This holds particular significance in regions with socioeconomic and environmental fragility, such as SSA, where weeds have the potential to exacerbate challenges related to food security (Bàrberi 2019). Additionally, manual labor is often the major input in these countries, and its availability is critical for timing operations to maintain productivity. Many weed management methods currently used to prevent yield reductions require extensive manual labor (Adesina et al. 1994; Ogwuike et al. 2014). In addition, smallholder farmers frequently face time constraints and shortages in labor availability for weeding (Dahlin and Rusinamhodzi 2019; Rodenburg and Johnson 2009). To reduce this labor demand and increase productivity, it is essential to enhance overall crop management and implement complementary weed control strategies, such as utilizing herbicides, fertilizers, and fungicides to enhance crop competitiveness against weeds and other pests (Ogwuike et al. 2014). However, intensive agricultural practices may have ecological and environmental costs (Stoate et al. 2009). While effective weed management is crucial for maintaining crop yield, fostering more diverse weed communities with low plant densities is a desirable objective owing to the stability and resilience they confer on agroecosystems (Smith and Gross 2006). Diverse weed communities have the capacity to diminish the prevalence of a few highly competitive species that tend to increase the control costs and reduce crop yield (Storkey and Neve 2018).

Crop rotation affects key weed processes such as weed establishment, growth, and fecundity, all of which modulate weed population growth rate. Although integrated weed management (Swanton and Weise 1991) comprises multiple weed control tools, crop rotation has a major impact on the selection, timing, and intensity of practices such as planting, irrigation, fertilization, herbicide application, tillage, cultivation, and harvesting, all influencing weed–crop interactions (Andrade et al. 2017). Such diversity of practices when implemented in variable ways creates an unstable environment that reduces the reproductive success of weeds (Gaba et al. 2014; Weisberger et al. 2019). In simplified and less variable environments, repetitive weed management practices tend to favor a few species over others, reducing plant diversity (Oreja et al. 2021). Diversification of crop rotation can be a suitable option to prevent weed communities becoming less diverse and dominated by a few aggressive and difficult to manage species (Adeux et al. 2019; Storkey and Neve 2018).

The level of application of external inputs (e.g., fertilizers, pesticides) to fields is another important factor that may shape weed communities (Booth and Swanton 2002). Weeds that take advantage of those inputs and exhibit lower sensitivity to pesticides will increase their reproductive output and disproportionately increase their populations compared with less fit species. For example, high levels of herbicide use can favor species with longer seed longevity and persistence in soil (Oreja et al. 2021), as well as species with low herbicide sensitivity (Hyvönen and Salonen 2002; Oreja et al. 2022). Additionally, systems with high fertilizer usage may favor species with more intense nutrient acquisition and utilization (Ryan et al. 2010; Yin et al. 2006).

Despite the adoption of high-input systems that would reduce the dependence on manual labor for Ghanaian farmers and the yield reduction risks, a better understanding of how these systems affect weed community structures could facilitate their adoption in a more sustainable manner. This information is scarce in SSA and completely absent in Ghana. Therefore, the objective of this study was to assess how different crop rotations and input levels influence the diversity and balance of weed communities in Ghanaian farms.

Materials and Methods

Experimental Site

An experiment was conducted at three locations in Ghana during the years 2019, 2020, and 2021: Council for Scientific and Industrial Research (CSIR)–Crops Research Institute (CRI), Fumesua Station (Kumasi), in the Ashanti Region (6.7139°N, 1.5313°W); and Savannah Agricultural Research Institute (SARI) stations at Nyankpala (Tamale) in the Northern Region (9.3908°N, 1.0068°W), and Tanina (Wa) in the Upper West Region (9.8858°N, 2.4624°W). Kumasi is wetter (~33% more rainfall) and cooler (~5 C lower temperature) than Tamale and Wa (Table 1). Kumasi falls within the semi-deciduous rainforest agroecological zone and experiences a bimodal rainfall pattern, with a long rainy season occurring between March and July and a short season between September and November, and the soil is Ferric Acrisol (IUSS Working Group WRB 2015). Tamale and Wa fall within the Guinea Savannah ecological zone, which experiences a unimodal rainfall pattern between May and October, and the soils are Plinthosols and Lixisols/Luvisols, respectively (IUSS Working Group WRB 2015). The three locations had distinct soil properties and marked differences in soil textures (Table 2).

Experimental Design and Treatments

A 3-yr-rotation experiment was conducted in three locations from 2019 to 2021. In Tamale and Wa, each having a single growing season per year, one experiment was established annually. In Kumasi, experiments were conducted during both the long and short seasons (Table 3). The experiment was a factorial design with three factors (i.e., crop rotation, input level, and crop variety)

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Table 2. Chemical and physical properties of soil profile (0–20cm) in experimental locations in Ghana

Location	pH[a]	OM	N	P	cmol kg^{-1} [b]				Texture			Textural class
					K	Ca	Mg	Na	Sand	Clay	Silt	
		%	% total	mg kg^{-1}	%							
Kumasi	5.4	1.70	0.11	11.5	0.27	1.19	0.73	0.05	75.1	11.5	13.4	Sandy loam
Tamale	4.5	1.09	0.09	5.9	0.23	1.94	0.98	0.06	76.8	2.8	20.4	Loamy sand
Wa	5.8	1.04	0.09	4.4	0.18	1.96	1.02	0.05	84.0	4.9	11.2	Loamy sand

[a]1:1 (H_2O).
[b]Mehlich 3.

Table 3. Crops included on each rotation and years in locations in Ghana: peanut–maize and maize–peanut in Kumasi and peanut–maize–peanut and maize–maize–peanut in Tamale and Wa

	Rotation 1	Rotation 2
Kumasi		
Year 1 (2019 Short)	Maize	Peanut
Year 2 (2020 Long)	Peanut	Maize
Year 2 (2020 Short)	Maize	Peanut
Year 3 (2021 Long)	Peanut	Maize
Year 3 (2021 Short)	Maize	Peanut
Tamale		
Year 1 (2019)	Peanut	Maize
Year 2 (2020)	Maize	Maize
Year 3 (2021)	Peanut	Peanut
Wa		
Year 1 (2019)	Peanut	Maize
Year 2 (2020)	Maize	Maize
Year 3 (2021)	Peanut	Peanut

arranged in split plots with three replications. There were two different rotations with maize and peanut with opposite crop phases to avoid confounding effects with year (i.e., maize–peanut–maize and peanut–maize–peanut. These crops were selected because they are two of the most important food crops in the area and are commonly rotated (Table 3). Treatment input levels were low input (LI), medium input (MI), and high input (HI) (Tables 4 and 5). Peanut varieties were 'Yenyawso' and 'Shi Tao Chi', and maize varieties were CRI 'Ahoɔf' as a hybrid and CRI 'Omankwa' as an open-pollinated variety; peanut and maize were planted at optimum dates for the region (Table 6). Rotations were designated as the main plots, while pairwise combinations of management program and varieties were randomly assigned to subplots within the rotations. Each plot was 5 m by 5 m with a 2-m alley between replications and a 1-m alley between plots. Peanuts were planted with one seed per hill at a spacing of 50 cm between rows and 20 cm within rows, while maize was planted with two seeds per hill at 80 cm between rows and 40 cm within rows. The integrity of each plot was maintained to ensure consistent rotations and the application of the same input intensity or crop variety throughout the experiment (2019 to 2021). In the first year, the experimental fields in all locations were plowed and harrowed; however, in subsequent seasons/years, plots were manually tilled/turned to preserve plot integrity.

Measurements

Weed density was evaluated at 3 wk after planting (WAP) by randomly placing a quadrat measuring 0.5 m by 0.3 m three times within the central three rows of maize plots and five times within the central four rows of peanut plots. The number of individuals per weed species within each quadrat was recorded.

Synthetic diversity indices were used to characterize the communities (Magurran 2013). Species richness (S) was the total number of species on each treatment; Shannon's diversity index (H') was calculated as:

$$H' = \sum_{i=1}^{S} p_i \, ln(p_i) \quad [1]$$

where p_i is the proportion of individuals of species i in relation with the total number of individuals of all species combined. The relative contribution of each species to the community was determined as evenness (J):

$$J = \frac{H'}{ln(S)} \quad [2]$$

J ranges from 0 to 1, with lower values indicating dominance of one or few species and higher values indicating a more equitable representation of each species within the community. Moreover, the population growth rate of all weed species together on each treatment, lambda (λ), was estimated as:

$$\lambda = \sqrt[t]{\frac{n_{t+1}}{n_t}} \quad [3]$$

where t is the number of seasons, n_t is the total number of plants registered at 3 WAP, and n_{t+1} is the total number of plants registered the next season at 3 WAP.

Statistical Analysis

To examine the impact of different rotations, input levels, and crop varieties on weed community richness, diversity, evenness, and population growth rate values, ANOVA was conducted. This was followed by Tukey's honestly significant difference (HSD) test based on a general linear model using the NLME package (Pinheiro et al. 2018) in R (R Core Team 2020). ANOVA assumptions (homoscedasticity and normal distribution of residuals) were tested, and when these assumptions were not met, the data were arcsine square-root transformed before the analyses. In cases in which transformations were not enough to achieve the homogeneity of variance, data were analyzed using the generalized least squares method, which corrected for heterogeneity of variances.

As the effects of crop management decisions on a particular species cannot be captured by a single index score, a principal component analysis (PCA) (Krzanowski 2000) was performed using PC-ORD Multivariate Analysis of Ecological Data v. 5.0. (Grandin 2006; McCune and Mefford 1999) for each location. The

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Table 4. Input intensity and details for peanut and maize production in Kumasi, Tamale, and Wa, Ghana

Crop	Input intensity	Weed control	Disease/insect control	Nutrient supply
Peanut	Low input	1 hand weeding	No disease control	No fertilizer
	Medium input	2 hand weeding	3 Alata soap applications	Fertilizer (N-P-K)
	High input	Preemergence + hand weeding	2 fungicide applications	Fertilizer (N-P-K and Ca)
Maize	Low input	1 hand weeding	No insecticide application	No fertilizer
	Medium input	2 hand weeding	1–2 insecticide applications	Fertilizer (urea)
	High input	Preemergence + hand weeding	2–4 insecticide applications	Fertilizer (N-P-K and urea)

Mixture of vegetable oils extracted from *Butyrospermum parkii* (G. Don) Kotschy (shea butter), *Cocos nucifera* L. (coconut Oil), *Elaeis guineensis* Jacqu. (palm kennel), *Theobroma cacao* L. (cocoa) sprayed foliarly.

Table 5. Active ingredient(s), rate and time of application of inputs for peanut and maize production in Kumasi, Tamale, and Wa, Ghana

Item	Active ingredient	Rate of application	Application time[a]
Preemergence	Pendimethalin 500 g L^{-1}	3 L ha^{-1}	0–2 DAP
Fungicide	1. Azoxystrobin (200 g) + difenoconazole (125 g L^{-1})	500 ml ha^{-1}	4 and 6 WAP
Alata soap	NA	1 g L^{-1} of H_2O	3, 4, and 5 WAP
Insecticide	1. Bt (55%) + monosultap (45%)	1. 500 g ha^{-1}	2–5 PRN
	2. Emamectin benzoate (19.2 g L^{-1})	2. 400 ml ha^{-1}	
N-P-K (15:15:15)	N–P_2O–K_2O (37.5 kg:37.5 kg:37.5 kg ha^{-1})	5 bags ha^{-1} (37.5 kg N:16.5 kg P:30 kg K ha^{-1})	10–14 DAP
Urea	46% N	2.5 bags ha^{-1} (57.5 N ha^{-1})	4–5 WAP
Calcium fertilizer	(0% N, 18% P_2O_5, 13% K_2O, 29% CaO)	3 bags ha^{-1} (31 kg Ca ha^{-1})	6 WAP

Mixture of vegetable oils extracted from *Butyrospermum parkii* (G. Don) Kotschy (shea butter), *Cocos nucifera* L. (coconut Oil), *Elaeis guineensis* Jacqu. (palm kennel), *Theobroma cacao* L. (cocoa) sprayed foliarly.
[a]Bt, *Bacillus thuringiensis*; DAP, days after planting; PRN, when needed; WAP, weeks after planting.

Table 6. Planting and harvesting dates in different locations and seasons in Ghana

Location and season	Planting–harvesting dates
Kumasi 2019 short season (S2)	July 15, 2019–October 17, 2019
Kumasi 2020 long season (S1)	May 7, 2020–August 7, 2020
Kumasi 2020 short season (S2)	October 6, 2020–January 16, 2020
Kumasi 2021 long season (S1)	May 20, 2021–August 26, 2021
Kumasi 2021 short season (S2)	September 28, 2021–December 20, 2021
Tamale 2019	July 25, 2019–November 3, 2019
Tamale 2020	July 17, 2020–November 3, 2020
Tamale 2021	July 7, 2021–October 11, 2021
Wa 2019	July 27, 2019–November 6, 2019
Wa 2020	July 19, 2020–November 6, 2020
Wa 2021	July 9, 2021–October 15, 2021

response variable used was the density at 3 WAP of each species in the last season (i.e., 2021), and the explanatory variables were the treatments. Treatment codes, weed scientific names, and codes of weed species in each location are listed in Table 7.

Results and Discussion

Community Structure

Since no differences on species richness (*S*) were observed among varieties and rotations in any location ($P = 0.74$, 0.81, and 0.05 for Kumasi, Wa, and Tamale, respectively), results were analyzed by pooling rotation data. In Kumasi, the number of species varied throughout the duration of the experiment (Figure 1A). Thus, *S* was lowered during long seasons compared with short seasons ($P < 0.0001$). In Tamale and Wa, *S* doubled from 2019 to 2021 ($P < 0.0001$) regardless of input levels and rotation (Figure 1B and 1C). Input management had a major impact on *S*, which was consistently lower ($P < 0.0001$) in treatments with high inputs compared with medium and low inputs across all locations and seasons (Figure 1).

Since no differences in H' were observed due to variety and rotation in any location ($P = 0.21$, 0.81, and 0.89 for Kumasi, Wa, and Tamale, respectively), the analysis was done by pooling rotation data. In Kumasi, no differences were observed in H' among seasons, with an average of 1.45 (Figure 2A). However, H' increased in Tamale and Wa from season 2019 to season 2021 ($P < 0.0001$), rising 64% and 44%, respectively (Figure 2). Regarding input levels, there was a notable difference ($P < 0.0001$) in H', with high-input levels resulting in lower H' values (1.19 in Tamale and 0.89 in Wa) than medium- and low-input levels (1.39 in Tamale and 1.38 in Wa) (Figure 2). In contrast, Kumasi had more variation, with H' being higher with high-input levels during the short seasons (2019 and 2020) compared with medium- and low-input levels, but it was lower at high-input levels during long seasons and the last short season compared with medium- and low-input levels (Figure 2).

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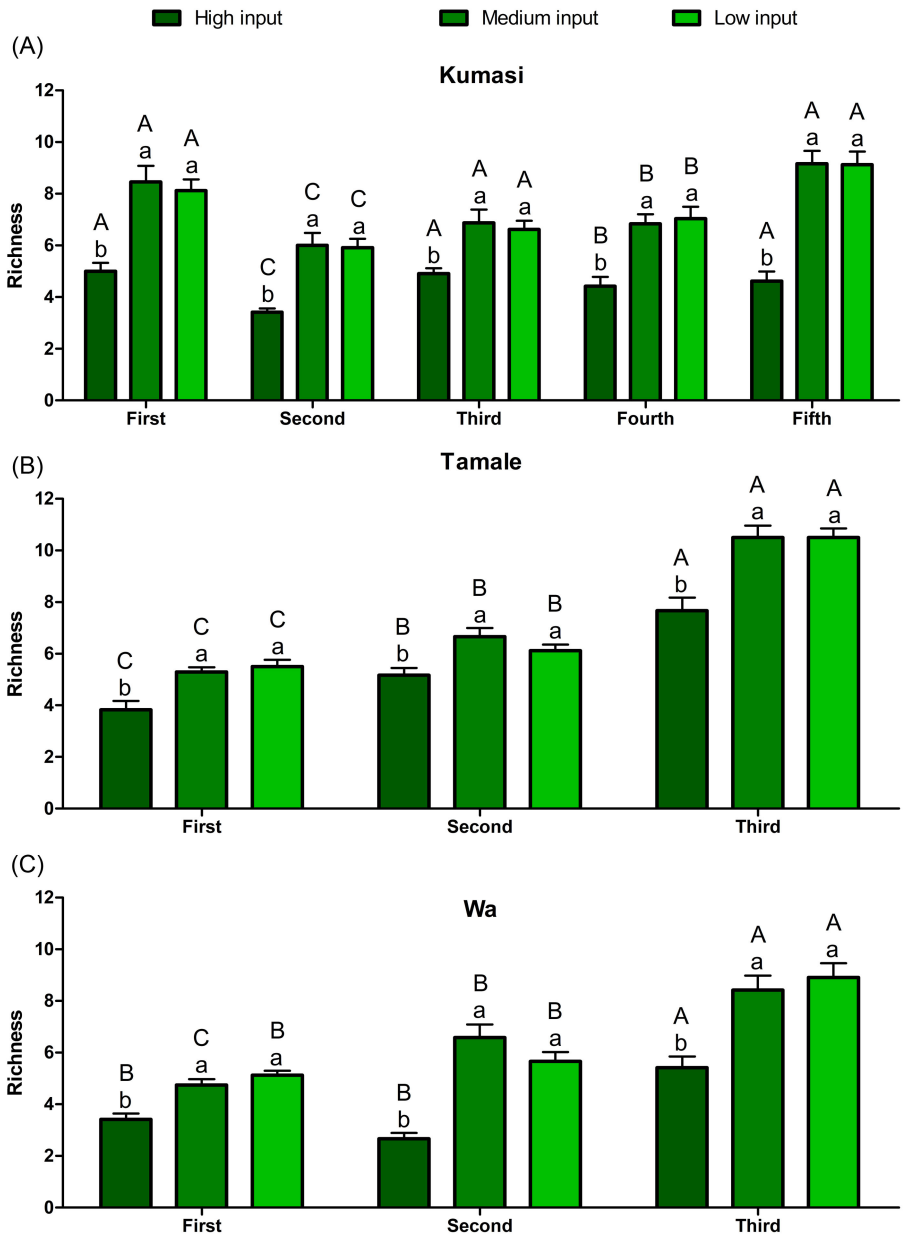


Figure 1. Richness (*S*) estimated during three seasons and for different input levels (high, medium, and low) in locations in Ghana: (A) Kumasi, (B) Tamale, and (C) Wa. Different uppercase letters indicate differences among seasons, and different lowercase letters among input levels according to Tukey's HSD ($P < 0.05$). Errors bars represent standard error of the mean.

Regarding evenness (*J*), no differences were observed among varieties and rotations in any location ($P = 0.09$, 0.28, and 0.39 for Kumasi, Wa, and Tamale, respectively). Therefore, seasons and inputs results were analyzed with data combined across rotations. In Kumasi, *J* was lower ($P < 0.0001$) in the last two seasons of the experiment compared with the second one (Figure 3A). On the other hand, in Tamale, *J* increased from season 2019 (0.64 on average) to season 2020 (0.75 on average) and season 2021 (0.74 on average) (Figure 3B). In Wa, a reduction in *J* was observed from season 2019 to season 2020, from 0.76 to 0.66 on average, but in season 2021, *J* increased ($P < 0.0001$) to the former level (0.74 on average) (Figure 3C). No differences were observed among input levels for *J* in Tamale ($P = 0.27$) and Wa ($P = 0.31$). In Kumasi, *J* was higher ($P < 0.0001$) in the high-input treatment than in the medium- and low-input treatments in long seasons. However, the reverse was observed in short seasons, when *J* was higher ($P < 0.0001$) in the medium- and low-input treatments than in the high-input treatment (Figure 3A), exhibiting an inverse pattern to that observed for H'.

In general, high-input treatments resulted in low *S* and H' across all locations and seasons. Additionally, a lower *J*, which results from the dominance of one or few species, was also associated with high inputs in comparison to medium and low inputs, although patterns varied across locations and seasons. This could be attributed to the use of herbicides in the high-input system, in contrast to the medium- and low-input levels, which did not employ herbicides. Herbicides are among the most important filters shaping weed community structures at field scale (Grundy et al. 2011; Owen 2008). In environments where the same herbicide program is repeatedly used, less-sensitive species are favored over

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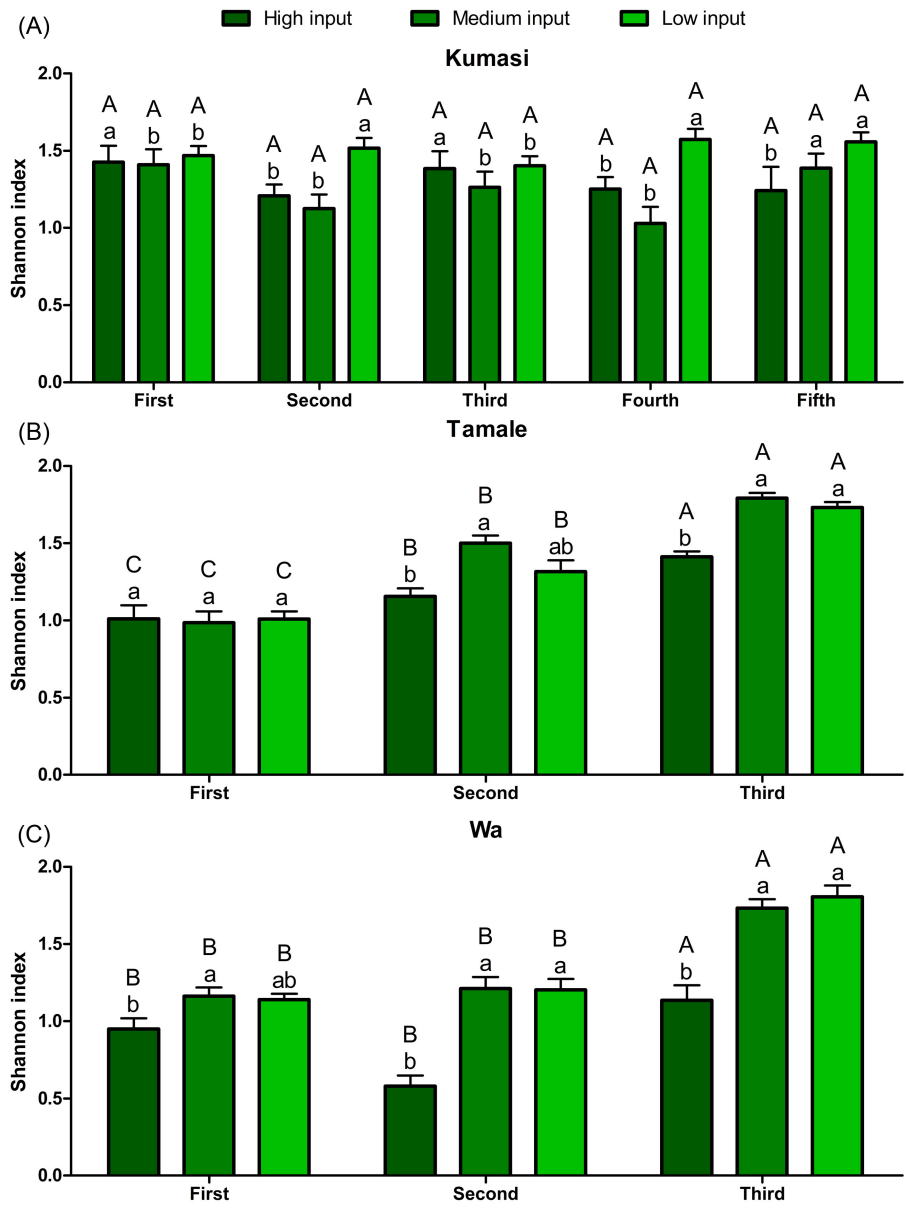


Figure 2. Shannon index (H') in response to input level (high, medium, and low) in different seasons in (A) Kumasi, (B) Tamale, and (C) Wa, Ghana. Different uppercase letters indicate significant differences among seasons, and different lowercase letters indicate significant differences among input levels according to Tukey's ($P < 0.05$). Errors bars represent standard error of the mean.

more-sensitive ones, leading to a reduction in the H' and J of the community (Oreja et al. 2021). Similarly, the use of fertilizers can influence weed composition due to variation in nutrient use among species (Pinke et al. 2016). It is important to mention that those factors do not act individually, so the joint effects of herbicides, fertilizers, and fungicides included in the high-input treatment (Table 4) likely determined how the potential for both crop competitive ability and weed interference were expressed. Gaba et al. (2018) reported that nitrogen fertilization increased the competitive ability of the crop, which resulted in lower weed biomass, including that of dominant species. Additionally, weeds with small seedbanks may experience significant reductions in their performance, potentially leading to eradication (Oreja et al. 2022). At the same time, weeds are not only competing with crops, but they are also competing with other weeds. In some cases, weed–weed competition can have a higher impact on weed growth than crop–weed competition (Romillac et al. 2023). In Tamale and Wa, there was a dramatic increase in S and H' from the beginning to the end of the experiment, regardless of input levels, rotations, and varieties. The lack of effects of different rotations on weed community structures at each location may be related to the similarity between the rotations evaluated. The rotations did not differ in crop types but only in the years the crops were planted. Weed species that are suppressed or favored in one season might experience the opposite in the next, thus compensating for any differences. Similarly, varieties with comparable cycle lengths or plant architectures could contribute to the lack of differences in weed community composition. For example, Haden et al. (2007) found no effect on weed community structure in response to the presence of either of two rice (*Oryza sativa* L.) cultivars differing in height and presumably weed-suppression potential. Similarly, Schöb et al. (2017) reported that there were no differences among

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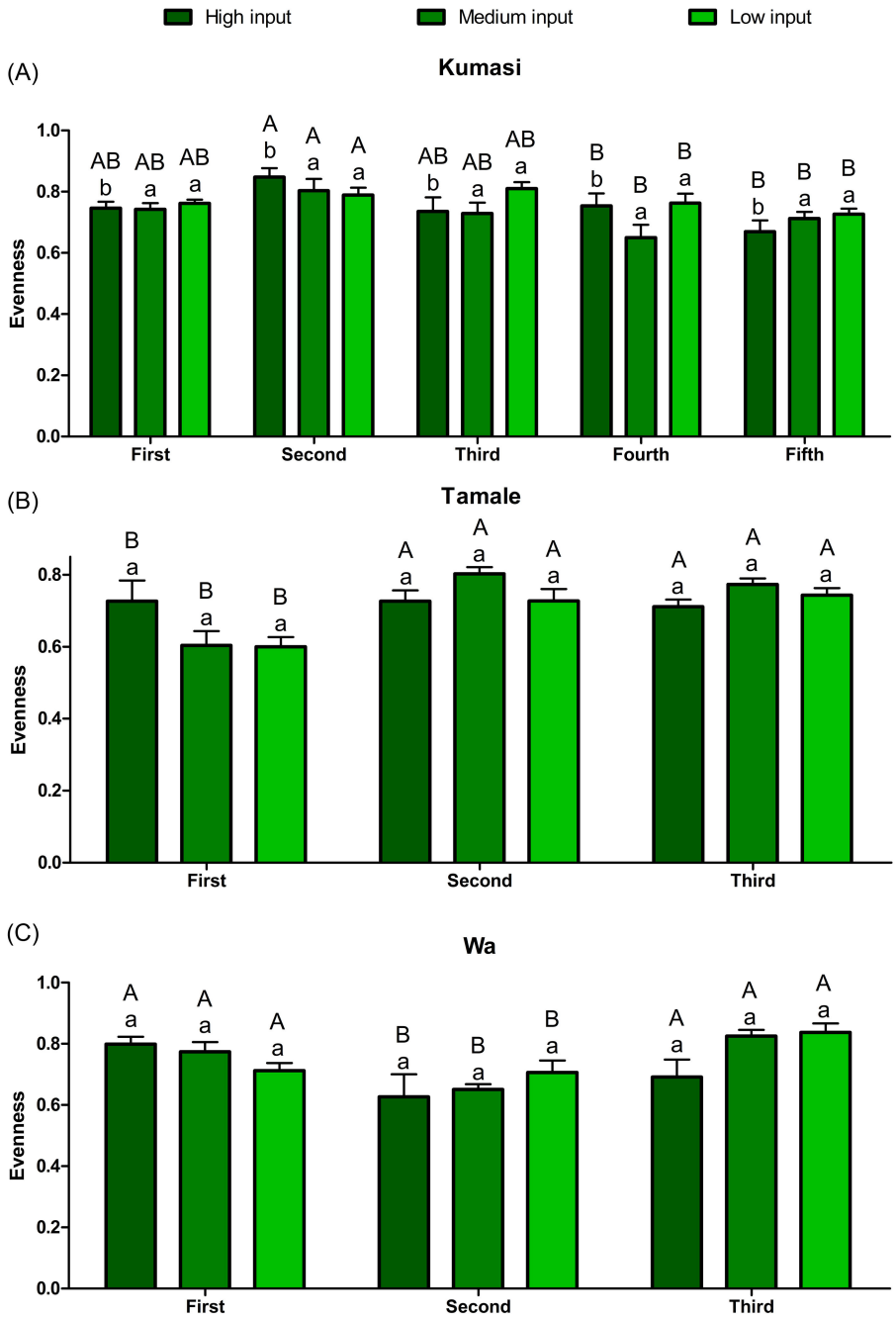


Figure 3. Evenness (*J*) estimated at different seasons and for different input levels (high, medium, and low) in locations in Ghana: (A) Kumasi, (B) Tamale, and (C) Wa. Different uppercase letters mean significant differences among seasons, and different lowercase letters mean significant differences among input levels according to Tukey's ($P < 0.05$). Errors bars represent standard error of the mean.

barley (*Hordeum vulgare* L.) genotypes on the establishment of new weed species and the richness of the community. They concluded that very small variation in growth traits among genotypes was the main cause of a lack of differential responses by weeds.

Evenness fluctuated across seasons but tended to increase toward the end of the experiment, indicating a balance in abundance among weed species. However, in Kumasi, the number of species and the H' remained relatively constant throughout the experiment, with fluctuations observed between long and short rainy seasons. At this location, *J* decreased over time until the last two seasons, indicating a disproportionate impact of management on the abundance of different weed species (Nkoa et al. 2015). Kumasi is located in a different agroecological zone with distinct rainfall patterns and soil types compared with Tamale and Wa (Table 1). These differences may modulate the community structure differently among locations. Pinke et al. (2016) reported that environmental variables, such as temperature and precipitation, which are highly dependent on location, were strong determinants in shaping species composition in the fields. In addition, Kumasi tended to have higher values of richness and diversity than Wa and Tamale throughout the seasons, except for Wa in season 2021. Kumasi has five crops in 3 yr compared with three crops in 3 yr in Wa and Tamale, meaning the surface was

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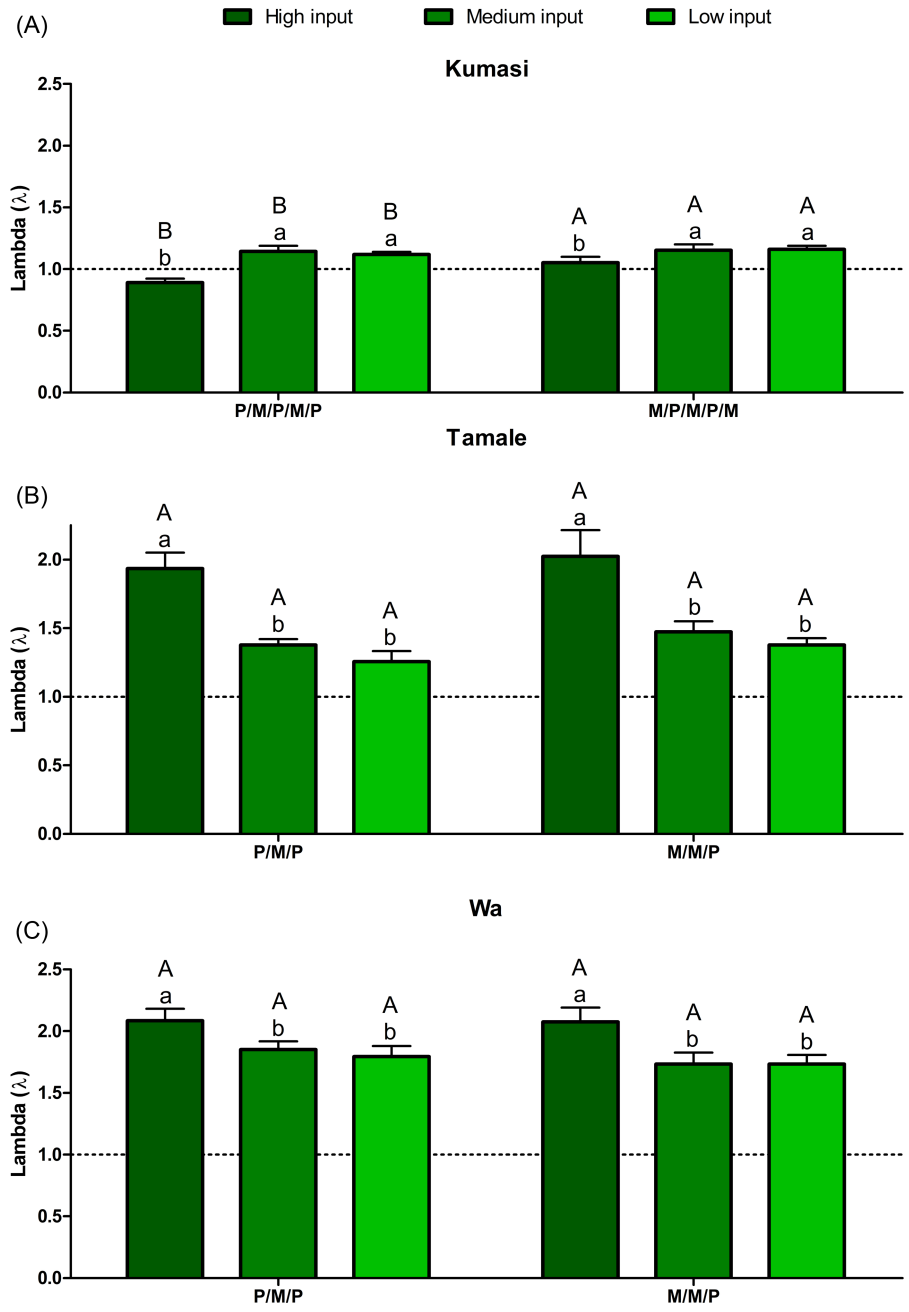


Figure 4. Population growth rate (lambda or λ) estimated at different crop rotations and for different input levels (high, medium, and low) in locations in Ghana: (A) Kumasi, (B) Tamale, and (C) Wa. Different uppercase letters indicate significant differences among crop rotations and different lowercase letters indicate significant differences among input levels according to Tukey's ($P < 0.05$). M, maize; P, peanut. Errors bars represent standard error of the mean.

covered with a crop during more time. Andrade et al. (2017) found that a field with a higher number of days with a high crop cover reduced the frequency of common weeds, which leads to reductions in the dominance of a few species and increases the diversity and evenness.

Weed Population Growth Index (λ)

Because no interaction was observed between Tamale and Wa for λ, data of these two locations were pooled for the analysis. Also, data were pooled for varieties due to the lack of responses to this factor. In Kumasi, a higher λ (1.12; $P = 0.02$) was observed in the maize–peanut–maize rotation than in the peanut–maize–peanut rotation ($\lambda = 1.05$) (Figure 4A), but no differences were observed between rotations in Tamale and Wa (Figure 4). Regarding input levels, a higher λ ($P < 0.0001$) was observed for treatments with medium- and low-input levels in Kumasi (1.15 for medium-input level and 1.14 for low-input level) compared with high-input levels (0.97). On the contrary, in Tamale and Wa, higher λ values ($P < 0.0001$) were registered in high-input levels (1.98 and 2.08 for Wa and Tamale, respectively) than in medium- (1.43 and 1.79 for Wa and Tamale, respectively) and low-input (1.32 and 1.76 for Wa and Tamale, respectively) levels (Figure 4).

The effects on population growth rate were very different depending on the location; in Kumasi, certain rotations and lower input levels were associated with higher λ, while the opposite trend

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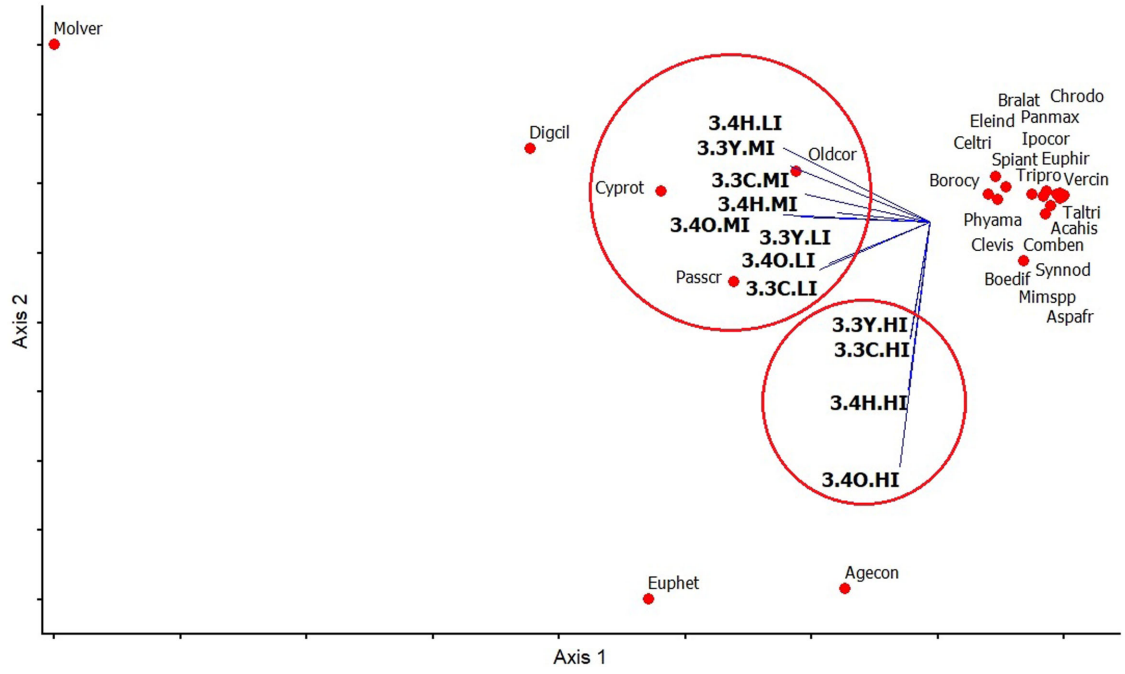


Figure 5. Principal component analysis (PCA) ordination of density values registered 3 wk after planting date in the last season in Kumasi, Ghana. Vectors represent the explanatory variable and are the treatments. See Table 7 for nomenclature. Rotations are the first two numbers; crop varieties are the letter and the last two letters for the input level.

was observed in Tamale and Wa. Despite these differences, all the locations and treatments showed λ values above 1, except for the peanut–maize rotation at high-input level (λ = 0.89). These λ values above 1 mean that weed populations increased from the beginning of the experiment to the end. The efficacy of manual weeding is highly dependent on weed density, Thus, if λ is low, manual weeding may be superior to herbicides. However, if weed density is very high, then manual weeding efficacy decreases (Beltran et al. 2012). On average among seasons and treatments, weed density was 2.6 and 2.1 times higher in Tamale and Wa than in Kumasi, respectively. This difference could explain the higher efficacy of treatments without herbicides compared with those with herbicides in Kumasi. Except for the peanut-maize rotation at high-input level, none of the evaluated programs were successful in reducing λ. In other words, all evaluated management programs had trajectories that will result in progressively more serious weed problems. Therefore, more weed management programs must be evaluated in order to reduce λ by maintaining weed populations at sustainable values and supporting diverse weed communities.

Species Analysis

In the PCA for Kumasi, axes 1 and 2 accounted for 70.6% and 16.8% of the total variation, respectively. Two distinct groups of explanatory variables were identified (Figure 5). One comprised treatments with high inputs (including residual herbicides) and the other group consisted of treatments with low and medium inputs (without herbicides). No associations were observed for rotations or crop genotypes. On average across all treatments, most species with low densities were positioned in the opposite direction of the treatment vectors. Conversely, species with high densities across treatments tended to be in the same direction as the treatment vectors (Figure 5; Table 7). The positioning of these species corresponded to their association with specific treatments. For instance, species such as carpetweed (*Mollugo verticillata* L.), southern crabgrass [*Digitaria ciliaris* (Retz.) Koeler], purple nutsedge (*Cyperus rotundus* L.), and flat-top mile (*Oldenlandia corymbosa* L.) were associated with low- and medium-input levels. Conversely, billygoat weed (*Ageratum conyzoides* L.) and wild poinsettia (*Euphorbia heterophylla* L.) were positively associated with high inputs (Figure 5).

In Tamale, axis 1 accounted for 85.0% and axis 2 for 7.4% of the total variation (Figure 6). As was observed in Kumasi, two distinct groups of explanatory variables were identified, one comprised treatment with high inputs (including residual herbicides) and the other group consisted of treatments with low and medium inputs (without herbicides) (Figure 6). No associations were observed for rotations or crop varieties. Most species with low densities, on average across all treatments, were positioned in the opposite direction of the treatment vectors. *Ageratum conyzoides* was the only species associated with high inputs. *Cyperus rotundus*, linear primrose-willow [*Ludwigia hyssopifolia* (G. Don) Exell], kodo-millet (*Paspalum scrobiculatum* L.), pignut [*Hyptis suaveolens* (L.) Poit.], arrasa con todo (*Gomphrena celosioides* auct. non Mart.; syn.: *Gomphrena serrata* L.), and *D. ciliaris* were more clearly associated with low and medium inputs (Figure 6).

In Wa, axis 1 accounted for 75.4% and axis 2 for 15.3% of the total variation. Two distinct groups of explanatory variables were identified but were not as separated as in the other two locations (Figure 7). No associations were observed for rotations or crop varieties. Only *C. benghalensis* was associated with treatments with high inputs. Regarding low- and medium-input levels, tropical girdlepod [*Mitracarpus villosus* (Sw.) Cham. & Schltdl. ex DC.] and *C. rotundus* exhibited the strongest associations, while Indian sandbur (*Cenchrus biflorus* Roxb.), marubio (*Hyptis spicigera* Lam.), *Cyanotis lanata* Benth., *H. suaveolens*, and *D. ciliaris* were also associated but to a lesser extent (Figure 7).

Species associations with input levels were consistent across locations, with certain species being more prevalent in low- to medium-input systems, while others were associated with high-

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Table 7. (A) Abbreviations (codes) for treatments representing the explanatory variables (vectors) and (B) weed codes representing species used for a principal component analysis (PCA) as shown in Figure 5

A. PCA abbreviations						
	Kumasi	Code	Tamale	Code	Wa	Code
Rotation	Peanut/maize/peanut/maize/peanut	3.3	Maize/maize/peanut	2.1	Maize/maize/peanut	1.1
	Maize/peanut/maize/peanut/maize	3.4	Peanut/maize/peanut	2.2	Peanut/maize/peanut	1.2
All locations						
Input level	Low input	LI	Medium input	MI	High input	HI
Peanut varieties	'Shi Tao Chi'	C	'Yenyawso'	Y		
Maize varieties	'Ahoɔf '	H	'Omankwa'	O		

B. Weed codes	
Kumasi	Code
Acanthospermum hispidum DC.	Acahis
Ageratum conyzoides L.	Agecon
Aspilia africana (Pers.) C. D. Adams	Aspafr
Boerhavia diffusa L.	Boedif
Borreria ocymoides (Burm. f.) DC.	Borocy
Brachiaria lata (Schumach.) C.E. Hubb.	Bralat
Celosia trigyna L.	Celtri
Chromolaena odorata (L.) R.M. King & H. Rob.	Chrodo
Cleome viscosa L.	Clevis
Commelina benghalensis L.	Comben
Cyperus rotundus L.	Cyprot
Digitaria ciliaris (Retz.) Koeler	Digcil
Eleusine indica (L.) Gaertn.	Eleind
Euphorbia heterophylla L.	Euphet
Euphorbia hirta L.	Euphir
Ipomoea cordatotriloba Dennst. var. torreyana (A. Gray) D. Austin	Ipocor
Mimosa spp.	Mimspp
Mollugo verticillata L.	Molver
Oldenlandia corymbosa L.	Oldcor
Paspalum scrobiculatum L.	Panmax
Phyllanthus amarus Schumach. & Thonn.	Passcr
Spigelia anthelmia L.	Phyama
Synedrella nodiflora (L.) Gaertn.	Spiant
Talinum triangulare (Jacq.) Willd.	Synnod
Tridax procumbens L.	Taltri
Urochloa maxima (Jacq.) R. Webster	Tripro
Vernonia cinerea (L.) Less.	Vercin
Tamale	Code
Ageratum conyzoides L.	Agecon
Andropogon tectorum Schumach. & Thonn.	Andtec
Brachiaria deflexa (Schumach) C.E. Hubb. ex Hutch. & Dalziel	Bradef
Cleome viscosa L.	Clevis
Commelina benghalensis L.	Comben
Corchorus tridens L.	Cortri
Cyperus rotundus L.	Cyprot
Digitaria ciliaris (Retz.) Koeler	Digcil
Eleusine indica (L.) Gaertn.	Eleind
Euphorbia heterophylla L.	Euphet
Euphorbia hirta L.	Euphir
Gomphrena celosioides auct. non Mart.	Gomcel
Hyptis suaveolens (L.) Poit.	Hypsua
Ipomoea involucrata P. Beauv.	Ipoinv
Kyllinga squamulata Thonn. ex Vahl	kylsqu
Ludwigia hyssopifolia (G. Don) Exell	Ludhys
Mimosa spp.	Mimspp
Mollugo verticillata L.	Molver
Oldenlandia herbacea (L.) Roxb.	Oldher
Paspalum scrobiculatum L.	Passcr
Phyllanthus amarus Schumach. & Thonn.	Phyama
Talinum triangulare (Jacq.) Willd.	Taltri
Tephrosia bracteolata Guill. & Perr.	Tepbra
Tridax procumbens L.	Tripro
Wa	Code
Brachiaria lata (Schumach.) C. E. Hubb.	Bralat
Celosia trigyna L.	Celtri
Cenchrus biflorus Roxb.	Cenbif
Cleome viscosa L.	Clevis
Commelina benghalensis L.	Comben
Corchorus tridens L.	Corlin

(*Continued*)

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Table 7. (*Continued*)

B. Weed codes	
Kumasi	Code
Croton lobatus L.	Crolob
Cyanotis lanata Benth.	Cyalan
Cyperus rotundus L.	Cyprot
Digitaria ciliaris (Retz.) Koeler	Digcil
Euphorbia heterophylla L.	Euphet
Euphorbia hirta L.	Euphir
Gomphrena celosioides auct. non Mart.	Gomcel
Hyptis spicigera Lam.	Hypspi
Hyptis suaveolens (L.) Poit.	Hypsua
Ipomoea cordatotriloba Dennst. var. *torreyana* (A. Gray) D. Austin	Ipocor
Ipomoea involucrata P. Beauv.	Ipoinv
Kyllinga squamulata Thonn. ex Vahl	kylsqu
Leucas martinicensis (Jacq.) W.T. Aiton	Leumar
Mitracarpus villosus (Sw.) Cham. & Schltdl. ex DC.	Mitvil
Monechma ciliatum (Jacq.) Milne-Redh.	Moncil
Oldenlandia corymbosa L.	Oldcor
Oldenlandia herbacea (L.) Roxb	Oldher
Paspalum scrobiculatum L.	Passcr
Phyllanthus amarus Schumach. & Thonn.	Phyama
Physalis angulata L.	Phyang
Rottboellia cochinchinensis (Lour.) W.D. Clayton	Rotcoc
Talinum triangulare (Jacq.) Willd.	Taltri
Tephrosia bracteolata Guill. & Perr.	Tepbra
Tridax procumbens L.	Tripro
Vernonia galamensis (Cass.) Less.	Vergal

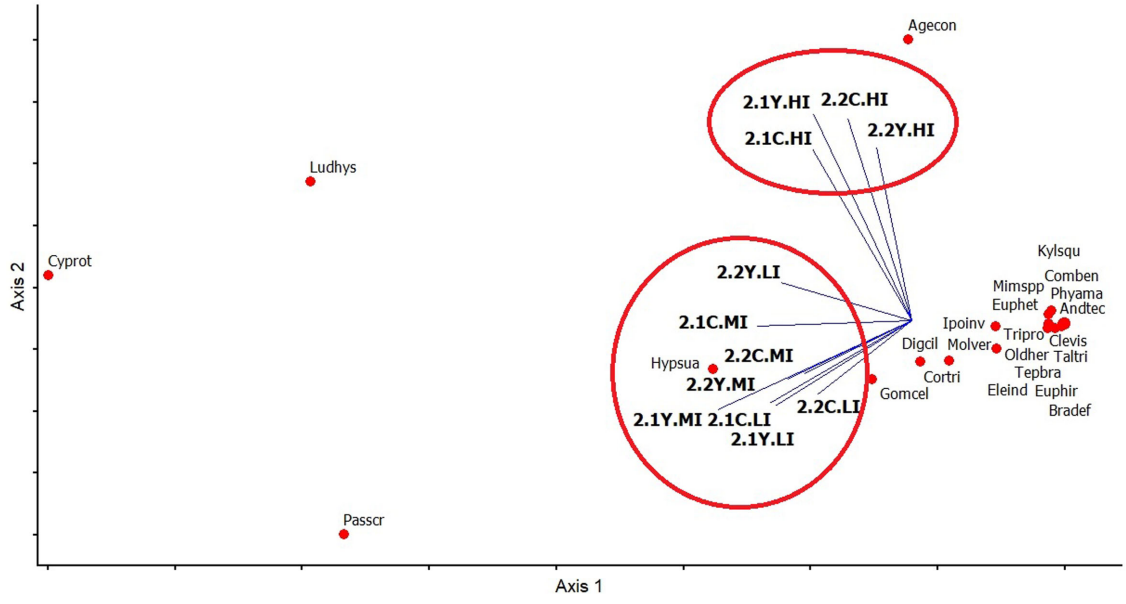


Figure 6. Principal component analysis (PCA) ordination of density values registered 3 wk after planting date in the last season in Tamale, Ghana. Vectors represent the explanatory variable and are the treatments. See Table 7 for nomenclature. Rotations are the first two numbers; crop varieties are the letter and the last two letters for the input level.

input systems. The differences observed among locations in community structures were also reflected in weed compositions. Out of the 47 different species identified in our study, only 10 (21%) were found in all three locations. This highlights the significant influence of environmental variables, such as temperature and precipitation, in shaping weed community compositions (Pinke et al. 2016). Most of the species registered in all the locations in this work, such as *Cleome viscosa* L., *C. benghalensis*, *C. rotundus*, *D. ciliaris*, *E. heterophylla*, *Euphorbia hirta* L., *P. scrobiculatum*, *Phyllanthus amarus* Schumach. & Thonn., *Talinum triangulare* (Jacq.), and *Tridax procumbens* L., were previously reported in other crop field surveys in SSA (Kent et al. 2001; Salaudeen et al. 2022).

Regarding the associations of species with input levels, some species were negatively associated with high input–level scenarios with herbicide and fertilizer applied. Most of those species,

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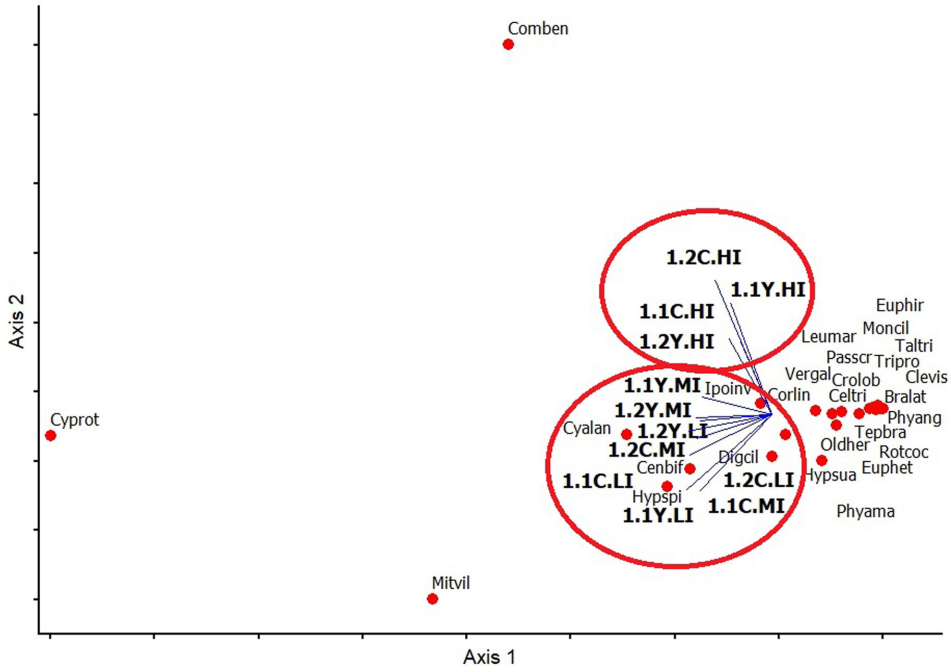


Figure 7. Principal component analysis (PCA) ordination of density values registered 3 wk after planting date in the last season in Wa, Ghana. Vectors represent the explanatory variable and are the treatments. See Table 7 for nomenclature. Rotations are the first two numbers; crop varieties are the letter and the last two letters for the input level.

including *D. ciliaris* (Ahmed and Chauhan 2015), *M. verticillata* (Kharel et al. 2022), *P. scrobiculatum* (Hossain et al. 2020), *H. suaveolens* (Imoloame 2017), and *C. biflorus* (Ahmed et al. 2017), are effectively controlled with pendimethalin. Conversely, the use of this herbicide may be favoring other species such as *E. heterophylla*, *C. benghalensis*, and *A. conyzoides*, because they are less sensitive (Jowers et al. 1986; Stoller et al. 1979; Yadav et al. 2017). This differential control favors the displacement of sensitive by less-sensitive species (Grundy et al. 2011). In the case of *C. rotundus*, this weed is poorly controlled with pendimethalin (Ahmed and Chauhan 2015), and hand weeding has been found to be more effective than herbicides (Stoller et al. 1979). Therefore, the evaluated herbicide program was not the most important factor determining its presence in the community. Instead, it is possible that the higher competitive ability of the crop in these treatments may be affecting the performance of this species. Previous research demonstrated the effectiveness of crop competition reducing the growth of this species (Iqbal et al. 2019; Neeser et al. 1997), especially once a crop closes its canopy, a process that is enhanced by the addition of fertilizer, ultimately shading weeds (Keeley 1987).

The present study indicates that fertilizer use and weed control intensity were more important than rotation structure and varieties in influencing weed species community composition. Herbicides may reduce manual labor and minimize risks of yield reduction (Ogwuike et al. 2014), but the fact that the evaluated production programs were unable to reduce weed population growth rates highlights the need for expanding the range of weed control practices. Special attention must be paid to the limited differences between maize and peanut phases of the rotation despite their contrasting morphology and growth. Therefore, there is a need for integration of more cultural practices and the design and implementation of a more diverse cropping system to favor the sustainability of weed management in Ghanaian farms (Leon and Wright 2018; Weisberger et al. 2019).

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Competing interests. The authors declare no conflicts of interest.

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