



Conservation agriculture systems reduce weed emergence and alter weed community structure in a cotton-based cropping system in Benin

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ABSTRACT

Weed management is a key to the adoption of conservation agriculture practices in Sub-Saharan Africa. This study assessed the effect of conservation agriculture practices, strip-tillage and direct mulch-based cropping system on weed emergence, biomass and community structure in cotton-based cropping systems in northern Benin. The experiment was conducted in 2023 and 2024 using a randomized complete block design with three replications under three cropping systems: conventional tillage, strip tillage (cotton in biannual rotation with maize-cowpea intercropping over strip tillage) and direct mulch-based cropping system (cotton in three-season rotation with maize and *Stylosanthes guianensis* intercropping and sorghum and soybean intercropping over direct mulch-based cropping system). Weed emergence and species were inventoried at seven-day intervals starting from the first rainfall triggering their germination. Weed biomass was measured at each weeding. Conservation agriculture systems significantly reduced weed emergence compared to conventional tillage. The reductions were 15 % (cotton) and 46 % (maize) under strip tillage, and 33 % (cotton) and 56 % (maize) under direct mulch-based cropping system. Weed biomass increased significantly under the strip tillage system, i.e. by 40 % in cotton plots and by 41 % in maize plots. Crop yields were not significantly affected by systems. Weed community structure was shaped by the interaction between the cropping system and seasons, with distinct indicator species associated with cropping systems. These findings demonstrate that conservation agriculture practices can reduce weed emergence and alter weed community structure without compromising yield performance. This is the first study to characterize weed management under conservation agriculture in Sub-Saharan African cotton-based cropping systems.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is the leading natural fiber produced and marketed worldwide. Its global annual economic impact is estimated at \$600 billion (Khan et al., 2020). In Sub-Sahara Africa, farmers commonly grow cotton as the first crop in a rotation with food crops,

mainly maize (*Zea mays* L.). Cotton production is subject to several biotic and abiotic constraints that limit potential production levels. Weeds are one of the main biotic constraints facing cotton production in developing countries (Etiabi et al., 2021). Competition with weeds limits the availability of the resources needed for crop growth (Tariq et al., 2020). The presence of weeds also attracts insect pests that affect crop

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health and reduce yield. Yield losses due to weeds vary from one crop to another but are always high. Some pernicious weed species (*Imperata cylindrica*, *Cyperus* spp., *Commelina* spp.) and parasites (*Striga* spp.) are very difficult to control, leading to substantial yield losses and threatening people's livelihoods (Vissoh et al., 2004). Chemical, mechanical, and manual control strategies are frequently used to control weed pressure in Sub-Saharan Africa (Lee and Thierfelder, 2017). Farmers remove weeds mechanically (Mohler et al., 2001), manually or with a hoe (Gantoli et al., 2015), or by plowing (Merfield, 2023). In Benin, manual control is limited due to the scarcity of farm labor, while on-farm mechanization remains limited. In recent years, weed scientists have increasingly advocated for a shift from purely chemical or mechanical control toward more integrated, ecological approaches (Westwood et al., 2018).

Conservation agriculture can limit weed infestation in cultivated plots (Thierfelder et al., 2012; Nichols et al., 2015). Reduced tillage combined with cover crop mulches significantly suppressed weeds compared to untreated controls (Weber et al., 2017). For instance, recent studies reported around 35 % less weeding labor under conservation agriculture, attributed to the weed-suppressive effects of live cover crops and surface mulch (Edralin et al., 2017). These findings highlight the importance of combining strip tillage (or no-till/direct seeding) with mulch-based cropping to maximize weed suppression. However, the degree of weed suppression achieved by conservation agriculture practices can vary according to management practices, environmental conditions, so highly context-dependent (MacLaren et al., 2020). Beyond effects on overall weed density, conservation agriculture practices alters weed community structure by reshaping the ecological and functional filters that govern weed assemblages through reduced soil disturbance, continuous residue cover, and diversified rotations (Derrouh et al., 2021). Over time, conservation agriculture systems often exhibit higher weed species richness and functional diversity due to increased habitat heterogeneity and reduced mechanical disturbance (Gaba et al., 2014). However, this ecological diversification can coincide with the rise of hard-to-control species such as *Cyperus* spp. and *Imperata cylindrica*, highlighting the need for context-specific, integrated weed management approaches (Lee and Thierfelder, 2017).

Despite the global progress in understanding conservation agriculture weed interactions, there is a notable knowledge gap regarding weed management under conservation agriculture in Sub-Saharan African cotton-based cropping systems (Matloob et al., 2020). Few studies have examined how conservation agriculture practices influence weed dynamics in cotton rotations of this region (Reddy et al., 2006). Most African conservation agriculture and weed research to date has focused on cereal-based systems in Eastern and Southern Africa (e.g. maize-legume rotations) (Stanzen et al., 2016; Mhlanga et al., 2022), or on other tropical regions, leaving cotton systems underrepresented. This is a critical gap because cotton's wide row spacing and slow early growth can make it vulnerable to weed competition, meaning the efficacy of conservation agriculture in suppressing weeds has high stakes for yield conservation agriculture adoption. There is an urgent need for Sub-Saharan Africa evidence on how conservation agriculture affects weed emergence, weed biomass, and community composition throughout the growing season in cotton-based rotations. Filling this gap is important not only academically but also for agroecological and smallholder development reasons. If conservation agriculture can demonstrably reduce weed pressure or shift weed communities toward less aggressive species in Sub-Saharan Africa cotton systems, it could save farmers significant time and reduce their reliance on herbicides, thus improving the sustainability and profitability of cotton production. Conversely, if conservation agriculture inadvertently favors certain weeds, management strategies must be adapted (e.g. integration of cover crops, targeted weeding) to ensure that conservation agriculture remains beneficial to the farmers. The present study addresses this need by investigating weed dynamics under conservation agriculture in a cotton-maize rotation in Benin. Studies of the specific effect of

conservation agriculture practices on weed community structure in Sub-Saharan Africa contexts are rare.

The aim of the present study was to assess weed emergence and biomass in conservation agriculture practices (strip tillage associated with cover crops, direct-mulched based cropping system) and conventional tillage in cotton-based cropping system in Benin. The specific objectives were to: (i) assess the effect of the cropping system on weed emergence, identify the biomass, count the number of emerged seedlings and weigh aerial weed biomass compared with under the conventional tillage system; and (ii) analyze the effect of the cropping system on weed community structure.

By examining weed dynamics in these contrasting systems, our work provides one of the first comprehensive evaluations of conservation agriculture practices on weeds in a Sub-Saharan Africa cotton/maize rotation. This system, combined with conservation agriculture practices, is increasingly promoted among cotton farmers in Benin as a way to achieve sustainable agriculture. The hypotheses to be tested are: conservation agriculture under strip tillage and direct mulch-based cropping (i) reduces weed pressure by limiting weed emergence and biomass; and (ii) modifies weed community structure by selecting certain weed species. The following section details the site description, experimental design, data collection procedures, and analysis methods used in this study to achieve the objectives set.

2. Materials and methods

2.1. Study site

The trials were conducted at the Permanent Experimentation Center of Okpara, located approximately 10 kilometers from Parakou in the northern Benin (2°41'East, 9°18' North, altitude 320 m above sea level). The climate is Sudano-Guinean (Aw according to Köppen climate classification), characterized by a single rainy season from May to October. Annual rainfall averages between 900 mm and 1110 mm, with mean temperature ranging from 25 °C to 29 °C and relative humidity between 31 % and 98 %, peaking in August (Gandji et al., 2020). The soil is classified as leached tropical ferruginous soil or Lixisol (World Reference Base classification), composed of 76 % sand, 15 % silt, and 9 % clay (Yemadje et al., 2022). The onset of the rainy season occurred in March 2023 and April 2024. Cumulative rainfall from the first weed-triggering rain to 100 days after sowing reached 675 mm in 2023 and 648.5 mm in 2024. Total annual rainfall was slightly higher in 2023 (1186 mm) than in 2024 (1144 mm) (Fig. 1).

2.2. Experimental design

The experiment evaluated three cropping systems differing in soil tillage and residue management:

- Conventional tillage (CT) based on disc plowing: A two-year rotation of cotton and maize managed under conventional tillage. Soil was tilled to 20 cm depth using a cultivator equipped with a moldboard plow. Both crops were grown each year alternating plots and rotated annually.
- Strip tillage (ST): A transition system combined minimum soil disturbance with partial residue cover. A two-season rotation of cotton with a maize-cowpea intercrop under minimum soil disturbance: seed rows were prepared for crop establishment, while 70 % of the soil surface remained untilled. Soil was tilled only in seed rows to a depth of 15–20 cm using a two-wheel tractor equipped with a two-tine strip-tiller. Like in the conventional tillage system, both crops in the rotation were present each season, and elementary plots were swapped around each year.
- Direct mulched-based cropping system (DMC): A no-till, three-year rotation comprising (i) maize intercropped with *Stylosanthes*

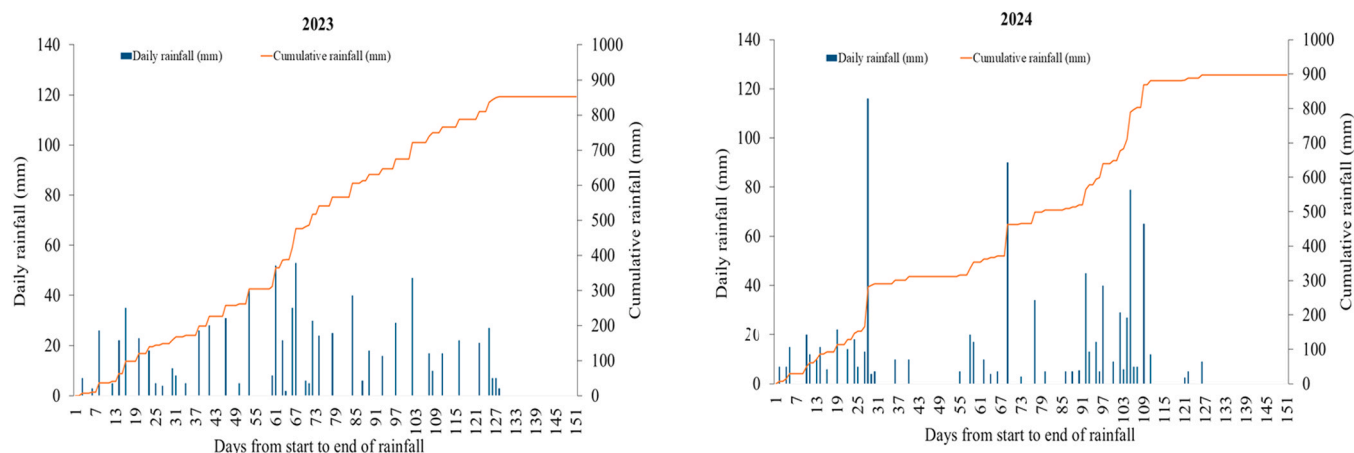


Fig. 1. Cumulative and daily rainfall (mm) after the first rainfall that triggered weed emergence in the two weed monitoring seasons at the Okpara research station located in Benin.

guianensis, (ii) cotton alone, and (iii) sorghum intercropped with soybean, under direct-seeding. The three terms of the rotation were present each season and in each repetition. In the elementary plots, the crops succeeded one another in the following order: cotton followed by maize intercropped with *S. guianensis*, and soybean intercropped with cowpea. Crop residues were left on the soil surface after harvest to ensure the soil cover remained in place throughout the season.

All systems were established in a cotton–maize rotation and maintained for four consecutive cropping seasons (2021–2024). Weed dynamics and community structure were monitored during 2023 and 2024, corresponding to the second and third years of system management. The experimental design was a randomized complete block with three replications. Each replication included seven elementary plots, corresponding to the seven terms of the three systems. Each elementary plots consisted of 10 rows measuring 50 m in length (400 m² per plot). The entire experimental area covered 11,000 m². All plots were established on uniform soil and topography to minimize environmental variability.

2.3. Crop management

2.3.1. Cotton management

The OKP 768 variety (180 days), the variety promoted by cotton research in the study area, was used. Sowing was mechanical with the seeding wheel set at 0.8 m spacing between rows and 0.3 m between holes. The day after sowing, Cotochem G 560 EC composed of 250 g l⁻¹ Fluometuron + 250 g l⁻¹ Prometryn + 60 g l⁻¹ Glyphosate (selective pre-emergence herbicide for cotton with a vast spectrum due to the combination of three active ingredients) was used at a rate of 2 l ha⁻¹ to control annual grasses and dicotyledons for the first 30 days after sowing (Table S1). Fifteen days after sowing, thinning was undertaken and only the most vigorous plant was kept in each hole, giving a total of 41,666 plants per hectare. In all the systems, weeding was carried out following the technical itinerary recommended for the cotton crop in Benin (Table S1). The conventional tillage plots were ridged. Fertilization and phytosanitary protection also followed the technical itinerary recommended for cotton cultivation in Benin (Table S1).

2.3.2. Maize management

The TZPB SRW variety, with a 120-day cycle, was used for the experiment. Sowing was mechanical, the seeding wheel was set at 0.8 m spacing between rows and 0.4 m between holes. Fifteen days after sowing, the plants were thinned to two plants per hole, giving a total of 62,500 plants per hectare. Weed management in the conventional tillage

and strip tillage systems involved applying SOFA 40 SL (Nicosulfuron 40 g l⁻¹), a post-emergence herbicide for maize, between the 17th and 22nd day after sowing at a rate of 2 l ha⁻¹, followed by three weedings (Table S1). Fertilization was at the rate recommended by research (Table S1).

2.3.3. Intercrop plant management

In the strip tillage system, cowpea (*Vigna unguiculata*, variety TAWA with a 90-day cycle) was intercropped with maize cowpea was sown in double rows in the maize interrows, with 0.4 m spacing between the two rows and 0.4 m between the holes. The distance between a row of cowpea and the maize row was 0.2 m. Cowpea was sown after application of nicosulfuron (post-emergence maize herbicide) 20 days after the maize was sown.

In the direct mulched-based cropping system, *Stylosanthes guianensis* intercropped with maize was planted in double rows in the maize inter rows just after maize emergence. *Stylosanthes guianensis* was sown in continuous rows. The distance between two *S. guianensis* rows in a maize interrow was 0.2 m. The following season, the *S. guianensis* biomass and maize residues served as soil cover for the cotton crop.

2.3.4. Sorghum-soybean intercrop

Sorghum (*Sorghum bicolor* L.) and soybean (*Glycine max* L.) intercropping was regularly established in June of each season. The crops were sown on the same day in alternating strips, with four soybean rows alternating with two rows of sorghum. Sorghum was planted at a rate of 3–4 seeds per hole with 0.4 m spacing between holes and 0.4 m between rows. Soybean (120-day variety TGx 1830–20E) was sown at a rate of two seeds per hole with 0.2 m spacing between holes and 0.4 m between rows. The intercropped plots were fertilized with NPKSB at a dose 150 kg ha⁻¹ 10 days after sowing over the whole plot, with a supplement of 17 kg ha⁻¹ of urea at 30 days after sowing, only on sorghum.

2.4. Data collection

Field measurements included weed emergence, weed biomass, crop yield, and residues biomass.

2.4.1. Weed emergence

Weed emergence was recorded in both 2023 and 2024 following the method of Ranaivoson et al. (2018). Measurements were carried within a 0.25 m² quadrat (0.5 × 0.5 m) in each elementary plot (n = 18 quadrats per year). Emerged weed seedlings (monocotyledons and dicotyledons) were counted and removed from the quadrats at seven-day intervals starting from the day of the first rainfall that triggered weed germination. Measurements were taken until 100 days after the first

rainfall. Emergence data were collected on 11 observations in 2023 and eight in 2024. All emerged seedlings were identified to species level using Adventrop key (West African Weeds) for field identification and the PROTA database (<http://www.prota4u.org/>) for confirmation.

2.4.2. Weed biomass

Weed dry matter production was measured in 2024. Samples were collected before each weeding operation using a 1 m² quadrat (1 m × 1 m) randomly located in each elementary plot (n = 18 quadrats per year). Three sampling dates were carried out each year. Aboveground weed biomass was harvested, sorted into monocotyledons and dicotyledons, placed in labeled envelopes, and oven-dried at 70 °C for 48 h until constant weight (Ranaivoson et al., 2018). Dry weights were determined using a Precisa 1620D precision balance (Max 3000 g × 0.1 g).

2.4.3. Crop yield

Cotton seeds yield was determined at full boll opening on the lines. The seed cotton was weighed in each elementary plot and converted into seed cotton production in kg ha⁻¹ (Zhou et al., 2021).

To estimate maize grain yield, maize cobs were harvested 4–6 weeks after physiological maturity. The cobs that were shelled came from an elementary plot, were harvested using a combine harvester. Yields were calculated by extrapolation.

2.4.4. Crop residue biomass

Total aboveground biomass left on the soil surface was determined in plots under strip tillage and direct mulched-based cropping systems in June 2024 before sowing the main crop. The biomass included crop residues and the remaining dry biomass of the intercropped legume. In each subplot, four 1 m² quadrats (1 m × 1 m) were established randomly, and all aboveground residues within these quadrats was collected as a representative sample. The residues collected were then oven-dried at 70 °C for 48 h and weighed to determine dry matter.

2.5. Statistical analysis

Weed emergence and biomass were analyzed separately per season and for each crop (cotton and maize). The data were then pooled across the two seasons and analyzed for each crop. A generalized linear mixed model (GLMM) was used to assess the effect of the cropping system, season, crop, and their interactions as fixed effects, and the plot as random effect, on cumulated weed emergence, with a Poisson error distribution. The adequacy of Poisson models was evaluated by assessing dispersion and residual diagnostics (no substantial overdispersion). The glmer function in the lme4 package of R software was used. A linear mixed model (LMM) was also used to assess the effect of cropping system, season, crop, and their interaction as fixed effects and plot as a random effect on weed biomass, with a Gaussian law. The lmer function in the lme4 package of R software was used for this analysis. A type III ANOVA ('lmerTest' in the R package) was used to assess the main effects of the factors, i.e. cropping system, crop and season, as well as the effect of their interactions on weed emergence and biomass. Estimated means of emerged seedlings and weed biomass were calculated and compared using Tukey's method ('emmeans' in the R package).

Because cotton is highly sensitivity to weed competition early in the season, weed emergence data were also analyzed according to the observation date for each season and each crop (Tariq et al., 2020). The plot was considered to be a random factor in this analysis. A correlation analysis was conducted to assess the relationship between weed seedling emergence and biomass as a function of the crop and the season.

Non-metric multidimensional scaling (NMDS) was performed to examine changes in weed species composition in response to the cropping system (CT, ST or DMC), the crop (cotton or maize), the season (2023 or 2024) and their interaction using the metaDMS function (vegan package) (Dawson et al., 2021; Ren et al., 2024). The NMDS analysis was

performed using 999 random permutations and a stable solution was sought by recovering the lowest stress value. The number of NMDS dimensions was set at two or three to allow a stress value lower than 0.2. The influence of the interaction between cropping system and crop, cropping system and season, crop and season and cropping system, crop and season on community structure was tested with a permutational ANOVA (adonis2 function, vegan package, with the Bray-Curtis distance calculation method). This analysis was combined with a post-hoc test (pairwise function. adonis2 from the pair-wise Adonis package) to test for significant differences between cropping system, season, and crop (Martinez Arbizu, 2022). We used the multipatt function in the indispes package to identify weed species significantly associated with each cropping system and crop as a function of the season (De Caceres et al., 2016). Following a Tukey's test, a linear model was used to compare seasonal and then two-season yields of seed cotton and grain maize between the systems. Relative yields were determined for cotton and maize as the ratio of the direct mulched-based cropping, and strip tillage systems with respect to the conventional tillage system and multiplied by 100. All statistical analyses were performed in R version 4.4.2.

3. Results

3.1. Weed emergence

The cropping system significantly influenced ($p < 0.05$) the emergence of monocotyledonous and total weed biomass and interacted with season in the maize plots (Table S2). Fewer weed seedlings emerged in the strip tillage (ST) and direct mulched-based cropping (DMC) systems than in the conventional tillage (CT) system, particularly in 2023 (Fig. 2).

Considered separately, the cropping system significantly ($p < 0.05$) influenced weed emergence in both the cotton and maize plots (Table 1). In 2023, in the maize plots, the number of seedlings of dicotyledonous, monocotyledonous and total weeds was significantly higher under the CT system than under the ST and DMC systems (Table 1). Only the emergence of monocotyledonous weeds varied significantly ($p = 0.029$) between cropping systems in the cotton plots. The most seedlings emerged (3995 ± 443 seedlings m⁻²) under the CT system. In 2024, weed emergence, particularly of dicotyledons and total weeds, was significantly lower under the DMC system compared to under the CT and ST systems (Table 1). Emergence of monocotyledonous weeds was significantly higher ($p < 0.05$) under ST. In maize plots, the number of dicotyledonous weed seedlings and the total number of weed seedlings recorded was significantly higher ($p < 0.05$) under the CT system (Table 1). Our results also highlighted a significant variation ($p < 0.05$) in weed emergence according to the cropping season. The number of emerged seedlings of dicotyledonous, monocotyledonous and total weeds was higher in 2023 than in 2024 in both cotton and maize plots (Table 1). Over two seasons, weed emergence was much higher under the CT system (CT > ST > DMC), although the difference between the systems was not significant in cotton (Table S2). Conservation agriculture systems reduced total weed emergence by 15 % (ST) and 33 % (DMC), compared to CT system in cotton plots. In maize plots, the percentage reduction in weed emergence was 46 % under ST and 56 % under DMC (Table S2).

3.2. Weed biomass

A significant effect of interactions between the cropping system and the season was observed on dicotyledonous weed biomass and total weed biomass in the maize crop (Table S2). The highest dicotyledonous and total weed biomass values were reached under the ST system in 2024 (Fig. 3).

In 2023, dicotyledonous weed biomass and total weed biomass was significantly ($p < 0.05$) greater under the ST system with cotton. In

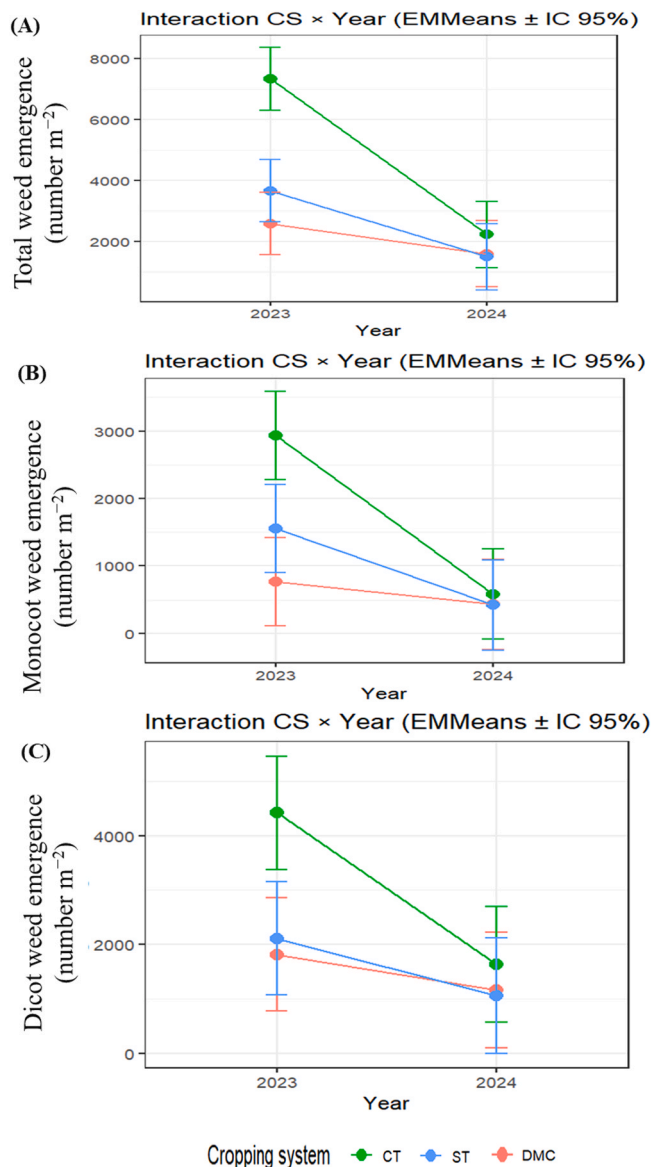


Fig. 2. Cumulated weed emergence under different cropping systems (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system) depending on the season in the maize plot. CS: cropping system, EMMeans: estimated marginal means, CI: confidence interval.

maize plots, no significant differences in the amounts of weed biomass were observed between systems (Table 1). In 2024, dicotyledonous and total weed biomass varied significantly ($p < 0.05$) between cropping systems only in maize plots. The highest levels of dicotyledonous weed biomass and total weed biomass were also recorded under the ST system. Dicotyledonous, monocotyledonous and total weed biomass also varied with the season, with significantly higher biomass production in 2024 than in 2023 (Table 1). Overall (averaged over two seasons), weed biomass was higher under the ST system and lower under the DMC system (CT > ST > DMC). The CT system resulted in an increase in total weed biomass of 40 % in cotton and 41 % in maize.

3.3. Weed emergence dynamics according cropping systems, type of crop and season

Overall, the strip tillage and direct mulch-based cropping systems reduced weed emergence more than the conventional tillage system (Fig. 4). In 2023, both the ST and DMC system did reduce weed

emergence. In cotton plots, the total number of emerged weed seedlings was higher under the CT system than under ST and DMC, although the difference was not statistically significant ($p > 0.05$; Fig. 4A). The CT system favored emergence of monocotyledonous weeds, while the ST and DMC systems favored emergence of dicotyledonous weeds, particularly up to the 60th days after sowing (Fig. 4B and C). In maize plots, weed emergence, monocotyledonous, dicotyledonous, and total weeds, was significantly lower ($p < 0.05$) in the ST and DMC systems than in CT system throughout the observation period (Fig. 4D, E, and F).

In 2024, overall weed emergence was weak across all systems (Fig. 4G, H, I, J, K, and L). In cotton plots, dicotyledonous and total weed seedling densities were slightly higher under CT and monocotyledonous weed seedling densities were slightly higher under ST. No significant difference ($p > 0.05$) was observed between systems. The trend in maize plots was almost identical to that observed in cotton plots, with slightly higher emergence of monocotyledonous weeds under the CT system (Fig. 4J, K, and L).

3.4. Weed biomass dynamics according cropping systems, type of crop and season

In 2023, weed biomass in the cotton plots was highest under the ST system, particularly dicotyledonous and total biomass. The differences were significant at 40 days after sowing (total biomass) and at 60 days after sowing (dicotyledonous biomass) ($p < 0.05$; Fig. 5A and C). No significant differences were observed in monocotyledonous weed biomass between cropping systems (Fig. 5B). In maize plots, monocotyledonous, dicotyledonous, and total weed biomass did not differ significantly among the cropping systems ($p > 0.05$; Fig. 5D, E and F).

In 2024, weed biomass in the maize plot was significantly higher under the ST system up to 40 days after sowing, particularly the biomass of dicotyledonous weeds (Fig. 5L). From 60 days after sowing, the CT system had significantly ($p < 0.05$) more dicotyledonous and total weed biomass than under conservation agriculture systems (DMC and ST) (Fig. 5J and L). In the cotton plots, no significant differences in monocotyledonous, dicotyledonous, and total weed biomass were observed across systems at any time point ($p > 0.05$) (Fig. 5G, H, and I). Under the ST system, monocotyledonous and total weed biomass was slightly higher at 40 days after sowing (Fig. 5G and H).

3.5. Correlation between weed biomass and weed emergence

Total weed emergence and total weed biomass were significantly and positively correlated across most plots ($p < 0.05$; $0.56 \leq r \leq 0.65$) (Fig. S1A, C, and D). In contrast, no significant correlation ($p > 0.05$) was observed between the same variables in the maize plots in the 2023 season (Fig. S1B). A strong significant correlation ($p < 0.05$) was observed between total weed biomass and the biomass of monocotyledonous and dicotyledonous weeds in both seasons (Fig. S1). Similarly, a significant correlation ($p < 0.05$) was found between total weed emergence and the emergence of monocotyledonous and dicotyledonous weeds (Fig. S1). No significant correlation ($p > 0.05$) was observed between emergence and biomass of monocotyledonous weeds or between those of dicotyledonous weeds (Fig. S1B and D).

3.6. Weed community analysis

We hypothesized that conservation agriculture practices (ST and DMC) alter weed community structure by selecting particular weed species. The results of the study revealed significant differences ($p < 0.05$) in weed community structure, both in terms of cropping systems and growing season.

3.6.1. Variation in weed community structure

Permutational analysis of variance showed that weed community structure was significantly influenced by the interaction between the

Table 1

Effect of the cropping system and the season on the cumulative number of seedlings and weed biomass. Mean $\pm$ standard error, p -values from the variance analyses are indicated.

Season	Cropping system (CS)	Cotton			—	Maize		
		Dicot	Monocot	Total		Dicot	Monocot	Total
Cumulative number of weed seedlings (number m ⁻²)								
2023	CT	2490 ± 347	3995 ± 443 ^a	6486 ± 763	4414 ± 370 ^a	2932 ± 292 ^a	7345 ± 611 ^a	
	ST	3344 ± 330	2023 ± 218 ^{ab}	5368 ± 450	2111 ± 307 ^{ab}	1554 ± 155 ^{ab}	3664 ± 369 ^b	
	DMC	3156 ± 314	1567 ± 133 ^b	4723 ± 357	1817 ± 190 ^b	766 ± 97 ^b	2583 ± 228 ^b	
	Mean	2997 ± 193 ^A	2529 ± 199 ^A	5525 ± 324 ^A	2780 ± 207 ^A	1751 ± 145 ^A	4531 ± 322 ^A	
	Effect - CS	p = 0.502	p = 0.029*	p = 0.249	p = 0.013*	p = 0.004**	p < 0.001***	
2024	CT	1649 ± 209 ^a	420 ± 56 ^{ab}	2069 ± 254 ^a	1642 ± 166 ^a	582 ± 51	2224 ± 216 ^a	
	ST	1169 ± 103 ^a	749 ± 92 ^a	1918 ± 188 ^a	1068 ± 123 ^b	421 ± 40	1489 ± 151 ^b	
	DMC	767 ± 87 ^b	284 ± 28 ^b	1051 ± 108 ^b	1162 ± 131 ^{ab}	430 ± 48	1592 ± 173 ^{ab}	
	Mean	1195 ± 92 ^B	484 ± 43 ^B	1679 ± 122 ^B	1290 ± 86 ^B	478 ± 28 ^B	1768 ± 110 ^B	
	Effect - CS	p = 0.032*	p = 0.029 *	p = 0.041 *	p = 0.009**	p = 0.065	p = 0.009**	
	Main effect - S	p = 0.005**	p < 0.001***	p < 0.001***	p = 0.002**	p < 0.001***	p < 0.001***	
Weed biomass (g m ⁻²)								
2023	CT	27 ± 7 ^b	46 ± 13	72 ± 18 ^b	47 ± 9	33 ± 14	80 ± 20	
	ST	111 ± 21 ^a	39 ± 10	150 ± 24 ^a	40 ± 8	34 ± 14	74 ± 22	
	DMC	48 ± 8 ^b	22 ± 10	70 ± 14 ^b	38 ± 10	32 ± 13	71 ± 21	
	Mean	62 ± 10 ^B	36 ± 6 ^B	97 ± 13 ^B	42 ± 5 ^B	33 ± 8 ^B	75 ± 12 ^B	
	Effect - CS	p = 0.009**	p = 0.393	p = 0.005**	p = 0.818	p = 0.998	p = 0.959	
2024	CT	161 ± 42	80 ± 29	240 ± 44	200 ± 45 ^{ab}	161 ± 33	361 ± 50 ^{ab}	
	ST	153 ± 31	154 ± 44	307 ± 72	400 ± 43 ^a	148 ± 34	547 ± 47 ^a	
	DMC	155 ± 32	116 ± 23	271 ± 46	183 ± 26 ^b	108 ± 30	292 ± 34 ^b	
	Mean	156 ± 20 ^A	117 ± 19 ^A	272 ± 31 ^A	261 ± 29 ^A	139 ± 18 ^A	400 ± 32 ^B	
	Effect - CS	p = 0.994	p = 0.523	p = 0.823	p = 0.016 *	p = 0.753	p = 0.012 *	
	Main effect - S	p = 0.030**	p = 0.030 *	p = 0.007 **	p < 0.001***	0.016 *	p < 0.001***	

CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system, Monocot: monocotyledon, Dicot: dicotyledon, S: season, CS: cropping system. For each season and for the means, values with different letters in the same column are significantly different at $p < 0.05$ according to Tukey's test. The values in bold in the table are key results.

cropping system and the season, and also between the crop and the season (Table 2). The same analysis also showed that weed community structure was significantly influenced by the cropping system, the season, and the type of crop. The season was the key factor that determined dissimilarity of weed species structure with $R^2 = 0.286$.

In both 2023 and 2024, the non-metric multidimensional scaling showed that weed community composition differed between systems, although some weed species were found in both (Fig. 6A). The results did not reveal a trend towards a particularly specific weed class (monocotyledonous or dicotyledonous) in any of the cropping systems (Fig. 6A). For each crop, in both 2023 and 2024, non-metric multidimensional scaling showed that weed community composition differed between crops, although some weed species were found in both (Fig. 6B).

A more detailed weed community analysis showed that in 2023, the weed communities in the cropping systems differed at the beginning of the cotton cycle. Over the course of the cycle, the communities gradually converged to become a nearly identical weed community at the end of the cycle (Fig. 7A). This was not the case in 2024 (Fig. 7B).

In maize in both 2023 and 2024, the results revealed different weed communities in the different cropping systems throughout the crop cycle (Fig. 7C and D).

3.6.2. Indicator weed species for cropping systems and crops

The abundance of certain weed species and indicator species that are of interest in assessing agroecological transitions varied with the cropping system, type of crop and season (Fig. 8). Overall, weeds were less abundant in 2024 than in 2023.

In cotton in 2023, *Commelina benghalensis*, *Cyperus esculentus* and *Galinsoga parviflora* were strongly linked to the ST system as indicator species (Fig. 8A). On the other hand, the ST and DMC systems were particularly associated with other weed species, including *Tridax*

procumbens, which was common to both. *Kyllinga squamulata* was the indicator weed species for the ST system while *Leucas martinicensis* was associated with the DMC system (Fig. 8A). In maize in 2023, *C. benghalensis*, *Digitaria horizontalis* and *T. procumbens* were particularly associated with the ST system, while *Brachiaria deflexa* and *T. procumbens* were particularly associated with the CT system (Fig. 8B). Only *G. parviflora* was associated with the DMC system.

In cotton in 2024, no weed species were particularly associated with the DMC system as indicator species. *Brachiaria deflexa* was associated with the CT system and *Ipomoea eriocarpa* was associated with the ST system (Fig. 8C). In maize in 2024, the three systems compared also contained different indicator species. The CT and ST systems had the *Oldenlandia corymbosa* species in common (Fig. 8D).

A more detailed analysis of indicator species, based on abundance matrices, enabled us to identify specific weed species in cotton or maize associated with different cropping systems (CT, ST, DMC), depending on the cropping period. This analysis also enabled us to understand the changes in status (indicator species or not) of weed species in the different cropping systems over the two seasons.

In 2023, the results showed a clear floristic differentiation between the three systems. In the case of cotton (Fig. 9A), three dicotyledonous (*G. parviflora*) and monocotyledonous (*C. benghalensis* and *C. esculentus*) species were clearly associated with the CT system. This illustrates their affinity for frequently disturbed environments. *Commelina benghalensis* and *C. esculentus* changed status over time and were no longer indicators of the CT system from the 59th and 73rd days after cotton sowing (Fig. 9A). The *G. parviflora* species became indicative of this system from the 31st day after cotton sowing (Fig. 9A). In contrast, *K. squamulata* and *T. procumbens* were identified as indicator species for the ST system, while *L. martinicensis* and *T. procumbens* were associated with the DMC system. While indicator species of the ST system changed over the course of the season, DMC indicator species disappeared completely after the

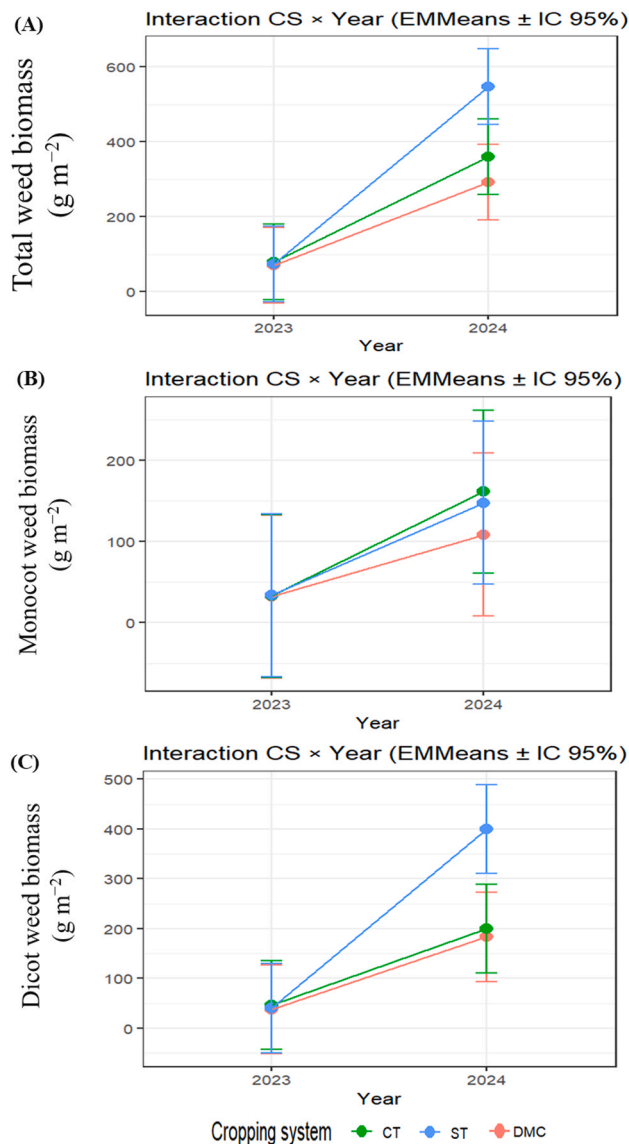


Fig. 3. Cumulated weed biomass under different cropping systems (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system) depending on the season in the maize plot. CS: cropping system, EMMeans: estimated marginal means, CI: confidence interval.

59th day after sowing (Fig. 9A).

In maize (Fig. 9B), the result was the same in that species became indicators (such as *G. parviflora* in the DMC system) while other species that were initially indicators changed status (*C. benghalensis* in the ST system) or disappeared (*T. procumbens* in the DMC system). *Brachiaria deflexa* (monocotyledon species) was a permanent indicator species of the CT system until the end of observations on the 87th day after sowing (Fig. 9B).

In 2024, in both cotton and maize, the indicator species for the three systems remained different throughout the season (Fig. 9). No indicator species for one cropping system changed status during the course of one season to become an indicator for another cropping system. In cotton in 2024, no weed species was particularly associated with the DMC system at any time during the season (Fig. 9C). In contrast, *B. deflexa* and *I. eriocarpa* were associated with both the CT and ST systems (Fig. 9C). In maize in 2024, *Gomphrena celosioides* was particularly associated with the DMC system throughout the season. *Richardia scabra* was an indicator species for the DMC system at the beginning (25th day after sowing) and end (74th day after sowing) of the season, while *L. martinicensis* was

particularly associated with this system between the 39th and 53rd day after sowing. *Oldenlandia corymbosa* was particularly associated with ST (between the 39th and 67th days after sowing) and CT systems (with a change in status between the 32nd and 53rd day after sowing to become a species that was simply present). *Tridax procumbens* was also associated with the ST system at some point during the season. In contrast, *Physalis angulata* became an indicator species for the CT system toward the end of the season.

3.7. Crop yield

The effect of the interaction between cropping system and season on crop yields was not significant (Table 3). Cotton yields did not differ significantly ($p > 0.05$) between the three systems in either 2023 or 2024. Maize yield varied significantly ($p < 0.05$) in 2023, and the CT system led to higher yields (Table 3). Yield penalties of maize were observed under the ST (31 %) and DMC (48 %) systems compared to under the CT system in 2023. In 2024, no significant differences were observed in the yields of maize ($p > 0.05$) between the three systems. Crop yield penalties in cotton and maize were lower in 2024 (Table 3). The yields of two crops were not significantly affected by the season (Table 3).

4. Discussion

The results of the present study showed that the strip tillage and direct mulch-based cropping systems systematically reduced weed pressure and limited the emergence of certain weeds species compared to the conventional tillage system. This confirms the well-documented role of tillage, cover crop and rotation design in shaping weed dynamics (Ranaivoson et al., 2017). In the cotton plot, the strip tillage system favored the emergence of dicotyledonous weeds in 2023 and monocotyledonous weeds in 2024, possibly due to crop rotation that included cowpeas intercropped with maize (cotton/maize + cowpea). As a legume, cowpea can enhance soil nitrogen availability up to 88 kg N ha⁻¹ under semi-arid conditions (Bationo et al., 2002), which improves soil fertility for the following crop. This improved fertility could inadvertently also favor weeds, by creating a nutrient-rich environment conducive to vigorous weed growth.

The quantity and quality of mulch differed substantially between systems, potentially contributing to weed emergence trends. This difference likely reflects the biomass production potential of crops used as cover crops (soybean and *Sorghum bicolor*) under direct mulch-based cropping thereby contributing more efficiently to surface mulching. Previous research showed that more than 10 t ha⁻¹ of crop residues are typically needed to limit both the emergence and growth of weed biomass efficiently (Ranaivoson et al., 2018). Partial soil cover, such as in strip tillage, may even stimulate weed emergence by creating favorable microclimatic conditions (Ranaivoson et al., 2017). This could explain the weed biomass peaks observed at 40 and 60 days after sowing under strip tillage (Fig. 5).

Overall, these results highlight that weed suppression in conservation systems is governed by complex interactions between the level of residues, soil fertility and the rotation design. Optimizing these components is essential to enhance the weed-suppression potential of strip tillage and direct mulch-based cropping systems in different agroecological contexts.

4.1. Effect of cropping systems on weed emergence

Strip-tillage and direct mulch-based cropping systems significantly reduced weed emergence compared to the conventional tillage system. This suppression may be due to reduced soil disturbance (Mishra et al., 2022), continuous soil cover (Puniya et al., 2023), or a combination of reduced soil disturbance and soil cover (Choudhary, 2023), which disrupt the germination conditions (light, temperature fluctuations,

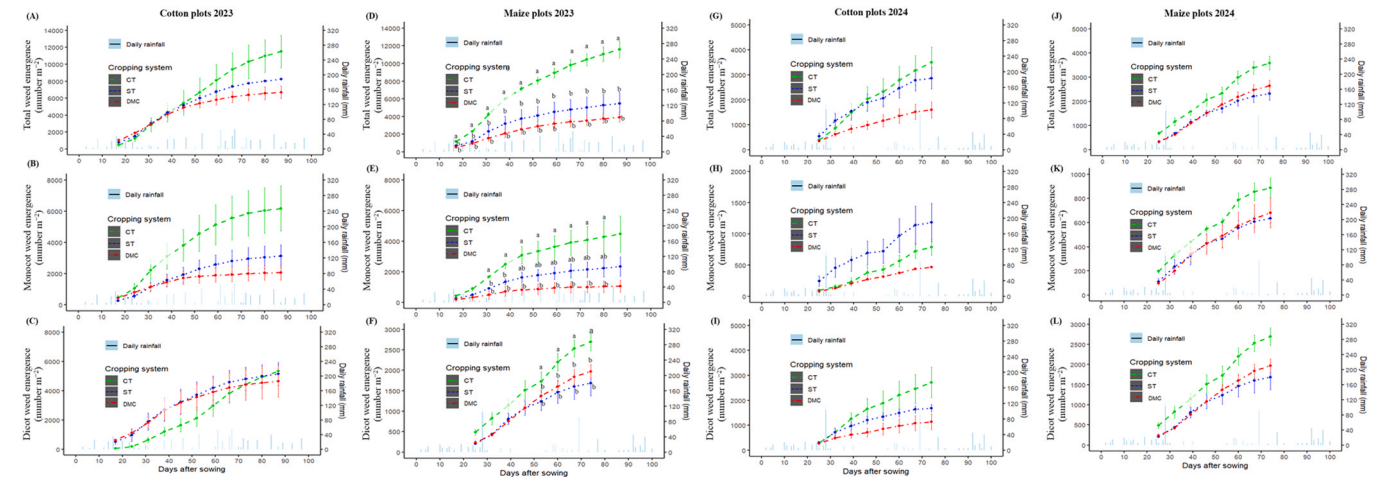


Fig. 4. Cumulated weed emergence in cotton plots (A, B, and C) and maize plots (D, E, and F) in the 2023 season, and in cotton plots (G, H, and I) and maize plots (J, K and L) in the 2024 season as a function of the cropping system (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system). Different letters on the same observation date indicate significant differences between systems at $p < 0.05$.

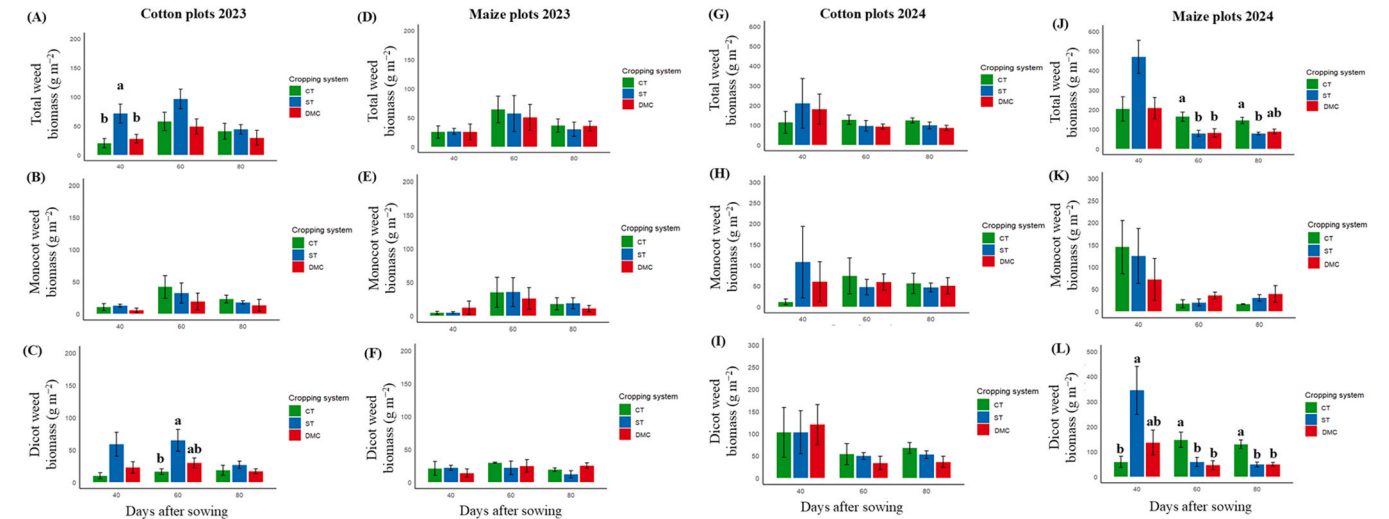


Fig. 5. Weed biomass in cotton plots (A, B, and C) and maize plots (D, E, and F) in the 2023 season and in cotton plots (G, H, and I) and maize plots (J, K and L) in the 2024 season as a function of the cropping system (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system). Different letters at the bars indicate significantly different biomass values between cropping systems at a 5% significance level for each observation date.

Table 2
Results of the PERMANOVA test of the effects of the cropping system, season, crop and their interactions on Bray-Curtis dissimilarities between weed species.

Response variable	Treatment	F _{Model}	R ²	P-value
Species composition	Cropping system (CS)	3.29	0.099	0.005**
	Season (S)	18.91	0.286	0.001***
	Crop (C)	3.00	0.045	0.022*
	CS x S	2.18	0.066	0.027*
	CS x C	1.71	0.052	0.074
	S x C	2.41	0.036	0.038*
	CS x S x C	1.73	0.052	0.061

*** indicates statistical significance at 0.001, ** indicates statistical significance at 0.01, and * indicates statistical significance at 0.05. The values in bold in the table are key results.

moisture dynamics) that many weed seeds require. Crop residues on the soil surface influence the seed bank in no-till systems by affecting microenvironments that cause fluctuations in soil temperature, which can affect weed seed germination (Weber et al., 2017). Crop residues left on the soil surface play several important physical barrier and agronomic

roles (Ranaivoson et al., 2017; 2018), intercept light and lowers red: far-red ratio (Rajcan et al., 2004), decrease soil temperature amplitude needed to release dormancy in some species (Unger, 1978). This mechanism would progressively reduce weed emergence over the seasons under these two systems. This would explain the drop in weed densities obtained under conservation agriculture systems and during the second season (2024) of this study. At the same site as the present study in Benin, Atakoun et al. (2023) reported similar findings, with reduced weed emergence under higher biomass cover. The reduction in weed emergence obtained in the present study could also be due to the allelopathic effect of the biomass of previous soybean and *Sorghum bicolor* (soil cover in direct mulch-based cropping) (Alsaadawi et al., 2019), and cowpea (soil cover in strip tillage) with the physical mulch barrier. According to Moyer et al. (2000), crop residues could also contain allelopathic substances that inhibit seed germination. In conservation agriculture, seeds mostly remain on the surface, where they are subjected to more stable conditions and often unfavorable to germination (Nichols et al., 2015). Prolonged exposure of seeds to the surface increases their mortality, due to desiccation, predation (Trichard et al., 2013), and microbial degradation (Hossain and Begum, 2015).

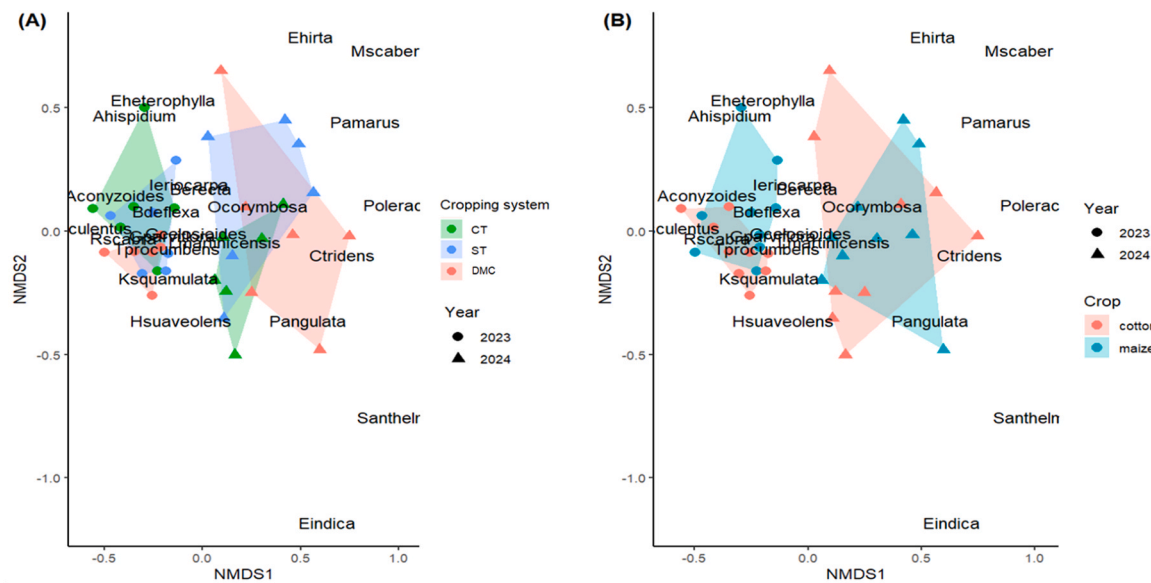


Fig. 6. Change in weed community structure using a non-metric scaling method (NMDS, k = 2, stress=0.19) under the effect of interactions between the cropping system (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system) and the season (A) and between the season and the crop (B).

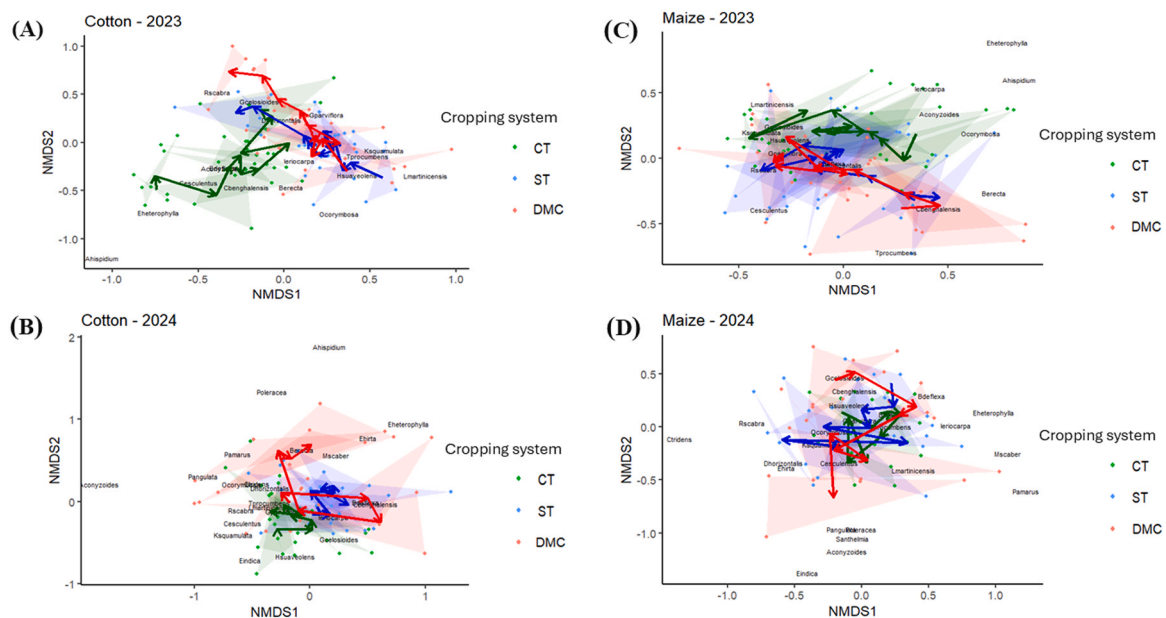


Fig. 7. Change in weed community structure using a three-dimensional non-metric scaling method (NMDS, k = 3, stress=0.15) under the effect of interactions between the cropping system (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system) the season during the crop cycles. Green, blue, and red arrows changes in community structure during the crop cycle.

The poor weed emergence observed with strip tillage and direct mulch-based cropping systems could also be explained by a progressive decrease in the number of viable seeds. This reduction would result from their prolonged exposure to the soil surface, promoting predation and degradation, as these authors have mentioned. Weed emergence was particularly low under the direct mulch-based cropping system. This result may be linked to longer rotation and diversification of the active ingredients in the herbicide (Shahzad et al., 2021). Nevertheless, other studies have produced different results showing that total weed emergence in strip tillage systems was higher than with conventional tillage (Demjanová et al., 2009). The difference between the results of the present study and those of the above mentioned authors could be linked to the weed species and environmental conditions that differed in the two studies (south-western Slovakia vs. northern Benin). Çeṫan et al.

(2022) also highlighted that reduced tillage system increases the quantity of weeds, particularly perennial weeds.

Seasonal and crop-specific variations also affected weed emergence patterns. These findings are in line with reports by Mavunganidze et al. (2020) and Palsaniya et al. (2024) emphasizing that the effect of tillage on weed emergence is highly context-dependent, and is influenced by seasonal weather patterns, the type of crop, and the cropping system. Overall, while strip tillage and direct mulch-based cropping systems effectively reduce weed emergence, their effectiveness varies with the environmental conditions and the type of crop (Fig. 2). This result reinforces the need to tailor weed management strategies to each specific system within the framework of conservation agriculture (Shrestha et al., 2002).

One solution to weed management under the strip tillage system to

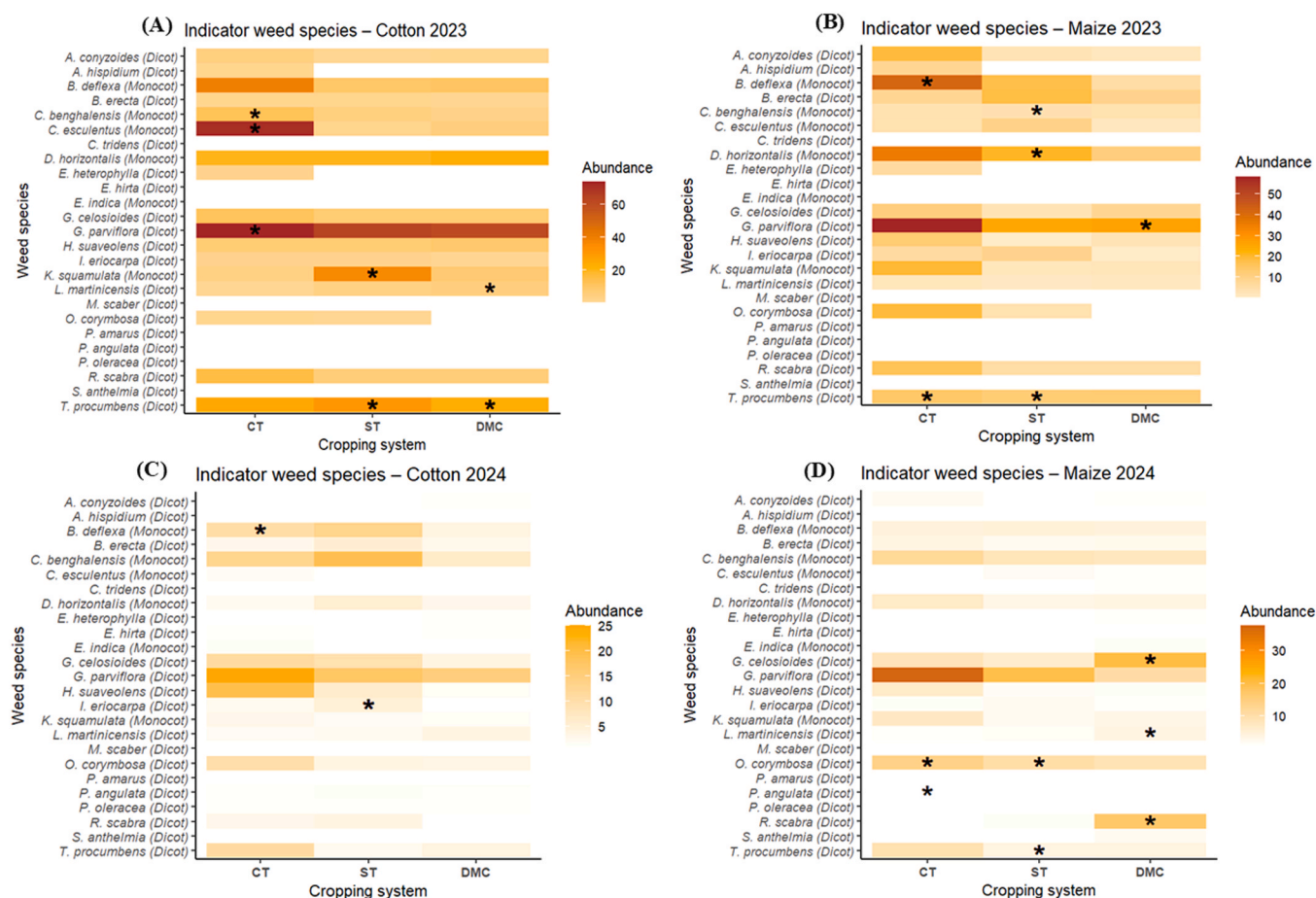


Fig. 8. Changes in the emergence of indicator weed species depending on the cropping system (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system) and crop. Indicator species (statistically associated with a condition, $p < 0.05$) are indicated by “*”. White spaces in the graph mean the species was not present. The white in the graphs indicates that the species is weakly present or absent.

facilitate its adoption would be to plant cover legumes such as *Crotalaria juncea*, *Mucuna pruriens*, *Vigna unguiculata* and *Vigna radiata* when the first rains start, to produce biomass into which the main crop is then sown after weeding. In the strip tillage system, this biomass is then used as a soil cover to prevent weeds developing, particularly during the first 40 days after emergence. It is essential to exploit the weed control potential of a mixture of annual/perennial species, for example mixtures of *Stylosanthes hamata*, *Chamaecrista rotundifolia*, *Crotalaria retusa*, *Centrosema pascuorum*, or those able to maintain themselves by their seeds in our dominant grazing contexts. Scavo and Mauromicale (2021) reported that strategies like intercropping, using cover crops as living or dead mulches, green manuring, and use of allelochemical-based bioherbicides were more effective when included in an integrated weed management strategy.

4.2. Effect of cropping systems on weed biomass

Total weed biomass was higher under conservation agriculture systems, particularly under the strip tillage system, indicating a disconnect between emergence and weed biomass (Table 1). This likely reflects differences in species composition and growth strategies. Fewer but bigger individuals could result in similar biomass under reduced emergence conditions. Similar trends were observed by Hofmeijer et al. (2019) and Feledyn-Szewczyk et al. (2020), who observed higher aboveground weed biomass under strip tillage systems despite lower weed densities. Similarly, Appah et al. (2024) found denser weed biomass under no-tillage conditions. These results highlight the need to implement weed management strategies adapted to conservation

agriculture systems to ensure their sustainable adoption. At low density, each weed plant has more space (Abdul Rahman et al., 2024), light, water and nutrients (Feng et al., 2020), which reduces intraspecific competition and promotes more vigorous individual growth. This could be the case in this study and would explain the high biomass observed under conservation agriculture systems, particularly the strip tillage system. The result could also be explained by greater weed seedling development in the strip tillage and direct mulch-based cropping systems, due to potentially greater availability of mineral elements. MacLaren et al. (2019) mentioned that the availability of mineral elements, particularly nitrogen, had the strongest influence on weed biomass. If integrated into strip tillage and direct mulch-based cropping systems, nitrogen-fixing legumes such as cowpea and *Stylosanthes guianensis*, would have improved nitrogen stocks in these systems. When there are fewer individual weeds in the vicinity, each plant has access to more resources, such as light, water, and nutrients. This situation allows the weeds that succeed in emerging to grow more strongly and to accumulate more biomass. Under strip tillage, the weed species that emerge may be those capable of growing rapidly with little competition. These could be the species that produce the most biomass as reported by Hossain et al. (2021), which would be the case in this study. In contrast, Nwagwu et al. (2022) reported a reduction in weed biomass in a no-till system compared to in a conventional tillage system in Nigeria.

In the present study, weed biomass was higher in the second season, even though weed emergence was higher in the first season. This likely resulted from reduced intraspecific competition in the second season, which allowed individual weeds to grow more vigorously. Higher rainfall during the biomass collection period in 2024 may also have

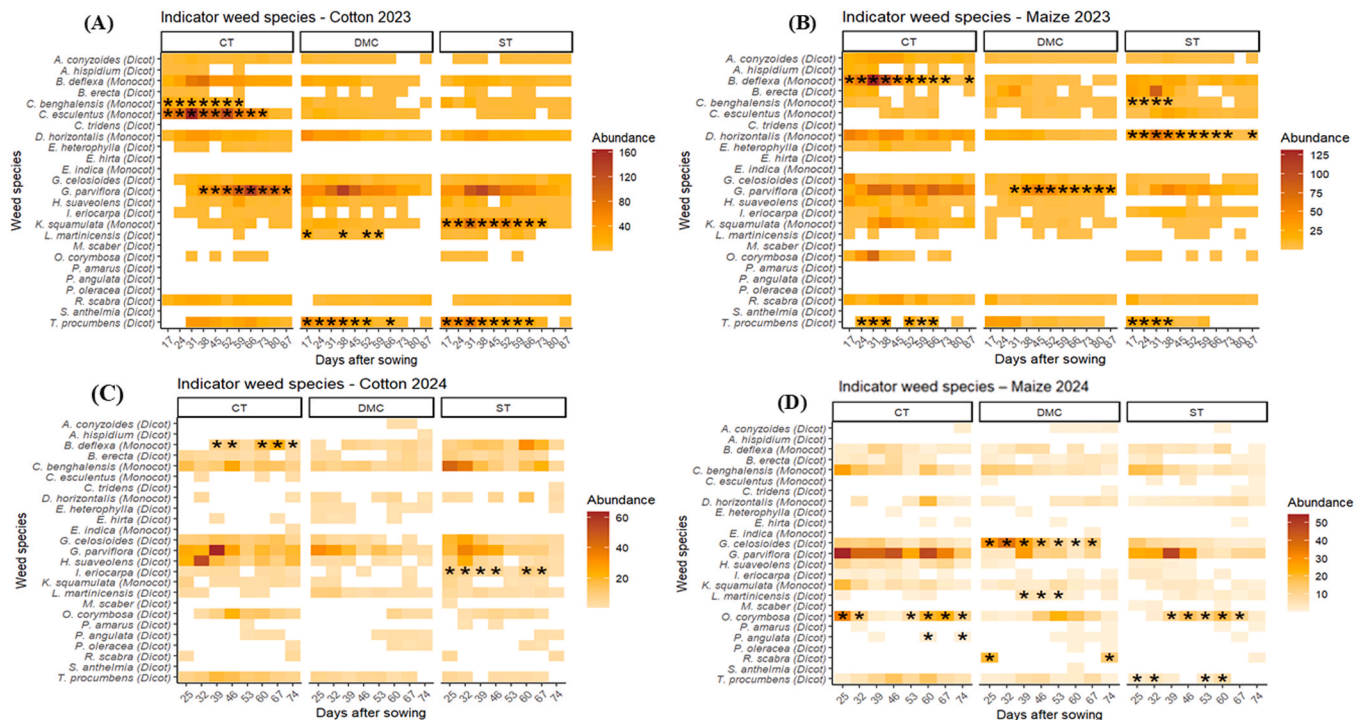


Fig. 9. Changes in the emergence of indicator weed species during the crop cycle, depending on the cropping system (CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system) and the crop. Indicator species (statistically associated with a condition, $p < 0.05$) are indicated by ‘*’. White spaces in the graph mean that the species was not present.

Table 3
Crop yields (cotton and maize) according to the system and the season (mean $\pm$ standard error).

Season	Cropping system	Cotton		–	Maize	
		Yield (kg ha ⁻¹)	Mean relative yield (%)		Yield (kg ha ⁻¹)	Mean relative yield (%)
2023	CT	1395 $\pm$ 67			1863 $\pm$ 355 ^a	
	ST	1007 $\pm$ 131	-28		1285 $\pm$ 301 ^b	-31
	DMC	1025 $\pm$ 110	-27		964 $\pm$ 69 ^b	-48
	Mean	1142 $\pm$ 67			1371 $\pm$ 189	
	Effect - CS	$p = 0.308$			$p = 0.019^*$	
2024	CT	1074 $\pm$ 88			1518 $\pm$ 198	
	ST	979 $\pm$ 61	-9		1400 $\pm$ 144	-8
	DMC	784 $\pm$ 44	-27		1339 $\pm$ 69	-12
	Mean	935 $\pm$ 41			1419 $\pm$ 78	
	Effect - CS	$p = 0.089$			$p = 0.697$	
Mean over two seasons	Main effect - S	$p = 0.115$			$p = 0.792$	
	CT	1235 $\pm$ 110			1690 $\pm$ 198	
	ST	993 $\pm$ 91	-20		1343 $\pm$ 151	-21
	DMC	905 $\pm$ 98	-27		1151 $\pm$ 94	-32
	Main effect - CS	$p = 0.112$			$p = 0.080$	
Interaction	CS x S	$p = 0.563$			$p = 0.285$	

CT: conventional tillage, ST: strip tillage, DMC: direct mulch-based cropping system, S: season, CS: cropping system. For each season and for the means, values with different letters in the same column are significantly different at $p < 0.05$ according to Tukey’s test. The values in bold in the table are the key results

enhanced weed development. In support of this hypothesis, Ren et al., (2023) showed that increased water availability significantly enhances aboveground biomass in *A. philoxeroides*, a highly invasive weed species. The higher biomass values recorded under the strip tillage system in the present study and could be a barrier to the adoption of this technique. As demonstrated by Mihelić et al. (2024), improvement of soil quality in the context of strip tillage combined with fertilizer plants, could promote its attractiveness in a context of agricultural sustainability. Interestingly, the correlation between weed emergence and biomass was not always significant (Fig. S1). This result shows that plant size and growth rate contribute more to biomass than seedling density.

This result also underlines the importance of monitoring both parameters for a comprehensive understanding of weed pressure. In light of these findings, early-season weed management is critical in strip tillage systems. Mechanical or chemical weed control during the first 40 or even 60 days after sowing appears essential to avoid yield losses. Weeds are most competitive when soil exposure is at its highest (Li et al., 2025).

4.3. Effect of cropping systems on weed communities

The shift in weed community structure among systems reflects trait-based sorting by the altered microenvironment. Conventional system

produced the highest weed abundance and diversity, favoring species such as *G. parviflora*, *C. esculentus*, *O. corymbosa*, *E. heterophylla*, *H. suaveolens*, and *T. procumbens* (Figs. 8 and 9). These fast-growing, opportunistic annuals thrive in disturbed soils and open canopy environments where germination is promoted by marked fluctuations in light and temperature. In contrast, by maintaining a continuous soil cover and avoiding mechanical soil disturbance, the direct mulch-based cropping system likely restricts the light and temperature fluctuations required by many of these species. The results of the present study clearly demonstrate the significant influence of the cropping system on weed community structure (Armengot et al., 2016), weed abundance, and species composition (Naeem et al., 2021), in line with previous studies. This result could be linked to the tillage method, the soil cover or even the nature of the species used as soil cover. Residues can act as a physical barrier: they can hinder weed emergence or slow down the progress of seedlings from inside the soil to the surface (Chauhan and Abugho, 2013). Surface residues in strip tillage and direct mulch-based cropping systems could significantly filter or even block light. Many weed species require a specific amount of light for their seeds to germinate, for phytochrome activation. Reduction in light could therefore reduce their emergence thereby altering the composition of the weed community (Nikolić et al., 2021).

Overall, seven weed species indicators of the conventional tillage system were identified, compared with six species for the strip tillage and five for the direct mulch-based cropping systems. Some of the species were common to all three systems (Fig. 8), whereas *Cyperus esculentus*, *Brachiaria deflexa* and *Phyllanthus amarus* were only associated with the conventional tillage system. *Kyllinga squamulata*, *Digitaria horizontalis* and *Ipomoea eriocarpa* were only associated with the strip tillage system, while *Leucas martinicensis*, *G. Celisoides* and *Portulaca oleracea* were only associated with the direct mulch-based cropping system. These results suggest that each system presents a specific condition favoring adapted species. Boscutti et al. (2015) reported that species composition was characteristic of each combination of a tillage system and a type of crop. The presence of these species could also be used as a bio-indicator to diagnose the level of soil disturbance. Understanding these associations could help target appropriate weed control strategies. For example, reduced tillage techniques may limit plow-tolerant weeds, but favor other species, allowing management methods such as weeding, rotation, cover crops to be adjusted. The choice of tillage is one of the main structural levers of weed composition (Nichols et al., 2015).

Some weed species (*E. heterophylla* and *O. corymbosa* in 2023) would have been suppressed by the conservation agriculture systems (direct mulch-based cropping and strip tillage) over the course of the season (Fig. 8). The suppressive capacity of these systems may also be linked to microclimatic conditions induced by reduced tillage and residue retention. These conditions can limit seed germination of light-sensitive or less competitive weed species, thereby gradually altering the composition of the weed community. Alarcón et al. (2018) reported the opposite, i.e., the weed community was almost identical under tillage and no-tillage conditions. Zhang and Wu (2021) pointed out that crop residue retention reduced weed density and could alter the species community. Crop residues or mulch left on the surface of plots may contain allelopathic substances that inhibit the germination or growth of certain weeds. The microclimate under the residues could favor a specific microbial community capable of modulating these effects, either by degrading compounds or through direct suppression. Awopegba et al. (2017) reported that certain types of crop residues may contain substances that affect weed growth or germination. These interactions mean that crop residue/cover crop management and microclimate can influence both the quantity of weeds and their composition, e.g. dominant species, the weeds' life cycle.

- Maintaining soil cover can reduce the emergence of light-sensitive species, favor tolerant or perennial weeds, and lead to a community that is less diverse but is often dominated by robust species.

- Understanding which species are favored by a given cropping system allows us to foresee changes in the weed community and choose the appropriate management strategies.

Multivariate analyses, non-metric multidimensional scaling and permutational tests revealed substantial variability in weed communities between the 2023 and 2024 seasons. This variability appears to be influenced by environmental factors, notably rainfall patterns, which were earlier and more regular in 2023. Previous studies (Borgy et al., 2016; Werner et al., 2020) have similarly emphasized the strong and persistent effects of interannual climatic variability on weed community dynamics. Interestingly, while weed communities initially differed across cropping systems, later in the season, they tended to converge (Fig. 7A). This convergence could be linked to the effect of cotton cultivation, which, due to its canopy structure and growth cycle, suppresses some weed species while favoring others. These dynamics highlight the role of the type of crop in shaping changes in the weed community within the same season.

Overall, cropping systems have a strong influence on weed communities. Conventional tillage encourages diverse and abundant weed species dominated by fast-growing annuals. Strip tillage provides partial control by limiting soil disturbance. Direct mulch-based cropping is most effective at suppressing weed emergence. The species composition observed under each system reflects their ecological strategies and tolerance to soil disturbance, residue cover, and competition, reinforcing the need for system-specific weed management approaches.

4.4. Effect of cropping systems on crop yields

Crop yields under strip tillage and direct mulch-based cropping systems did not significantly exceed those under conventional tillage system in our two-year study. In fact, yields were broadly similar across systems. These results are broadly consistent with those of several authors who observed limited yields penalties of cotton seed yield (Yemadje et al., 2022; 2025) and maize grain (Kombiok and Alhassan, 2007) when transitioning in conservation agriculture systems. The lack of a yield benefit, despite reduced weed emergence, indicates that even low weed emergence can constrain crop productivity: the few large weeds in strip tillage and direct mulch-based cropping likely competed strongly for soil moisture and nutrients at critical times. These yield penalties that are linked to conservation agriculture practices rather than to conventional agriculture could be explained by soil nutrient immobilization (Lowry et al., 2021), poor germination and increased competition from weeds (Graham et al., 2020). These yield penalties could also be explained by poor drainage, some of which may result from the transition from conventional to conservation agriculture. In the present study, the lack of increase in yield with conservation agriculture practices can be explained by competition from weeds, particularly weed biomass which competes with the main crops. Mashingaidze et al. (2012) showed that one of the main challenges to conservation agriculture systems is weed management: without sufficient weeding or adequate mulching, weeds proliferate. This can limit gains or delay the expected increase in yield under conservation agriculture systems. Mafongoya et al. (2016) and Buah et al. (2017) obtained an improvement in maize grain yield with conservation agriculture systems (no-tillage, rip-line seeding) compared to in plowed plots.

The lack of maize yields benefit under strip tillage and direct mulch-based cropping systems compared to conventional tillage could also be explained by competition from associated legumes for environmental resources i.e. nutrients, water, air. Rapholo et al. (2020) showed that intercropping produced significantly lower maize yields compared to maize as a monocrop. Yield penalties in agroecological transition processes are compromises to be made by farmers in view of the many long-term benefits of these practices. Conservation agriculture practices (strip tillage and direct mulch-based cropping) showed tradeoffs between reducing weed emergence and crop yields as no significant

difference was found between the three systems over the two seasons. These practices will restore biodiversity and minimize fertilizer use thanks to intercropping with diverse legumes. Such diversity will help reduce environmental problems while increasing yields in the long term (Mudare et al., 2022).

The main advantage of strip tillage and direct mulch-based cropping in this cotton system was their weed emergence reduction effect, which can reduce herbicide use and stabilize crop establishment in the long term. However, their effect on yield is limited by the persistent influence of the weeds that do emerge. This underscores the need for integrated weed management: even in conservation agriculture systems, timely control (e.g. mechanical weeding or targeted herbicide applications during the first 40–60 days after sowing) will be crucial to protect yields. Future research should continue to monitor yield responses over multiple seasons and rotations and investigate how supplementing conservation agriculture with additional practices (cover crops, optimized fertilization) can translate the ecological benefits into agronomic gains.

4.5. Limitations of study

The results strongly support the integration of cover crops and crop rotations into cotton-based cropping systems as an effective strategy for weed management. The study was conducted at a single site (the Okpara permanent experimental station). This may limit the generalizability of the findings to other agroecological zones in Benin and West Africa. The responses observed are likely influenced by local soil and climate conditions, including soil texture, rainfall and crops rotation. Future multi-site studies are recommended to confirm these results on a broader scale, but the evidence presented here clearly highlights the benefits of these practices for sustainable weed control.

Yield analysis reveals no significant differences between systems. However, the study does not determine the precise causes of these variations or their economic impact. A detailed technical and economic analysis, including the costs of implementing conservation agriculture practices, labor, herbicide savings, and gross margins, would be essential to assess the actual profitability of these systems. However, two recent technical-economic studies conducted on cotton-based conservation agriculture cropping systems in northern Benin have shown that these practices can reduce variability and economic risks (Akplo et al., 2025). These studies also showed that these systems improve gross margin, labor productivity, benefit-cost ratio, and return to labor for cotton compared to conventional tillage system.

The relatively short duration of the experiment (two seasons of observation) does not allow to understand the long-term effects of conservation agriculture on weed dynamics and productivity. Agro-ecological transition processes require couple of years to reach a stable ecological balance.

5. Conclusion

This study investigated the effects of two conservation agriculture options (strip tillage and direct mulch-based cropping) compared to those of conventional systems on weed emergence, biomass, and community structure in cotton-based cropping systems in northern Benin. This study provides the first empirical evidence that conservation agriculture practices can effectively reduce weed emergence and reshape weed community structure in cotton-based cropping systems in Sub-Saharan Africa. By comparing strip tillage and direct mulch-based cropping with conventional tillage, we demonstrate that conservation agriculture systems can significantly lower weed emergence without reducing crop yield. The distinct weed assemblages identified under each conservation agriculture system indicate that soil disturbance and residue management jointly determine community trajectories, with implications for long-term weed ecology and management. These results advance the understanding of conservation agriculture and weed interactions under tropical smallholder conditions, filling a major

knowledge gap in the region. Beyond their scientific contribution, the findings offer practical guidance for designing integrated weed management strategies that enhance sustainability, reduce labor and herbicide dependence, and support the wider adoption of conservation agriculture among cotton producers in sub-Saharan Africa.

CRediT authorship contribution statement

Lucien Imorou: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Pierrot Lionel Yemadje:** Writing – review & editing, Methodology, Conceptualization. **Lalaina Ranaivoson:** Writing – review & editing, Methodology, Formal analysis. **Mathias Christina:** Writing – review & editing, Supervision, Formal analysis. **Pierre Gbènoukpo Tovihoudji:** Writing – review & editing, Methodology. **Moussa Zime Soko N'Douro:** Writing – review & editing, Formal analysis. **Cyrille Kanlindogbé:** Writing – review & editing, Methodology. **Valérien Zinsou:** Writing – review & editing, Supervision, Methodology. **Oumarou Balarabe:** Writing – review & editing, Supervision, Methodology. **Stéphane Boulakia:** Writing – review & editing, Methodology, Conceptualization. **Emmanuel Sekloka:** Writing – review & editing, Supervision, Methodology. **Pablo Tittoneil:** Writing – review & editing, Supervision, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2026.110262](https://doi.org/10.1016/j.agee.2026.110262).

Data availability

Data will be made available on request.

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