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RESEARCH ARTICLE

No-tillage and intercropping improve the yield and profitability of maize-cotton rotations in Northern Benin

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Abstract

This study investigated the effect of conservation agriculture (CA) practices (e.g. no-tillage (NT) and maize-soybean (MS) intercrops) on the yield and profitability of maize and cotton within the first two years of a crop rotation system. A factorial design that compared two tillage practices (conventional tillage, CT and NT) and two cropping systems (sole maize, M and MS) was implemented on an experimental station in Northern Benin. All treatments were replicated thrice in 2022 and 2023. Soybean yield, maize grain yield and yield components, and seed-cotton yield and yield components were measured. Gross margin, labour productivity, and benefit:cost ratio were calculated, and a sensitivity analysis was done on the economic indicators under five scenarios (S0: gross margin calculation based on actual costs; S1: 30% higher fertiliser price; S2: 30% lower fertiliser price; S3 and S4, respectively: considering +/−1 standard deviation to the maize grain + soybean and seed-cotton yield). Tillage options and cropping systems significantly affected maize and cotton performance, but effects tended to vary between seasons. Treatment NT+MS produced the highest grain yield (4487 kg ha^{-1}) and rain use efficiency (4.12 kg mm^{-1}) in 2022, while CT+M produced the highest grain yield (3195 kg ha^{-1}) and rain use efficiency (2.84 kg mm^{-1}) in 2023. In the case of cotton, NT produced higher seed-cotton yield (1720 kg ha^{-1}), boll number (7.38 bolls/plant), and rainfall use efficiency (1.56 kg mm^{-1}) compared to CT in 2022. In 2023, cotton preceded by maize-soybean intercrops (NT+MS and CT+MS) produced significantly higher yield, aboveground and belowground biomass than cotton preceded by sole maize (NT+M and CT+M). For maize plus soybean, treatment NT+MS resulted in a significant increase in the gross margin, with an average of 582 US$ ha^{-1} with respect to CT+M under all scenarios in 2022, whereas CT+M and NT+MS attained a significantly higher maize/soybean gross margin in 2023. In the case of cotton, NT increased gross margin by 90-314% compared to CT across the sensitivity analysis scenarios in 2022. In 2023, cotton preceded by MS intercrops (NT+MS and CT+MS) showed a higher gross margin than preceded by sole crops (NT+M and CT+M) across all scenarios. To the well-documented effects of diversification on crop productivity, this study adds evidence on its positive impact on economic performance in a West African context. On-farm research and rural extension are necessary to further fine-tune these practices to fit the reality of smallholder cotton-based cropping systems of Benin.

Keywords: Agroecological transition; conservation agriculture; profitability; maize-legume intercropping; Cotton/maize rotation

Introduction

Cotton (*Gossypium hirsutum* L.) is one of the main tradable crops of West African countries, representing the main agricultural export of Benin. Its production significantly contributes to the region's economy, accounting for nearly 30% of exports and contributing 7% to the Gross Domestic Product (Soumaré *et al.*, 2020). It also benefits food crops and livestock production as African farmers often rotate cotton crops with cereals such as millet (*Pennisetum glaucum* (L.) R. Br.), sorghum (*Sorghum bicolor* (L.) Moench), and maize (*Zea mays* L.). These second crops benefit from inputs and capital goods financed through cotton contract farming. However, while global cotton yields have been rising steadily since the 1960s, cotton yields in West Africa have been stagnant since the 1980s and have even declined in some countries, such as Benin [The Food and Agriculture Organisation of the United Nations (FAO) statistics: https://faostat.fao.org/].

Soil fertility decline and climate change are some of the most important limiting factors to crop yield in West Africa (Dossouhoui *et al.*, 2025; Sultan *et al.*, 2010). Poor soil fertility, low and erratic rains coupled with inappropriate tillage, monocultures, over-exploitation of land, inadequate use of inputs, and the burning of crop residues are key factors in soil fertility decline (Dossouhoui *et al.*, 2023; Hermann *et al.*, 2016). In Benin, cotton is primarily grown on tropical ferruginous soils (Acrisols or Lixisols) in the central and northern regions, where the rainfall ranges between 900 and 1200 mm (Sodjinou *et al.*, 2015). The soils in these cotton-producing zones exhibit notable deficiencies in nutrients (N, P, and K) and organic matter, and are susceptible to water erosion (Youssouf and Lawani, 2000). There is, therefore, a growing need to shift towards more sustainable land management practices that reduce soil disturbance, enhance the addition of organic matter, and promote crop diversification to build and maintain soil organic matter (SOM) stocks.

Several sustainable land management techniques, and in particular conservation agriculture (CA) have been tested worldwide and in sub-Saharan Africa (SSA) (Akplo *et al.*, 2025; Yemadje *et al.*, 2025; Grabowski *et al.*, 2014; Obalum *et al.*, 2011; Temesgen *et al.*, 2012; Thierfelder *et al.*, 2013). CA has been promoted as 'a concept of crop production at a high and sustained production level to achieve acceptable profit while saving the resources along with conserving the environment' (FAO 2019). CA is a set of techniques, including minimum soil disturbance or no-tillage (NT), permanent soil cover, diversified cropping systems, and integrated weed management (Friedrich *et al.*, 2012; Hobbs *et al.*, 2008). There is scientific evidence that CA practices and, in particular, NT can reduce many adverse effects of conventional farming practices such as soil erosion (Akplo *et al.*, 2024), SOM decline (Martinsen *et al.*, 2019), water loss (Wolschick *et al.*, 2021), soil physical degradation (Fernández-Ugalde *et al.*, 2009; Obalum and Obi, 2010), fuel use (Jat *et al.*, 2019), and crop yield (Yemadje et al., 2022). Several authors (Akplo *et al.*, 2025; Omulo *et al.*, 2022; Thierfelder *et al.*, 2015) highlighted the economic advantages of CA, such as fuel savings, increased work productivity, and profitability. However, it is well established in the literature that the agronomic and economic benefits of CA may take time to manifest, with positive yield effects becoming apparent over a period of 5 to 15 years (Corbeels *et al.*, 2014; Salem *et al.*, 2015).

Among CA practices, diversified cropping systems through intercropping and crop rotation have explicitly been recommended to achieve sustainable intensification (Rapholo *et al.*, 2020). Intercropping entails the simultaneous (or relayed) cultivation of two or more crops in the same field (Smith and McSorley, 2000), and it has been demonstrated to have many advantages. Legume-based intercropping systems were shown to be a beneficial for soil functioning and rhizobacterial community diversity, while contributing to the reduction of external inputs (Sánchez-Navarro *et al.*, 2024; Y. Wang *et al.*, 2025), enhanced crop yields and land equivalent ratios, improved soil N and P content and carbon (C) sequestration and storage (W. Wang *et al.*, 2025), and stimulation of beneficial organisms (Cuartero *et al.*, 2022; Hei *et al.*, 2021; Yang *et al.*, 2025; Zhang *et al.*, 2024). In-row or alternate row intercropping of maize with common bean

(*Phaseolus vulgaris* L.), soybean (*Glycine max* (L.) Merr.), groundnut (*Arachis hypogaea* L.), and cowpea (*Vigna unguiculata* (L.) Walp.) is widely practiced in SSA (Mudare *et al.,* 2022; Vanlauwe *et al.,* 2019). While the effects of maize-soybean intercropping are well known in SSA (Berdjour *et al.*, 2020; Kamara *et al.*, 2019; Kermah *et al.*, 2017; Kolawole, 2012; Tchegueni *et al.,* 2022; Vanlauwe *et al.*, 2019), information on its residual effect on cotton within a NT system is still scarce.

The objective of this study was to assess the impact of CA practices (e.g. NT and MS intercropping) on the yield and profitability of maize and cotton within the first two years of a crop rotation system. We hypothesised that (i) the two-year cumulative effects of NT improve crop yields and profitability compared to conventional tillage (CT); and (ii) intercropping maize with soybean limits the initial cotton yield penalties that are associated with the transition toward NT.

Methodology

Study site

This study was carried out at Angaradébou (11°70' N latitude and 2°56' E longitude) in the commune of Kandi, located in the cotton-growing zone of Northern Benin. This region has a dry tropical climate with a single growing season per year, from May to September (Atakoun *et al.*, 2023). The average annual rainfall ranges from 900 to 1300 mm (Peel *et al.*, 2007). The soil in the region is classified as a ferruginous tropical type in the French soil classification system, which corresponds to Acrisols or Lixisols according to the World Reference Base (Baxter, 2007). The soil at the site is clay in texture, with an acidic pH of 5.6, a very low nitrogen content of 0.04%, a very low soil organic carbon content of 0.54%, and a slightly low assimilable phosphorus content of 18.80 ppm (Amonmide *et al.*, 2021). The soil at the end of the season is hydromorphic, making it very difficult to work.

During the 2022 experiment period, there were 61 rain events, resulting in a cumulative rainfall of 1087 mm. In comparison, the 2023 experiment period had 49 rain events and a cumulative rainfall of 1122 mm (Supplementary Material Fig. S1). The 2022 rainfall events were well distributed, with some exceeding 70 mm. However, the distribution of rain events in 2023 appeared uneven, with some days having over 250 mm of rainfall and others having less than 5 mm.

Experimental design

The trial was a factorial design with two factors (tillage systems and cropping systems), each with two modalities and three replications for cotton and maize. The four treatments are described as follows:

For maize

- Factor 1 – soil management
  - Conventional tillage (CT): flat ploughing to a depth of 20 cm with a tiller equipped with a share plough, followed by harrowing. The soil surface was not covered.
  - No-tillage (NT): NT and no soil surface cover. The planting was done with a pointed stick.
- Factor 2 – cropping systems
  - Sole maize
  - Maize intercropped with soybean

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For cotton

- Factor 1 - soil management
  - Conventional tillage (CT): flat ploughing to a depth of 20 cm with a tiller equipped with a share plough, followed by harrowing. The soil surface was not covered.
  - No-tillage (NT): NT and no soil surface cover. The planting was done with a pointed stick.
- Factor 2 – previous crop
  - Cotton preceded by sole maize
  - Cotton preceded by MS

Table S1 shows the characteristics of the treatments compared regarding crop sequence, soil, and residue management. The experiment was conducted in 2022 and repeated in 2023 using the same plots. Each year, both terms of the rotation, maize and cotton, were tested. The plots that were sown with maize in 2022 were used for cotton in 2023, and vice versa. In 2022, both factors (i.e. soil tillage and cropping systems) were tested on maize, while only the effect of soil management was tested on cotton. In 2023, the plots previously sown with cotton were split to correspond to the plot of maize (M, MS). Each elementary plot had an area of 175 m^2 (25 m × 7 m) and was separated from adjacent plots by 5-metre-wide grass strips. The experimental plots were uniform regarding soil type, topography, and cropping history. A biannual sequence of cotton and maize + cover crops (*Crotalaria retusa*) was practiced on these plots until 2021. At the beginning of the 2021 season, the plough hardpan was broken by a 30 cm sub-soiler pass after clearing.

Crop management

Prior to cotton sowing, plots were treated with glyphosate (480 g l^{-1}) to control weeds. Cotton (variety ANG 956, 180 maturity days) was sown 06th 2022 and 12th June 2023. Seeding was conducted at an early stage (eight days before the commencement of the CT plots) on the NT plots following significant precipitation. Seeding was performed manually at a 0.80 m × 0.30 m, with three or four seeds per hole at 5 cm depth and further thinned to one plant hill one month after sowing, resulting in a density of 41,666 plants ha^{-1}. Weed control and phytosanitary protection were conducted following the technical recommendations for cotton production in Benin. In both years, the cotton was fertilised with 250 kg ha^{-1} of $N_{14}P_{18}K_{18}S_6B_1$ + 50 kg ha^{-1} of urea (46%N), corresponding to 58 kg ha^{-1} N, 20 kg ha^{-1} P, 38.75 kg ha^{-1} K, and 3 kg ha^{-1} S.

Maize (variety 2000 SYNEE, 90 maturity days) was also sown on 06th June 2022, and 12th June 2023. For the sole maize treatment, planting was performed at 0.80 m x 0.40 m with three to four seeds per hole following the farmer's practice. Following emergence, the plants were thinned to two per hole, resulting in a density of 62,500 plants ha^{-1} for the maize-only treatments. For the MS intercropping treatment, a narrow-wide row intercrop configuration was adopted, with soybean planted at the standard row distance, with two rows of maize and four rows of soybean. Soybean cultivar TGX 1830-20E was planted on the same date as maize each year. The within-row spacing was 0.40 m for maize and 0.20 m for soybean, while the inter-row space was 0.80 m for maize and 0.40 m for soybean.

In both years, the recommended types and doses of fertilisers for maize in the study area were followed. A total of 200 kg ha^{-1} $N_{13}P_{17}K_{17}S_5B_{0.5}Zn_{1.5}$ + 50 kg ha^{-1} of urea (46%N) (equivalent to 49 kg ha^{-1} N, 16 kg ha^{-1} P, 29.3 kg ha^{-1} K, and 2 kg ha^{-1} S) were applied to the maize in both years. The weed control and phytosanitary protection measures were implemented by the technical recommendations for maize production in Benin.

Data collection

Yield and yield components

Cotton biomass (both above- and below-ground) was collected post-harvest within three 1 m^2 harvest areas per plot, oven-dried at 65°C until constant dry weight, and reported to kg ha^{-1}. The number of bolls per plant (NB/P) was determined on 20 randomly chosen plants from central lines of each plot. Cotton was harvested twice – first when 70% of the bolls opened and again for the remaining bolls – with open bolls collected from a 48 m^2 (20 m × 2.4 m) harvest area to estimate yield (kg ha^{-1}). The average boll weight (BW) was calculated by dividing the total weight (including both seed cotton and lint) by the number of bolls.

Maize grain yield, above- and below-ground biomass, and the thousand grain weight (TGW) were measured at harvest (90 JAS). The harvest area was 48 m^2 on sole maize and 56 m^2 on MS intercropping (4 rows of maize and 4 rows of soybean). Above-ground biomass was cut at approximately 2 cm from the soil surface. Maize cobs were sun-dried and shelled, and grain weight was determined at a standardized moisture content (12.5%) before reporting to a per-hectare basis. Above-ground biomass was weighed at harvest, then sun-dried for 10 days until weight stabilisation, while belowground biomass was sun-dried first and then oven-dried at 65°C for 72 hours prior to weighing. TGW was determined after shelling the harvested cobs.

Rainfall use efficiency

Rainwater use efficiency (RUEg) (kg ha^{-1} mm^{-1}) was determined for cotton and maize as the quotient of total yield over between the yield (cotton or maize) per millimetre of rain fallen within the cotton and maize cycles each year using Eq. (1) (Peng *et al.*, 2020).

$$\mathrm{RUEg} = \frac{\mathrm{Y}}{\mathrm{R}} \tag{1}$$

where Y is the seed-cotton yield (kg ha^{-1}) or maize grain yield (kg ha^{-1}), and R is the seasonal rainfall (in mm).

Economic analysis

The input costs for both crops are summarised in Table S2. The economic indicators were determined following the methodology proposed by Penot *et al.* (2021). Operational costs are the expenses incurred during production, processing, and marketing. This study includes all costs related to seeds, fertilisers, phytosanitary products (herbicides, insecticides), and operational costs from planting to harvest (Table S2). The prices of fertilisers, insecticides, seed cotton, and herbicides were based on the rates provided by the Société pour le Développement du Coton (SODECO). The temporary salary costs were based on the rates used in farmers' fields. We calculated the gross income (US\$ ha^{-1}) by multiplying the crop yield (kg ha^{-1}) by the national selling price (US\$ kg^{-1}). The average Beninese government price for the last five seasons was used for cotton (300 FCFA kg^{-1}). We used the average market selling price in the previous five years (200 FCFA kg^{-1}) for maize and soybean to account for periods of abundance and scarcity. In the MS systems, the gross margin was estimated based on the cumulative yield (maize + soybean). The gross margin was determined as the difference between the gross income and the operational costs (Penot *et al.*, 2021). For all of the costs, we considered US\$1 = 610 FCFA.

A sensitivity analysis was conducted to gain a more comprehensive understanding of the impact of the treatments on the gross margin. Five scenarios were considered (Table S3). Other economic indicators, such as labour productivity, the benefit-cost ratio, and the return to labour, were determined. The labour productivity is measured as kg of maize grains or seed-cotton per day of labour following equation (2) (Hunt, 2000).

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$$\text{Labour productivity}\left(\frac{\text{kg}}{\text{person}-\text{day}}\right)=\ \text{Yield}\ (\text{kg/ha})/\text{Working time}\ (\text{person}-\text{day/ha}) \qquad (2)$$

The benefit-cost ratio was determined by dividing the gross margin by the operational cost, as shown in equation (3).

$$\text{Benefit}-\text{cost ratio}\ =\text{Gross margin/Operational cost} \qquad (3)$$

The return to labour was determined as the ratio of the gross margin by the working time as in equation (4).

$$\text{Return to labour}\ \left(\frac{\text{US\$}}{\text{person}}-\text{day}\right)=\text{Gross margin}\ (\text{US\$/ha})/\text{working time}\ (\text{person}-\text{day/ha}) \qquad (4)$$

Statistical analysis

The data were first checked for normality using the Shapiro–Wilk test (Shapiro and Wilk, 1965) and for homogeneity of error variances using the Bartlett test (Bartlett, 1937). Linear mixed-effects models were performed using R 4.3.2 software. For maize-soybean, the effects of tillage options and cropping systems on yield (maize and maize + soybean), yield components, above- and below-ground biomass, and profitability were analysed for 2022 and 2023, with 'block' treated as a random factor in both years. For cotton, only the effect of tillage options was examined in 2022, whereas in 2023, both tillage options and the previous cropping systems were tested for their impact on yield, yield components, above- and below-ground biomass, and profitability. In both years, 'block' was included as a random factor.

The R package lmerTest was used to test the models (Kuznetsova *et al.*, 2017). The variables 'number of bolls per plant', 'thousand-grain weight', and 'number of grains per cob' were Box-Cox transformed because they did not fit a normal distribution according to the Shapiro–Wilk test. Using the mixed model established in the package *lmerTest*, adjusted means were computed with the '*emmeans'* function of the *emmeans* R package based on default parameters (Lenth, 2019). The interclass correlation coefficient (ICC) was used to determine the variability between the levels of the random factors. The variability between the levels of the random factors was overall low (ICC$\leq$ 30%), indicating that the experimental sites were well-homogenised.

When the fixed effects were significant (p-*value* < 0.05), the *multcompView* R package with default parameters was used for computing the multiple comparisons of the levels of the fixed factor with the Tukey's Honestly Significant Difference (HSD) method (Graves *et al.*, 2024). However, due to interactions between tillage and cropping systems on maize, the main effects were not reported for both years. For cotton, the main impact of tillage was reported in 2022, and the effect of tillage x previous cropping systems interaction was reported in 2023. A T-Student test was performed on the agronomic variables to compare the examined years.

Results

Agronomic performance

Maize and soybean

Maize grain yield, aboveground biomass, and rainfall use efficiency were significantly ($p < 0.005$) affected by tillage and intercropping in both years, although with varying trends (Table 1). In 2022, NT+MS intercropping (NT+MS) produced the highest grain and aboveground biomass yields and rain use efficiency (4487 kg ha^{-1}, 12683 kg ha^{-1}, and 4.12 kg mm^{-1}, respectively) (Table 1). Conventional and NT+MS intercropping (i.e. NT+MS and CT+MS) increased the

Table 1. Maize yield components and rainfall use efficiency as affected by tillage options and cropping systems in 2022 and 2023. (mean ± standard deviation)

Year	Tillage	Cropping systems	Grain yield	Aboveground biomass	Below- ground biomass	Thousand Grains Weight	Number of Grains per cob	Rainfall Use Efficiency
				kg ha^{-1}		g	#/cob	kg mm^{-1}
2022	Conventional tillage	Sole maize	3460 ± 419ab	4905 ± 897c		287 ± 42	344 ± 37	3.2 ± 0.4ab
		Maize-soybean intercrops	3622 ± 410ab	12611 ± 819a		295 ± 25	392 ± 93	3.3 ± 0.4ab
	No-tillage	Sole maize	3165 ± 1115b	6511 ± 353b		290 ± 35	393 ± 77	2.9 ± 1.0b
		Maize-soybean intercrops	4487 ± 900a	12683 ± 905a		309 ± 42	392 ± 47	4.1 ± 0.8a
	Mean		3683 ± 373A	9178 ± 1140A		295 ± 14A	377 ± 70A	3.4 ± 0.3A
	p-values	Tillage	0.6415	0.3148		0.0445	0.4549	0.6417
		Cropping system	0.1401	<0.0001		0.1653	0.4832	0.1407
		Tillage*Cropping system	0.0054	0.0357		0.609	0.4569	0.0055
2023	Conventional tillage	Sole maize	3195 ± 436a	4005 ± 1728	1463 ± 447	245 ± 22	317 ± 38b	2.8 ± 0.4a
		Maize-soybean intercrops	1977 ± 225c	4016 ± 1168	1217 ± 207	239 ± 24	404 ± 35a	1.8 ± 0.2b
	No-tillage	Sole maize	2677 ± 234b	4105 ± 913	1283 ± 417	262 ± 14	285 ± 38c	2.4 ± 0.3ab
		Maize-soybean intercrops	2417 ± 273b	3744 ± 854	1346 ± 409	262 ± 17	320 ± 44b	2.6 ± 0.4ab
	Mean		2565 ± 500B	3968 ± 581B	1353 ± 393	252 ± 19B	331 ± 41B	2.3 ± 0.9B
	p-values	Tillage	0.7485ns	0.806	0.3178	0.1575	<0.0001	0.7461
		Cropping system	0.0002	0.6182	0.2189	0.5732	<0.0001	0.0003
		Tillage*Cropping system	0.0036	0.5962	0.3749	0.6203	0.0338	0.0038

In a given year and for a given parameter, values with the same lower-case letter are not significantly different at $p < 0.05$. p-values = probability of significance. ns = non-significant.

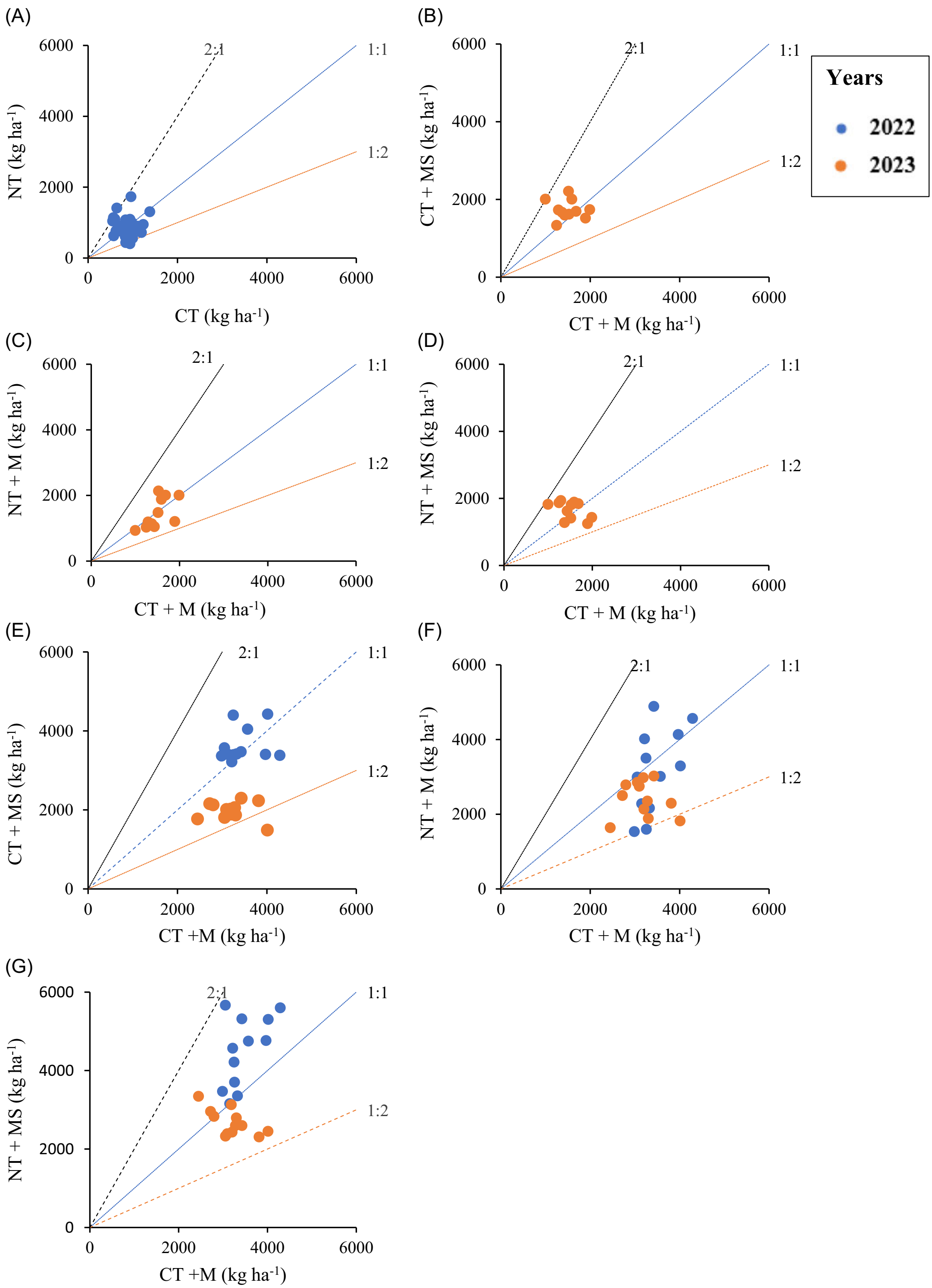

Figure 1. Relative yields (kg ha^{-1}) of other treatments compared to the conventional system (CT). (A) Cotton under no-tillage (NT) in 2022; (B) Cotton after conventional maize-soybean intercrops (CT+MS) in 2023; (C) Cotton after no-tillage sole maize (NT+M) in 2023; (D) Cotton after no-tillage maize-soybean intercrops (NT+MS) in 2023; (E) Maize under conventional maize-soybean intercrops (CT+MS); (F) Maize under no-tillage sole maize (NT+M); and (G) Maize under no-tillage maize-soybean intercrops (NT+MS). Dashed lines represent the 1 :2; 1 :1 and 2 :1 lines.

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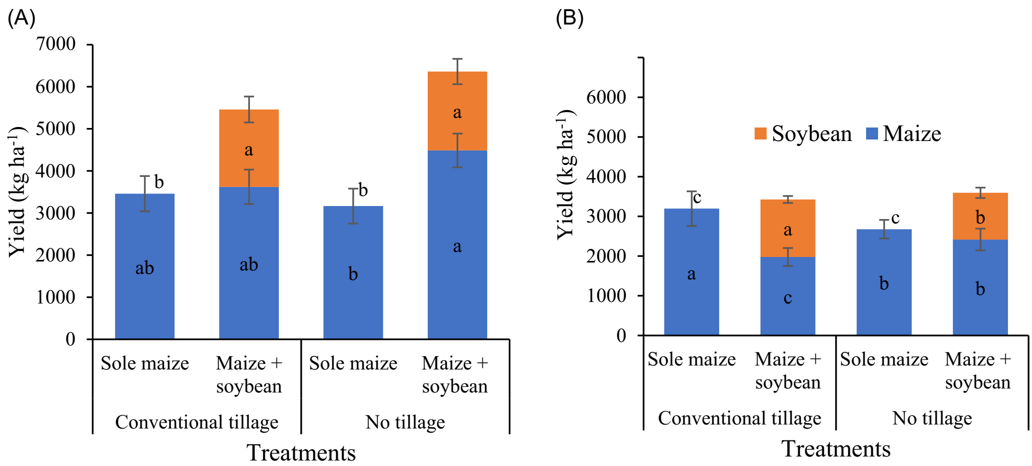

Figure 2. Cumulative maize soybean yield (mean ± standard deviation) in 2022 (A) and 2023 (B). For each crop, means with the same letter are not significantly different at $p < 0.05$.

maize grain yield relative to conventional sole maize (CT+M) (cf. dots on or above the 1:1 line in Fig. 1E and G). In 2023, CT+M produced the highest grain yield (3195 kg ha^{-1}) and rain use efficiency (2.84 kg mm^{-1}) while conventional CT+MS produced the lowest yields (1977 kg ha^{-1}), and the largest number of grains per cob (Table 1). In contrast to 2022, CT+MS, NT+M, and NT+MS exhibited maize yield penalties with respect to CT+M in 2023 (cf. dots below the 1:1 line in Fig. 1E, F, and G). The rainfall use efficiency reflects the grain yield differences described above. Treatments NT+MS and CT+MS showed the highest rainfall use efficiency, respectively, in 2022 (4.12 kg mm^{-1}) and 2023 (2.84 kg mm^{-1}) (Table 1). Moreover, the cumulative maize and soybean yield was greater with NT+MS in 2022 and 2023 (6362 kg ha^{-1} and 3593 kg ha^{-1}, respectively) (Fig. 2).

Although total rainfall during the season was slightly higher in 2023, cumulative rainfall during the first two months after sowing was almost half than in 2022 (Supplementary Material Fig. S1). Based on the T-student test used to compare both study years, maize yield (3683 kg ha^{-1}), aboveground biomass (9178 kg ha^{-1}), the TGW (295 g), the number of grains per cob (377.05 grains/cob), and rain use efficiency (3.38 kg mm^{-1}) were significantly higher in 2022.

Cotton

Type of tillage and the preceding cropping system type (M or MS intercropping) and their interactions significantly affected seed-cotton yield, belowground biomass, boll number, and rain use efficiency, and had no significant effect on aboveground biomass and seed-cotton weight per boll (Table 2). The year had a significant effect on all variables. In 2022, NT produced significantly higher seed-cotton yield (1720 kg ha^{-1}), higher boll number (7.38 bolls/plant), and greater rain use efficiency (1.58 kg mm^{-1}) than CT (Table 2, Fig. 1A). The latter exhibited higher belowground biomass (832 kg ha^{-1}). In 2023, the interaction of tillage x cropping systems was significant ($p <$ 0.05) for seed-cotton yield, aboveground biomass yield, and rain use efficiency. Cotton preceded by MS intercrops produced significantly higher yield and aboveground biomass than cotton preceded by sole maize, equally under CT and NT (Table 2). Compared to CT+M, intercropping MS before cotton, irrespective of tillage method (CT+MS and NT+MS), led to higher seed-cotton yields (Fig. 1B and D) and rainfall use efficiency (Table 2), whereas NT+M led to a yield penalty in subsequent cotton (cf. Fig. 1C). Cotton grown after NT+MS intercrops exhibited 5 to 29% greater aboveground biomass production than the rest of the treatments. The T-test indicated significantly

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Table 2. Seed-cotton yield and yield components, above- and below-ground biomass, and rainfall use efficiency (mean ± standard deviation)

Year	Tillage	Cropping systems	Seed-cotton yield	Aboveground biomass	Belowground biomass	Boll number	Seed-cotton mass per boll	Rainfall Use Efficiency
			kg ha^{-1}			#/plant	g/boll	kg mm^{-1}
2022	Conventional tillage		1411 ± 84b	6686 ± 269	832 ± 58a	6.3 ± 0.2b	4.4 ± 0.1	1.3 ± 0.1b
	No-tillage		1720 ± 92a	6869 ± 406	678 ± 50b	7.4 ± 0.4a	4.2 ± 0.1	1.6 ± 0.1a
	Mean		1565B	6778A	755B	6.8B	4.3A	1.4B
	p-values		0.0043	0.7092	0.0101	0.0427	0.2260	0.0045
2023	Conventional tillage	Preceded by sole maize	2134 ± 137b	5828 ± 595b	1591 ± 294	12.5 ± 0.8	3.4 ± 1.1	1.9 ± 0.4b
		Preceded by maize-soybean intercrops	2522 ± 171a	6306 ± 239ab	1835 ± 277	13.1 ± 0.2	3.0 ± 1.3	2.3 ± 0.15a
	No-tillage	Preceded by sole maize	1900 ± 156b	5111 ± 372c	1472 ± 360	11.7 ± 0.9	3.3 ± 0.6	1.7 ± 0.4b
		Preceded by maize-soybean intercrops	2430 ± 128a	6611 ± 468a	1634 ± 252	13.2 ± 0.4	3.1 ± 0.7	2.2 ± 0.1a
	Mean		2247A	5748B	1633A	12.4A	3.2B	2.0A
	p-values	Tillage	0.1999	0.2875	0.0923	0.5514	0.9070	0.1812
		Cropping system	<0.0001	<0.0001	0.0351	0.0905	0.4398	0.0001
		Tillage*Cropping system	0.0163	0.0115	0.6575	0.4635	0.7555	0.0174

In the given year and for a given parameter, values with the same lower-case letter are not significantly different at $p < 0.05$. p-values = probability of significance. ns = non-significant.

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higher seed-cotton yield, belowground biomass, boll number, and rain use efficiency in 2023, and significantly higher aboveground biomass and seed-cotton mass per boll in 2022 (Table 2).

Economic indicators

Gross margin of maize plus soybean and cotton

Type of tillage, cropping system type, and/or their interaction significantly influenced ($p < 0.05$) the gross margin of maize plus soybean and cotton, both under current and alternative sensitivity analysis scenarios (Table 3).

In the MS systems, the gross margin was estimated based on the cumulative yield (maize + soybean). In 2022, the highest maize plus soybean gross margin was obtained with NT+MS under current price and yield conditions, as well as under scenarios 1, 2, 3, and 4 (Table 3). NT+MS significantly increased gross margin by an average of 582 US\$ ha^{-1} with respect to CT+M under all scenarios. In 2023, CT+M and NT+MS attained a significantly higher maize plus soybean gross margin under virtually all scenarios except scenario 1, in which it did not differ significantly from NT M (Table 3).

Cotton attained significantly higher gross margins under NT than tilled in 2022, and also across all sensitivity analysis scenarios, in the order of 90 to 314% increase as compared to CT (Table 3). In 2023, the effect of tillage and the preceding cropping systems was significant on the gross margin of cotton. Cotton preceded by MS intercrops (NT+MS and CT+MS) attained a higher gross margin than preceded by sole crops (NT+M and CT+M) across all scenarios.

Labour productivity, return to labour, and benefit-cost ratio

When measured in terms of maize plus soybean production, labour was more productive with MS intercropping (CT+MS and NT+MS, respectively, 158 and 184 kg person day^{-1}) than with NT sole maize or with CT sole maize in 2022 (Table 4). In 2023, labour productivity was highest CT+M, CT+MS, and NT+MS (101, 99, and 104 kg person day^{-1}, respectively). When measured in terms of seed-cotton production, NT increased labour productivity in 2022, and was significantly higher when cotton was preceded by MS intercropping than sole maize in 2023, irrespective of tillage system (Table 4).

The return to labour of maize plus soybean production was highest with NT+MS and CT+MS (31 and 26 US\$ person day^{-1}, respectively) and in 2022 and with CT+M, NT+MS, and CT+MS in 2023 (Table 4). In 2022, the return to labour of cotton production was higher under NT (18 US\$ person day^{-1}) than CT (12 US\$ person day^{-1}). In 2023, the return to labour was significantly higher when cotton was preceded by intercrops (14 US\$ ha^{-1}) than by sole maize (Table 4).

The benefit-cost ratio of maize plus soybean was significantly greater under NT+MS than the rest of the treatments in 2022, whereas CT+MS had less favourable cost-benefit ratios in 2023 (Table 4). For cotton, NT led to a higher benefit-cost ratio for cotton as compared to CT in 2022 (Table 4). In 2023, cotton preceded by maize intercrops (CT+MS and NT+MS) exhibited significantly higher benefit-cost ratios (1.01 and 1.09, respectively) than by sole maize, irrespective of tillage system.

Discussion

Yield penalties during the early phases of transition to CA often deter smallholder farmers from adopting these practices. This study aimed to assess the agronomic and economic impacts of implementing CA practices in the first two years of a cotton-maize crop rotation system in Benin's cotton-growing zone. During these first two years, the treatments that combined two key components of CA, namely NT and legume intercropping, limited the yield penalties for maize and for cotton grown in rotation the following year. NT and legume intercropping allowed

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Table 3. Gross margin of maize plus soybean and cotton production under the effect of tillage options and cropping systems

Crop	Year	Tillage	Cropping system	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
				US$ ha^{-1}				
Maize and soybean	2022	Conventional tillage	Sole maize	424c	275c	343c	343c	504c
			Maize-soybean intercrops	824b	601b	669b	623b	878b
		No-tillage	Sole maize	405c	255c	324c	332c	481c
			Maize-soybean intercrops	1063a	840a	909a	843a	1136a
		Mean		679A	493A	561A	535A	750A
		p-values	Tillage	0.4329	0.3949	0.4329	0.4143	0.4404
			Cropping system	0.0257	0.0311	0.0204	0.0326	0.0336
			Tillage*Cropping system	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	2023	Conventional tillage	Sole maize	363ab	131b	283a	220a	506a
			Maize-soybean intercrops	354ab	204a	200b	126b	435ab
		No-tillage	Sole maize	293b	144b	213b	173ab	377b
			Maize-soybean intercrops	427a	214a	273a	194a	504a
		Mean		359B	173B	242B	178B	456B
		p-values	Tillage	0.1472	0.1472	0.1472	0.05654	0.2563
			Cropping system	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
			Tillage*Cropping system	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cotton	2022	Conventional tillage		100b	64b	147b	36b	110b
		No-tillage		237a	197a	280a	149a	337a
		Mean		169B	131B	214B	93B	224B
		p-values		0.014	0.0015	0.0015	0.0018	0.002
		Conventional tillage	Preceded by sole maize	367b	338b	407b	261b	484b
			Preceded by maize-soybean intercrops	549a	510a	579a	412a	676a
	2023	No-tillage	Preceded by sole maize	329b	300b	363b	235b	434b
			Preceded by maize-soybean intercrops	563a	535a	603a	442a	696a
		Mean		452A	421A	488A	338A	573A
		p-values	Tillage	0.7708	0.7769	0.765	0.9139	0.5535
			Cropping system	0.0202	0.02	0.0199	0.0197	0.2021
			Tillage*Cropping system	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

For each crop in the given year and for a given parameter, values with the same lower-case letter are not significantly different at $p < 0.05$. p-values = probability of significance. ns = non-significant.

Table 4. Average labour productivity return to labour, and benefit-cost ratio for maize-soybean and cotton production under the effects of tillage and cropping systems

Crop	Year	Tillage	Cropping systems	Labour productivity kg day^{-1}	Return to labour US$ day^{-1}	Benefit-cost ratio
Maize and soybean	2022	Conventional tillage	Sole maize	123b	13b	1.14c
			Maize-soybean intercrops	158a	26a	1.88b
		No-tillage	Sole maize	90b	12b	1.26c
			Maize-soybean intercrops	184a	31a	2.74a
		Mean		139A	21A	2A
		p-values	Tillage	0.77	0.69	0.285
			Cropping system	0.023	0.027	0.018
			Tillage*Cropping system	<0.0001	<0.0001	<0.0001
	2023	Conventional tillage	Sole maize	101a	12a	0.98a
			Maize-soybean intercrops	99a	8b	0.81b
		No-tillage	Sole maize	85b	12a	0.94a
			Maize-soybean intercrops	104a	11a	1.09a
		Mean		97B	11B	1B
		p-values	Tillage	0.0006	0.7037	0.03119
			Cropping system	<0.0001	<0.0001	<0.0001
			Tillage*Cropping system	<0.0001	<0.0001	0.00232
Cotton	2022	Conventional tillage		40b	12b	0.17b
		No-tillage		53a	18a	0.44a
		Mean		47A	15A	0.31B
		p-values		0.0011	0.0016	0.0011
	2023	Conventional tillage	Preceded by sole maize	42b	9b	0.66b
			Preceded by maize-soybean intercrops	47a	14a	1.01a
		No-tillage	Preceded by sole maize	39b	10b	0.63b
			Preceded by maize-soybean intercrops	46a	14a	1.09a
		Mean		43A	12A	0.86A
		p-values	Tillage	0.2598	0.2525	0.074
			Cropping system	<0.0001	<0.0001	<0.0001
			Tillage*Cropping system	0.0016	0.0294	0.0292

For each crop in the given year and for a given parameter, values with the same lower-case letter are not significantly different at $p < 0.05$. p-values = probability of significance. ns = non-significant.

reducing economic risk variability, producing higher gross margins, cost-benefit ratios, and returns to labour, even under scenarios in which fertiliser costs were 30% higher or the crop yield decreased by one standard deviation (i.e. scenarios 1–4). However, the impact of NT and intercropping varied between the two years of the experiment, suggesting interactions between climatic variability and the performance of these CA practices.

Impact of tillage options and cropping systems on crop productivity

The maize and cotton yields attained in this experiment in both years were above the average yields attained by farmers in cotton-growing regions of Northern Benin (respectively, 1400 and 1000–1100 kg ha^{-1}) (Honfoga, 2018; Tovihoudji *et al.*, 2023). While NT+MS intercropping exhibited superior performance in terms of maize grain yield in 2022, conventional sole maize (CT+M) showed higher maize grain yields in 2023 (cf. Table 1). Adding up the maize yields of both years (CT+M = 6655 kg ha^{-1}, CT+MS = 5599 kg ha^{-1}, NT+M = 5842 kg ha^{-1}, NT+MS = 6904 kg ha^{-1}) results in virtually similar cumulative yield levels under CT+M and NT+MS. In addition to maize, soybean grain yield was higher under intercropping treatments (NT+MS and CT+MS) in both years (cf. Fig. 2). The highest seed-cotton yields were attained

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with NT in 2022, and when the cotton was preceded by intercrops in 2023 (cf. Table 2). These results are in line with recent studies in SSA (Bitew *et al.,* 2022; Nasar *et al.,* 2024). The substantial increase in maize performance (grain yields and total biomass) with NT and legume intercropping during the first year could be attributed to the effect of minimum soil disturbance on the efficient utilisation of available resources (light, water, and plant nutrients), plus the nitrogen-fixing ability of the soybean. Recent evidence from northern Benin cotton zones also indicates greater soil biological activity and trophic networks favouring nutrient cycling and availability under CA than CT (Dassou *et al.*, 2024). Whether the impact of CA practices studied is due to water or nutrient effects remains to be elucidated through further research.

Legumes play a crucial role in enhancing the sustainable intensification of farming systems, with their contributions to the soil nitrogen (N) pool varying depending on their growth habits and nitrogen-fixing abilities. For instance, short-cycle bush beans provide modest contributions, while dual-purpose soybean and pigeon pea can significantly impact the N pool in soil (Vanlauwe *et al.*, 2019). Soybean is particularly beneficial in low-input farming systems, such as those prevalent in Northern Benin, as it contributes to the soil N budget through biological N_2 fixation (BNF) (Ciampitti and Salvagiotti, 2018). BNF can benefit the associated crop and subsequent crops. Although the BNF potential of soybean was not directly assessed in this study, it is reasonable to assume that the cotton planted in 2023 benefited from the residual nitrogen fixed by soybean in 2022. This could explain the higher seed-cotton yield recorded in 2023 when cotton was preceded by MS intercropping, irrespective of the tillage option (CT or NT). Several studies (e.g. Zhao *et al.*, 2022; Corbeels *et al.*, 2020) have shown that well-designed maize-legume intercrops in both time and space are highly productive and efficient in resource utilisation under sub-humid conditions, resulting in maintenance or improvement of the yield of the main crop.

It has been broadly reported that shifting from CT to CA is characterised by yield penalties in the first years of adoption (Akplo *et al.*, 2025; Bruelle *et al.*, 2015; Thierfelder *et al.*, 2016; Yemadje *et al.*, 2025), so that positive yield effects can take 5 to 15 years to become apparent (Salem *et al.*, 2015; Corbeels *et al.*, 2014). In a recent study, Akplo *et al.* (2025) showed that during the first two years of a transition towards CA, be it towards minimum or NT, yield penalties persist, affecting the economic performance of both cotton and maize in Northern Benin. Through a literature review, Corbeels *et al.* (2020) reported that when the three CA principles of minimal soil disturbance, continuous soil cover, and crop diversification are implemented concomitantly, maize yield increased by an average of 8.4% in SSA. Here, we recorded maize yield increases in the order of 30% (1 t ha^{-1} extra grain) by combining NT and soybean intercropping with respect to CT+M the first year, as well as a carry-over 14% increase in seed-cotton yield the subsequent year. Intercropping with CT led to a merely 5% maize yield advantage, yet the subsequent cotton yielded 18% more than when preceded by sole maize. NT without legume intercropping led to a 13% yield penalty compared with CT in the first year, as well as a 10% yield penalty in the subsequent cotton crop. It must be noticed also that the CA principle of soil cover with mulch was not met in this experiment, as free-grazing animals foraged on the maize crop residues during the dry season.

Furthermore, we observed significant variation in maize aboveground biomass and number of grains per cob (cf. Table 1) and in cotton above- and below-ground biomass, and boll number (cf. Table 2), suggesting that soil management can have subtle yet significant effects on crop yield components, as seen earlier in Benin (Akplo *et al.,* 2025; Yemadje *et al.,* 2022) and elsewhere (Li *et al.*, 2020; X. Zhao *et al.*, 2022). Aboveground biomass plays a key role in the accumulation and redistribution of assimilates required for grain or seed formation, but it is influenced by various factors, including genetics, environmental conditions, and management practices (Jumanov *et al.*, 2023). Root development and its pattern of distribution are largely determined by several factors, including the soil environment (Mehra *et al.,* 2025). Our results showed greater cotton belowground biomass under CT than NT, probably indicating better conditions for root establishment through facilitating water and air circulation and soil penetrability in tilled soils (Kiboi *et al.*, 2019; Kurothe *et al.*, 2014; Yemadje *et al.,* 2022), especially during the first years of a

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transition to CA. A less developed root system may also contribute to explaining the differences in the performance of CA practices between the first and second years of this experiment. Although the total seasonal rainfall was similar in both years, in 2023, crops received during the first two months of the season about half of the rainfall received in the same period in 2022 (cf. Supplementary Material Fig. S1). Among the impacts that CA has on crop water availability, that of water retention with mulching is a key one (Abdallah *et al.,* 2021; Bruelle *et al.,* 2017; Mhlanga and Thierfelder, 2021), and this was not achieved in the current experiment.

The results demonstrated a notable disparity in rainfall use efficiency for cotton in 2022, with the highest value observed in the NT treatment relative to the CT control. In 2023, intercropping maize and soybean before cotton, irrespective of tillage method (CT+MS and NT+MS), led to rainfall use efficiency by cotton. However, the interactive effect of tillage practices and cropping systems was found to be significant on rainfall use efficiency for maize, with the NT+MS intercropping system exhibiting superior rainfall use efficiency. The positive impact of CA practices over conventional systems could be attributable to their high aboveground biomass production observed in this study. This aboveground biomass can act as mulch and lead to improved soil moisture conditions (Feng *et al.,* 2023). NT limits soil disturbance, thereby reducing water loss and creating conditions favourable for water conservation on site and efficient water use by plants (Giller *et al.,* 2015). In a recent review, Liu *et al.* (2025) reported that intercropping increases plant water availability and water use efficiency. Previous studies have demonstrated that intercropping practices increase water availability by enhancing both the above- and below-ground biomass, modifying canopy structure, and increasing the underlying surface complexity due to variation in crop cover over time (Barry *et al.,* 2019; Luo *et al.,* 2024).

Economic implications of no-tillage and intercropping

The economic analysis provided evidence on the impacts of NT and intercropping on cropping system profitability and financial sustainability. Overall, the effect of the treatments on the gross margin reflected the differences in maize plus soybean yield and seed-cotton yield previously described, but these varied alongside the different scenarios examined. For all scenarios, NT and intercropping showed a greater gross margin for maize plus soybean production. Cotton preceded by intercrops, tilled or not, presented higher gross margins than preceded by sole maize, consistently across scenarios that assumed +/-30% fertiliser price variation and +/-1 standard deviation maize or cotton yield variation. The performance of NT and intercropping observed in this study can be explained by the fact that these treatments increased yields and required fewer financial inputs than conventional practices (cf. Table S2). Previous studies indicate that, although the short-term crop yield benefits expected from NT are relatively small, the immediate advantage of eliminating time- and cost-consuming ploughing is significant (Corbeels *et al.,* 2020; Hobbs *et al.,* 2008).

Intercropping legumes (e.g. soybean) with cereals (e.g. maize) has the potential to increase farmer profitability by optimising land use and labour (Tine *et al.,* 2023), while also reducing fertiliser and pesticide application and enhancing crop yields and yield stability (Tzemi *et al.,* 2025). A recent study (Erythrina *et al.,* 2022) reported an additional net return gain of USD 153 ha^{-1} in MS intercropping compared to maize sole. The economic advantages of cereal/legume intercrops were reported for cereal/legume including groundnut/pearl millet (Rao and Singh, 1990), maize-common bean (Alemayehu and Bewket, 2016), or maize-pea (Yang *et al.*, 2018). However, in our experiment, maize-legume intercropping under CT was more sensitive to price and yield changes. This may be associated with the high cost of ploughing, which is in addition to the other production costs common to all other treatments (cf. Table S2). Omulo *et al.* (2022) reported lower gross margin under disc harrowing (CT) compared to ripping tillage and NT in Zimbabwe.

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Under all scenarios, NT exhibited a higher cotton gross margin than that CT in 2022. The carry-over effect of maize-legume intercropping on subsequent cotton yield was also reflected in higher cotton gross margins in 2023, under all scenarios. Likewise, Jat *et al.* (2014) reported lower production costs, higher net returns and benefit-cost ratio, and lower labour and energy requirements for NT compared to the CT. Other studies (Aryal *et al.*, 2016; Kumar *et al.*, 2013) showed that shifting from CT to NT in wheat decreased input costs by 20–59% and increased net revenues by 28–33%. By decreasing production costs, even if yields remain similar, slightly above or below CT, NT may contribute to reducing economic risks in a context of increasingly frequent crop failures due to climate variability.

Conclusion

The primary objective of this research was to examine the short-term agronomic and economic performance of CA practices, namely NT and MS intercropping, on a cotton-based cropping system in Northern Benin. In this study, NT with intercropping soybean and maize compensated for the yield penalties associated with the initial years of the transition to CA, allowed reducing economic risks, and resulted in higher gross margins, even when the fertiliser costs or the yield varied, during both the cereal crop and the subsequent cotton crop. However, the opposite yield trends among treatments observed in the second year, associated with a drier start of the season, would indicate that water capture and availability were not improved under CA due to the lack of mulching or crop residue incorporation in the soil. In such conditions, particularly during the early transition years, the expected CA impacts on soil structure may still be limited, and CT may continue to create better conditions for root growth and water dynamics than NT, as shown by cotton belowground biomass trends.

Our study focuses on the comparison of different tillage options and cropping systems without considering other potential factors that could influence agricultural productivity, such as soil type, climate variability, crop varieties, and planting dates, which could have an impact on productivity. To inform farmers' management decisions effectively, it is essential to assess such options from agronomic and economic perspectives using multilocation experimentation over a longer time span.

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Data availability statement. Data will be made available on request.

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Competing interests. The authors declare they have no competing interest.

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