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Limited yield penalties in an early transition to conservation agriculture in cotton-based cropping systems of Benin

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Transitioning toward minimum or no tillage is challenging for smallholder farmers in sub-Saharan Africa (SSA), due to the possible yield penalties during the initial years of a transition. Understanding the early impacts of such transitions is crucial in a cash crop such as cotton, on which farmers rely for their income, and is necessary to inform agroecological strategies to cope with both these challenges. This study explores the combined impact of minimum or no tillage and fertilizer regimes on agronomic parameters of cotton–cereal rotations, as practiced by smallholder farmers in Benin. A multilocation experiment was set up in three different agroclimatic zones, namely, Savalou (7°55′41″, 1°58′32″), Okpara (2°48′15″, 7°72′07″), and Soaodou (10°28′33″, 1°98′33″). In each area, the experiment was laid out as a split-plot design with four replications (main plot = soil preparation; subplot = fertilizers regimes). The treatments consisted of three different forms of soil preparation, namely, tillage, strip tillage, and no tillage or direct seeding, and four fertilization regimes, namely, basal mineral fertilizers (BMF, 200 kg ha^1 of $N_{14}P_{18}K_{18}S_6B_1$ + 50 kg ha^1 of urea), BMF + A (200 kg ha^1 of calcium phosphate amendment, $22P_2O_5$-43CaO−4S), BMF + C (400 kg ha^1 of compost), and BMF + A + C. At all sites, direct seeding led to lower below-ground biomass growth and seed cotton yields compared with conventional tillage in an early transition to conservation agriculture starting from degraded soils (2% to 25%). Weak rooting under direct seeding resulted in lower cotton yields compared with that under tillage (−12%) and strip tillage (−15%). At 45 and 90 days after emergence, cotton plants were shorter under direct seeding compared with tillage (−9% and −13%, respectively) and strip tillage (−23% and −6%, respectively). Fertilizer regimes affected seed cotton yields differently across sites and treatments, with marginal responses within soil preparation methods, but they contributed to increase yield differences between conventional and no tillage. Considering the need for sustainable practices, in the context of degraded soils and poor productivity, such limited yield penalties under CA appear to be a reasonable trade-off in the first year of a transition. Alternatively, the results from the first year of this experiment, which is meant to continue for another 5 years, suggest that strip tillage could be a sensible way to initialize a transition, without initial yield penalties, toward more sustainable soil management.

KEYWORDS

yield penalties, direct seeding, strip tillage, root, biomass, conservation agriculture, cotton

Highlights

- Conventional tillage, strip tillage, and direct seeding were tested in three cotton-growing regions of benin.
- At all the sites, yields were 6–20% lower under direct seeding than those under conventional tillage.
- increasing fertilizer inputs did not contribute to overcoming such yield declines under conservation agriculture.
- Observed yield penalties were associated with lower root numbers and below-ground biomass.
- Strip tillage appears as a sensible way to initialize a transition toward more sustainable soil management.

Introduction

Soils in sub-Saharan Africa (SSA) are degraded, mainly due to the expansion and intensification of agriculture in efforts to feed its growing population (Tully et al., 2015). Soil degradation affects the livelihoods of the majority of the population that depends directly on agriculture for food and income. There is an urgency in transitioning toward more sustainable soil management practices in SSA, particularly in Benin, where soils are extremely degraded. Conservation agriculture (CA) has the potential to halt soil degradation and even restore their productivity over the long term in SSA (Thierfelder et al., 2016; Ranaivoson et al., 2017; Kassam et al., 2019; Martinsen et al., 2019). CA is based on a set of sustainable agricultural practices that fulfill the following three main principles: (1) minimal soil disturbance or no tillage/direct seeding; (2) continuous soil cover—with crops, cover crops, or a mulch of crop residues; and (3) crop rotation and the use of cover crops (FAO, 2015). There is scientific evidence that CA can enhance crop yields (Mupangwa et al., 2019), especially when all three principles are deployed together (Corbeels et al., 2020). Several studies, however, reported contradictory results on the impact of CA on soils, crop productivity, and weed infestation, and these discrepancies need to be understood (Giller et al., 2009; Ranaivoson et al., 2017; Alarcón et al., 2018; Ginakes et al., 2018; Nafi et al., 2020; Buesa et al., 2021; Singh et al., 2021).

Published research on no tillage/direct seeding shows that it can maintain, increase, or decrease yield levels over time (Giller et al., 2009; Brouder and Gomez-Macpherson, 2014). A number of studies showed that no tillage/direct seeding practices can reduce crop yield due to the potential for soil waterlogging and/or cooler soil temperatures which can inhibit the nutrient release and crop growth (Ogle et al., 2012). Minimum tillage, on the contrary, has been proposed as an alternative to no tillage and widely discussed in the literature, with divergent effects reported depending on the type of crop, the biophysical conditions, and the timescale of the practice (Githongo et al., 2021). When compared with no tillage, minimum tillage may have a minor positive or neutral impact on crop dry matter and grain yield (Conyers et al., 2019). Minimum tillage was shown not to improve soil quality parameters, yield, the productivity of wet season and winter crops and cropping systems, net yields, or water use efficiency (Singh et al., 2021).

One of the factors that deter farmers in sub-Saharan Africa from transitioning toward CA is the initial yield penalties they may experience (Tittonell et al., 2012). Most of the existing studies involving minimum tillage or no tillage/direct seeding investigated the long-term impact of those agricultural practices. Very few studies have focused on the impact of minimum tillage or no tillage/direct seeding on agronomic and environmental parameters at the early phase of the transition, and they show varying impacts (positive, neutral, or negative) (Baudron et al., 2012; Gill and Aulakh, 1990; Thierfelder and Mhlanga, 2022). For example, Mafongoya et al. (2016) reported yield penalties under direct seeding during the first 2 years, but not after subsequent years. Such short-term effects are important because they determine the attractiveness of CA to farmers and thus its potential for adoption. The variability in short-term crop responses to CA is primarily due to the interactive effects of crop needs, soil characteristics, and the climate (Giller et al., 2009). Also, several studies have shown a need to initially increase fertilizer inputs in CA systems due to a short-term decline in nitrogen availability (Sainju et al., 2006).

The objective of this study was to investigate the combined effect of soil preparation methods (tillage, strip tillage, and no tillage) and different fertilization regimes on seed cotton yields, the main cash crop in Benin, during the first year of a long-term experiment. We hypothesized that adjusted fertilization regimes, adding compost and calcium phosphate, may contribute to overcoming the initial yield penalties expected during the first steps in a transition to conservation agriculture, relying on no or minimum tillage, and starting from moderately degraded soils. A multilocation trial was established in three cotton-growing regions of Benin, which exhibit poor soils that were historically managed under conventional tillage, and is meant to be conducted over 5 years. Here, we focus on the first 2 years of the experiment (cover crop + main crop) to assess the extent of yield penalties in the early phases of the transition toward CA and hence to be able to quantitatively characterize the trade-off between short-term productivity and long-term soil fertility restoration under CA.

Materials and methods

Site description

This study was carried out during the 2021 growing season in three different agroclimatic zones of Benin, namely, Savalou, Soaodou, and Okpara (Figure 1). Savalou (7°54′24″, 1°55′31″) is part of the Sudano-Guinean climatic zone, which is characterized by a growing season with a bimodal distribution, allowing two crops per year. The precipitations were approximately 1,000–1,200 mm, spread over a vegetative growth period of 240 days, and one constant and intermediate dry season. During the growing season, the rainfall period spans from March to July and September to November. The soils at Savalou are ferruginous tropical soil (Haplic Luvisol) according to the World Reference Base classification (FAO, 2006). The soils are sandy with low clay. The soils are not particularly fertile and require the application of agroecological practices to improve soil fertility.

The experimental center of Soaodou (10°29′42″, 1°99′05″) is located at Péhunco, a city in the northwest part of the country. Soaodou is characterized by a Sudano-Sahelian climate with an average unimodal rainfall of 900–1,300 mm of water per year. The growing season ranges from May to November and the dry season ranges from December to April. The vegetative growth period is between 140 and 189 days. The soils at Soaodou are Fluvisols according to the World Reference Base classification (FAO, 2006). Soil type and physicochemical characteristics at the experimental sites are presented in Table 1.

The experimental center of Okpara (9°21′11″, 2°41′02″) is located 10 km from the city of Parakou. Okpara is characterized by a Sudanian climate with an average unimodal rainfall ranging from 900 mm to 1,200 mm and an average daily temperature of approximately 27.5°C. It is also characterized by a growing season extending from May to October and a dry season from November to April. The soils are classified as ferruginous tropical soil in the French system of classification of soils, which corresponds to Acrisols or Lixisols according to the World Reference Base classification (FAO, 2006).

Experimental design and layout

A multilocation experiment was conducted for one season under a split-plot design with four replications (main plot =

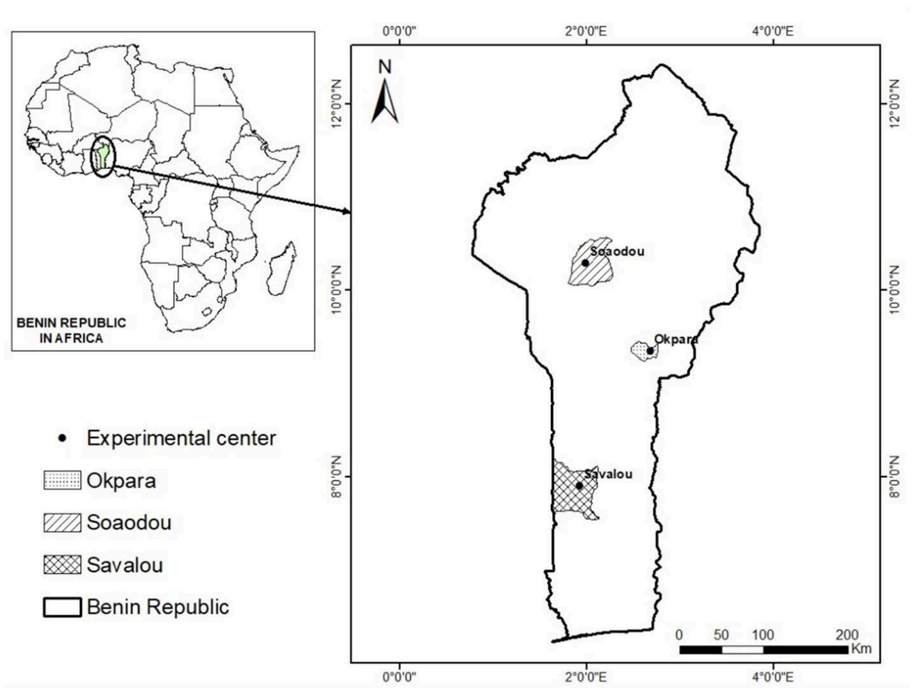

FIGURE 1
Experimental centers location at Benin Republic.

TABLE 1 Physico-chemical characteristics of the soil at experimental sites.

Site	Soil type	Physical parameters	Chemical parameters in 2019						
			C total (g kg^{-1})	N total (g kg^{-1})	P (g kg^{-1})	K (cmol + kg^{-1})	Ca (cmol + kg^{-1})	Mg (cmol + kg^{-1})	Na (cmol + kg^{-1})
Soaodou	Luvisols	High clay content	0.44	0.59	5.9	0.10	1.95	0.43	0.21
Okpara	Aerisols or Lixisols	Sandy loam	0.54	0.58	14	0.12	1.36	0.39	0.19
Savalou	Haplic Luvisol	Sandy with low clay	0.71	0.59	15.9	0.39	3.26	0.63	0.21

TABLE 2 Seed cotton yield (kg ha^{-1}; means are followed by standard deviation).

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	1290 ±66 c	1578 ± 76 b	1333 ± 48 c
Strip till	1433 ±47 a	2091 ± 53 a	1499 ± 88 a
Tillage	1399 ±35 b	1983 ± 55 a	1425 ± 43 b
Yield penalty (%) direct seeding/tillage	8 %	20%	6%
Fertilizers regimes			
BMF	1421 ± 73 a	1917 ± 71 a	1415 ± 97 a
BMF + A	1342 ± 36 b	1908 ± 98 a	1418 ± 67 a
BMF + C	1330 ± 60 b	1838 ± 98 a	1412 ± 61 a
BMF + A + C	1402 ± 65 a	1872 ± 90 a	1426 ± 67 a
Soil preparation: Fertilizers regimes			
Direct seeding: BMF	1380 ± 210 bcd	1745 ± 129 a	1231 ± 59 f
Direct seeding: BMF + A	1246 ± 56 ef	1548 ± 170 a	1343 ± 131 e
Direct seeding: BMF + C	1219 ± 109 f	1499 ± 205 a	1395 ± 94 de
Direct seeding: BMF + A + C	1314 ± 146 de	1520 ± 114 a	1365 ± 102 de
Strip till: BMF	1476 ± 109 a	2067 ± 89 a	1677 ± 241 a
Strip till: BMF + A	1454 ± 51 ab	2191 ± 151 a	1524 ± 139 b
Strip till: BMF + C	1394 ± 96 abcd	2041 ± 78 a	1262 ± 128 f
Strip till: BMF + A + C	1406 ± 134 abc	2063 ± 116 a	1486 ± 166 bc
Tillage: BMF	1406 ± 46 abc	1937 ± 133 a	1338 ± 101 e
Tillage: BMF + A	1326 ± 42 cde	1985 ± 60 a	1387 ± 81 de
Tillage: BMF + C	1376 ± 115 bcd	1975 ± 121 a	1550 ± 75 b
Tillage: BMF + A + C	1485 ± 58 a	2034 ± 140 a	1426 ± 88 cd
Soil preparation	0.00 ***	0.00 ***	0.00 ***
Fertilizers regimes	0.00 ***	0.85 ns	0.95 ns
Soil preparation: Fertilizers regimes	0.00 ***	0.80 ns	0.00 ***

, * significant at 5 % (0.01 < P < 0.05), and 1 % (P < 0.01), respectively; ns, not significant at P ≤ 0.05. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

soil preparation; subplot = fertilizers regimes). The basic plot size was 96 m^2. The treatments consisted of three different forms of soil preparation, namely, tillage (CT), strip tillage (ST), and no tillage or direct seeding (DS), and four fertilization regimes, namely, basal mineral fertilizers (BMF, 200 kg ha^{-1} of $N_{14}P_{18}K_{18}S_6B_1$ + 50 kg ha^{-1} of urea); BMF + A (200 kg ha^{-1} of calcium phosphate amendment, $22P_2O_5$-43CaO−4S) at the emergence, near the seeding line; BMF + C (400 kg ha^{-1} of compost) at the emergence, near the seeding line; and BMF + A + C at the emergence, near the seeding line. NPKSB and urea were applied on the plots at 15 and 40 days, respectively, after emergence. The plots were cultivated with two varieties of cotton (*Gossypium hirsutum* L.) recommended according to the agroecological zones. The varieties represent those that are disseminated in each area, OKP 768 at Savalou and Okpara and ANG 956 at Soaodou. A tiller was used to prepare the soil on tillage and strip till plots. The strip till was set up in dry conditions, in March at Savalou and at the beginning of May at Soaodou and Okpara. In the first season, *Crotalaria juncea* was sown on all the plots after the first precipitations. On the till plots, tillage was done in the second season, at a depth of 20 cm, using a moldboard plow by burying *Crotalaria* crop residues. At Savalou, Okpara, and Soaodou, the plots were prepared with glyphosate (480 g l^{-1}) 15 days before cotton seeding to control soil weeds. After the glyphosate, the roller was used to put down the biomass. Seeding was performed early (15 days before tillage plots) on the strip till and direct seeding plots after important precipitations. Seeding was performed manually at 0.80 m inter-row and 0.2 m on the row with three or four seeds per hole. The seedlings were separated 15 days after emergence by keeping one plant per pocket, which means 41,666 plants per hectare. Weed management and phytosanitary protection were carried out according to the technical recommendations for cotton production in Benin (Houndete et al., 2015).

Agronomic data collection

Roots and below-ground biomass were estimated through the number of roots and the elbow frequency. Above-ground and below-ground biomass was measured 40 days after emergence. Plant height was measured at 30, 45, and 90 days after emergence. On two lines, after three steps along the first line, the first plant was measured and marked with a wire. The 14 following plants were measured and the same sampling was performed on the second line. Seed cotton yields were estimated on the central lines. The first harvest was performed when 50% of the capsules were opened, and the second harvest was performed when all the capsules were opened.

Data analysis

The statistical analysis was performed using the R statistical software (v4.1.2; R Core Team, 2021). Prior to analysis, the data were curated and extreme outliers were removed. Descriptive statistics were obtained using the psych package. Variables that satisfied the conditions of normality and homoscedasticity were subjected to an ANOVA using the split-plot design. The Student–Newman–Keuls test was used to separate the significantly different means. A probability level at a p-value of ≤ 0.05 was used as the critical value. The analysis of area clustering was performed using the linear mixed-effect model and the generalized linear mixed model using the Template Model Builder. Tukey's test was used to compare the estimated means obtained with the function "lsmeans."

Results

Seed cotton yields

Yields in the three regions were in the order of those obtained by local farmers on average (1,200 kg ha^{-1}), significantly ($p < 0.05$) greater at Okpara (1884.31 ± 44.40 kg ha^{-1}) than at Savalou and Soaodou (1410.38 ± 36.79 and 1373.92 ± 30.03 kg ha^{-1}, respectively). On average, seed cotton yields were significantly ($p < 0.05$) lower under direct seeding than those under conventional (−6, −20, and −8%, at Savalou, Okpara, and Soaodou, respectively) or strip tillage (−9.4, −24.5, and −9.9% at Savalou, Okpara, and Soaodou, respectively; Table 2). Yields under strip tillage were higher than those under conventional tillage at Soaodou and Savalou. There were no significant ($p > 0.05$) differences across fertilizers regimes at Okpara and Savalou. At Soaodou, basal mineral fertilizers regimes and basal mineral fertilizers with compost and calcium phosphate amendments produced significantly ($p < 0.05$) higher seed cotton yields compared with the other regimes. Absolute yield differences between conventional tillage and no tillage or direct seeding varied across sites, and were much wider at Okpara and tended to increase with full fertilization regimes (Figure 2).

Above-ground biomass

The patterns of variation observed for seed cotton yields were partially also reflected in the variation of above-ground biomass growth, which was assessed 40 days after emergence (Table 3). On average, plants established through direct seeding exhibited the same levels of above-ground biomass 40 days after emergence compared with the conventional tillage at

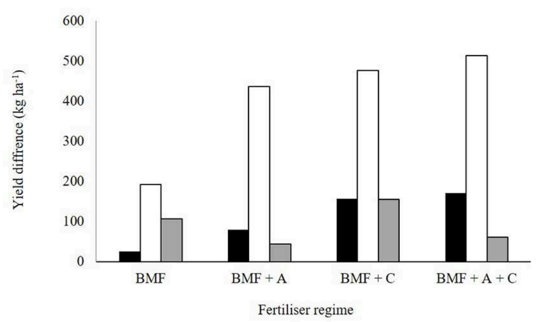

FIGURE 2
Absolute seed cotton yield differences (kg ha^{-1}) between conventional tillage and no till at Soaodou (black bars), Okpara (white bars) and Savalou (grey bars). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N).

TABLE 3 Aboveground biomass (g plant^{-1}) at 40 days after emergence (means are followed by standard error).

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	8.32 ± 0.89 a	9.15 ± 0.73 b	8.62 ± 0.31 b
Strip till	10.36 ± 1.24 a	12.46 ± 1.48 a	12.77 ± 0.53 a
Tillage	10.71 ± 1.33 a	9.99 ± 0.70 b	12.26 ± 1.55 a
Fertilizer regimes			
BMF	11.46 ± 1.61 a	11.06 ± 0.95 a	11.02 ± 0.86 a
BMF + A	9.05 ± 0.61 a	9.84 ± 1.80 a	10.72 ± 1.07 a
BMF + C	7.99 ± 1.67 a	11.27 ± 1.05 a	10.02 ± 1.21 a
BMF + A + C	10.70 ± 1.17 a	9.95 ± 1.18 a	13.10 ± 1.68 a
Soil preparation: Fertilizer regimes			
Direct seeding: BMF	8.46 ± 2.43 a	10.11 ± 2.26 a	7.96 ± 0.33 b
Direct seeding: BMF + A	8.65 ± 1.45 a	8.83 ± 1.19 a	8.06 ± 0.92 b
Direct seeding: BMF + C	8.69 ± 2.56 a	10.13 ± 1.21 a	9.27 ± 0.44 b
Direct seeding: BMF + A + C	7.50 ± 1.48 a	7.51 ± 1.15 a	9.22 ± 0.47 b
Strip till: BMF	10.95 ± 1.54 a	12.59 ± 1.98 a	12.94 ± 0.45 ab
Strip till: BMF + A	8.34 ± 0.66 a	13.56 ± 4.89 a	13.76 ± 0.55 ab
Strip till: BMF + C	13.20 ± 3.22 a	12.21 ± 3.71 a	13.41 ± 1.27 ab
Strip till: BMF + A + C	8.96 ± 3.67 a	11.50 ± 2.34 a	10.96 ± 1.28 b
Tillage: BMF	14.96 ± 3.48 a	10.49 ± 0.30 a	12.16 ± 1.16 b
Tillage: BMF + A	10.16 ± 0.99 a	7.14 ± 1.63 a	10.36 ± 2.10 b
Tillage: BMF + C	10.21 ± 3.33 a	11.47 ± 0.72 a	7.39 ± 2.51 b
Tillage: BMF + A + C	7.51 ± 0.41 a	10.85 ± 1.33 a	19.13 ± 1.96 a
Soil preparation	0.12 ns	0.03 **	0.00 ***
Fertilizers regimes	0.07 ns	0.70 ns	0.05 ns
Soil preparation: Fertilizers regimes	0.48 ns	0.63 ns	0.00 ***

*, *** significant at 5 % (0.01 < P < 0.05), and 1 % (P < 0.01), respectively; ns, not significant at P ≤ 0.05. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

Soaodou and Okpara (Table 3). However, at Savalou, above-ground biomass was significantly ($p < 0.05$) lower under direct seeding compared with conventional tillage. Similarly, above-ground biomass was greater at Okpara and Savalou compared with Soaodou ($p < 0.05$). Fertilizer regimes did not affect the above-ground biomass between the sites or treatments in our experiment.

Above-ground biomass growth was also assessed non-destructively, by measuring plant height at 30, 45, and 90 days after emergence (Figure 3). At 30 days after emergence, no significant differences in plant height were observed between the different soil preparation treatments at any of the locations ($p > 0.05$). At 45 days after emergence, only at Okpara soil preparation affected plant height, where plants under direct seeding were 34% shorter than those under conventional tillage ($p < 0.05$). No significant differences in plant height were observed across soil preparation treatments at Savalou and Soaodou. At 90 days after emergence, plants were significantly shorter under direct seeding than those under conventional or strip tillage at Okpara and Soaodou (−20 and −18%, respectively) ($p < 0.05$). Fertilizer regimes did not significantly ($p < 0.05$) affect the cotton plant height at 30, 45, or 90 days after emergence at any of the three experimental sites.

Below-ground biomass and roots

Below-ground biomass

The observed differences in yield and above-ground biomass between treatments were not consistently reflected by root biomass. At 40 days after emergence, plants established through direct seeding had less below-ground biomass than those under conventional tillage and similar average values as under minimum strip tillage (Table 4). However, these differences in means can be explained by the differences observed at Soaodou and Savalou, but not at Okpara. Similarly, root biomass was significantly ($p < 0.05$) greater at Okpara and Savalou than at Soaodou ($p < 0.05$). Fertilizer regimes did not affect the below-ground biomass at any of the experimental sites or across treatments.

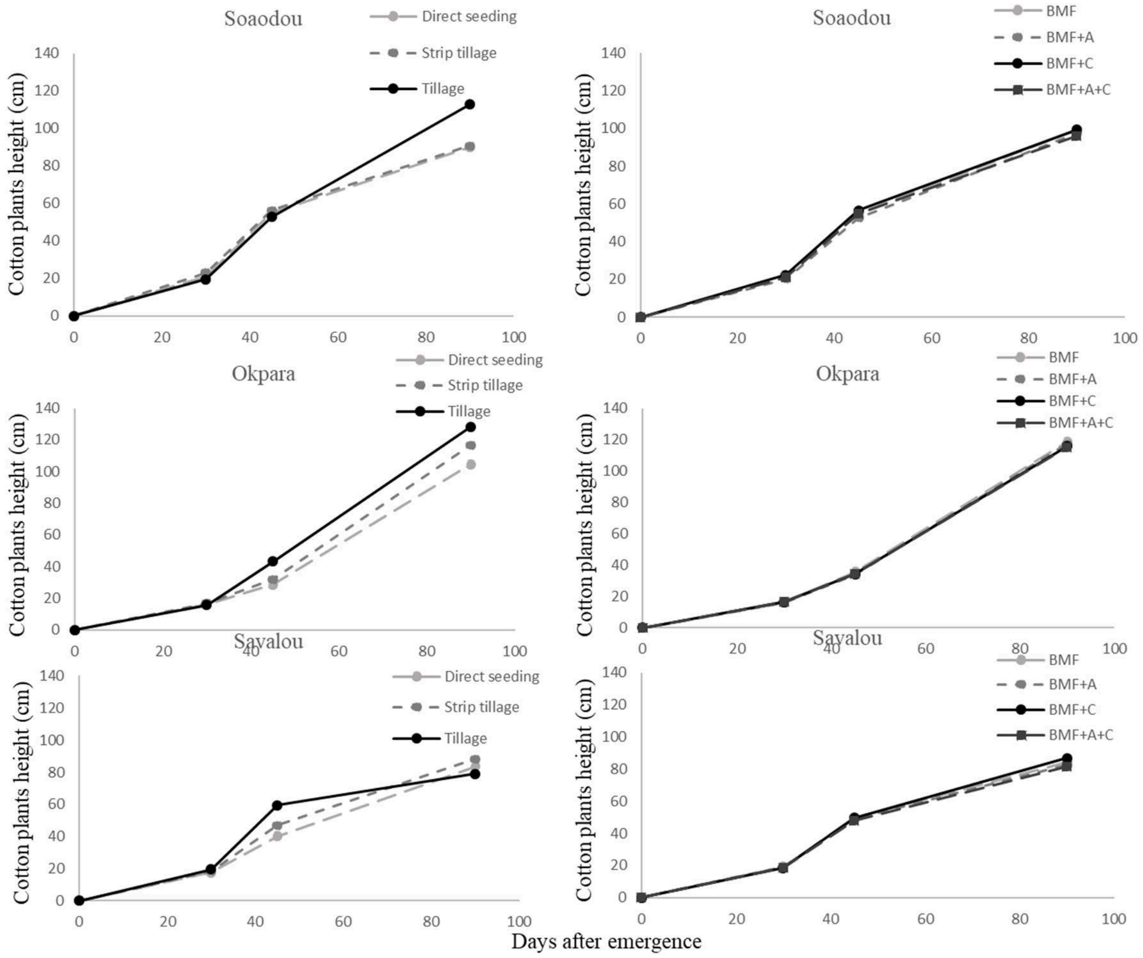

FIGURE 3
Cotton plant height at 30, 45 and 90 days after emergence. A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N).

Number of roots

At 40 days after emergence, the number of roots was significantly ($p < 0.05$) greater under conventional tillage than that under direct seeding or strip tillage only at Okpara, but not at Savalou or Soaodou (Figure 4). This trend is consistent with the variation observed in seed cotton yields (cf. "Seed cotton yield"). At Okpara, the number of roots was −52% under direct seeding compared with tillage, and there was no difference between strip tillage and direct seeding ($p > 0.05$). There was a significant interaction ($p < 0.05$) between soil preparation and site for the number of roots, while fertilizer regimes did not affect the number of secondary roots at any of the sites ($p > 0.05$).

Elbow frequency

Elbow frequencies differed broadly across sites and treatments (e.g., 91% for BMF+A+C conventional tillage in Okpara versus 4.4% for BMF direct seeding at Savalou), hampering the ability of the ANOVA to detect significant differences in an early transition to conservation agriculture in cotton-based cropping systems (Table 5). At Savalou, elbow frequencies were significantly lower (−87%) compared with those at Okpara and Soaodou. The same is true for soil preparation, which affected significantly ($p < 0.05$) the elbow frequency 40 days after emergence at the different sites (Table 5). Plants established under direct seeding and strip tillage had lower elbow frequencies compared with conventional tillage ($p < 0.05$). Fertilizer regimes affected root elbow frequencies at Soaodou and Okpara, but not at Savalou.

Discussion

Yield penalties

Our results suggest that direct seeding entails yield penalties in the order of roughly 6% to 20% compared with conventional tillage, in the first year of a transition to conservation agriculture (CA) in a cotton-based cropping system starting

TABLE 4 Belowground biomass (g plant^{-1}) in cotton based cropping systems at 40 days after emergence (means are followed by standard error).

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	1.41 ± 0.11 b	2.18 ± 0.19 a	1.49 ± 0.15 b
Strip till	1.47 ± 0.13 b	3.00 ± 0.35 a	1.86 ± 0.27 ab
Tillage	2.02 ± 0.23 a	2.23 ± 0.22 a	2.51 ± 0.31 a
Fertilizer regimes			
BMF	1.78 ± 0.29 a	2.47 ± 0.35 a	1.94 ± 0.35 a
BMF + A	1.69 ± 0.15 a	2.42 ± 0.32 a	2.12 ± 0.32 a
BMF + C	1.61 ± 0.22 a	2.52 ± 0.40 a	1.71 ± 0.30 a
BMF + A + C	1.47 ± 0.17 a	2.48 ± 0.25 a	2.05 ± 0.34 a
Soil preparation: Fertilizer regimes			
Direct seeding: BMF	1.13 ± 0.19 a	2.09 ± 0.60 a	1.43 ± 0.44 a
Direct seeding: BMF + A	1.67 ± 0.18 a	2.49 ± 0.16 a	1.53 ± 0.28 a
Direct seeding: BMF + C	1.18 ± 0.23 a	2.13 ± 0.29 a	1.32 ± 0.21 a
Direct seeding: BMF + A + C	1.67 ± 0.19 a	2.01 ± 0.53 a	1.69 ± 0.38 a
Strip till: BMF	1.46 ± 0.33 a	3.18 ± 0.76 a	1.93 ± 0.62 a
Strip till: BMF + A	1.32 ± 0.27 a	3.14 ± 0.66 a	2.20 ± 0.52 a
Strip till: BMF + C	1.18 ± 0.15 a	2.68 ± 0.46 a	1.84 ± 0.94 a
Strip till: BMF + A + C	1.30 ± 0.28 a	3.02 ± 0.22 a	1.49 ± 0.04 a
Tillage: BMF	2.76 ± 0.37 a	2.12 ± 0.34 a	2.48 ± 0.81 a
Tillage: BMF + A	2.08 ± 0.13 a	1.63 ± 0.41 a	2.64 ± 0.74 a
Tillage: BMF + C	1.82 ± 0.59 a	2.42 ± 0.56 a	1.99 ± 0.22 a
Tillage: BMF + A + C	1.43 ± 0.43 a	2.74 ± 0.32 a	2.96 ± 0.79 a
Soil preparation	0.01 ***	0.37 ns	0.00 ***
Fertilizers regimes	0.61 ns	0.98 ns	0.72 ns
Soil preparation: Fertilizers regimes	0.07 ns	0.97 ns	0.86 ns

**, ***significant at 5 % (0.01 < P < 0.05), and 1 % (P < 0.01), respectively; ns, not significant at P ≤ 0.05. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N). A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

from moderately degraded soils (Table 1). Given the low average productivity across all treatments, such yield penalties were on average equivalent to roughly 100–400 kg less seed cotton yields per hectare. Yield differences varied between the experimental sites, and were widest at Okpara (Figure 2) and associated with differences in the number of roots and below-ground biomass. Although it was hypothesized that correcting soil fertility would reduce yield penalties associated with the transition to CA, virtually the opposite was observed. Adding compost and/or calcium phosphate to the basal fertilization regime increased the yield differences between tillage and no tillage, especially in sites where average yields were higher (up to 25% less yield under no tillage). The observed yield differences between sites can be partly explained by the different varieties used, according to local recommendations (varieties OKP 768 at Okpara and Savalou and ANG 956 at Soaodou were used), and by the environmental conditions during the experiment at the three sites.

Other studies reported short-term yield penalties in the transition to CA to be on either the neutral or negative trend (Vogel, 1993; Nyagumbo, 2002), have limited yield effects (Kitonyo et al., 2018; Rodenburg et al., 2020), or have substantial yield declines (Brouder and Gomez-Macpherson, 2014) under direct seeding (no tillage). The yield penalties can be explained by the immobilization of soil nutrients, poor germination, increased competition of weeds, stimulation of crop diseases, and poor drainage (Giller et al., 2011; Sommer et al., 2014; Bruelle et al., 2015, 2017). The negative effects of zero tillage have also been observed in soils, particularly poor in clays, which are widely distributed soils in semiarid environments with weak soil structure (Aina et al., 1991; Baudron et al., 2012; Corbeels et al., 2020). A global meta-analysis of the impact of the most prominent components of CA (no tillage and crop residue mulching) on yield was performed by Pittelkow et al. (2015), based on 5,463 paired yield observations, from 610 studies, across 48 crops and 63 countries. This analysis showed that no tillage reduces yields, yet this response is variable, and under certain conditions, no tillage can produce equivalent or greater yields than conventional tillage. When no tillage

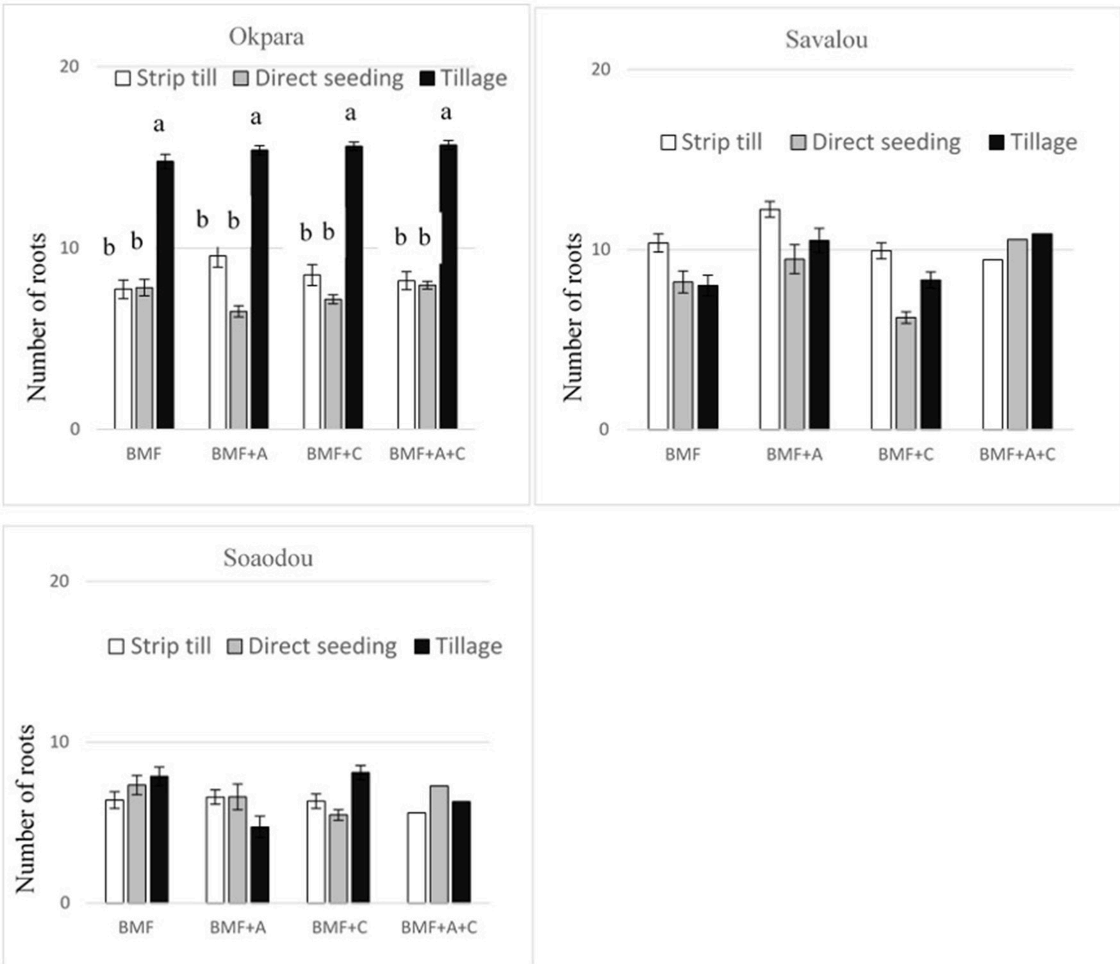

FIGURE 4
Number of roots at 40 days after emergence.

is combined with the other two principles of CA, namely, residue retention and crop rotation, its initial negative yield impacts are minimized (Corbeels et al., 2020). Büchi et al. (2018) reported similar results and highlighted the trade-offs between the preservation of agricultural soils, initially reduced yields, and weed management problems.

Beyond creating oxidative conditions in the soil that accelerates nutrient release and their assimilation by crops, tillage contributes to burying the weeds and incorporating in the soil organic matter lying on the surface, while making the soil loose, well-aerated, and easier for the roots to penetrate. In our experiment, tillage may have contributed to increasing deep water storage in the soil due to better infiltration of rainwater. The cotton plant has a dominant tap root system that requires loose soil to penetrate and meet its nutrient needs. These advantages, which may contribute to explaining the significant positive yield effect of tillage we observed during the first year, tend to disappear after years of practicing CA, as shown by different mid- to long-term studies (e.g., Lal, 1979; Mafongoya et al., 2016). Practicing minimum tillage instead of direct seeding resulted in higher average yields than with conventional tillage at Savalou and Soaodou, but not at Okpara, with positive yield differences ranging from extra 30 kg ha^{-1} to 70 kg ha^{-1} of seed cotton (i.e., 2–5% increase, Table 2). Minimum tillage, strip tillage in our case, appears as a reasonable compromise to minimize yield penalties in an early transition to CA.

Above- and below-ground biomass

Below- and above-ground biomass was significantly different across the three sites, mirroring the trends observed for seed cotton yields. Yet, soil preparation had stronger effects on seed cotton yields than on below- and above-ground cotton biomass production. Under direct seeding, below-ground cotton biomass was on average lower compared with that under conventional tillage, while above-ground biomass was

TABLE 5 Elbow frequency (%) on the taproot.

Factors/Levels	Soaodou	Okpara	Savalou
Soil preparation			
Direct seeding	33.11 ± 5.53 b	27.22 ± 6.84 b	7.22 ± 2.24 b
Strip till	35.33 ± 4.22 b	24.44 ± 5.59 b	8.33 ± 2.19 b
Tillage	43.03 ± 3.96 a	90.00 ± 3.33 a	15.56 ± 2.51 a
Fertilizers regimes			
BMF	36.38 ± 5.52 ab	56.30 ± 11.82 a	11.11 ± 3.69 a
BMF + A	37.78 ± 7.44 ab	45.93 ± 12.19 b	9.63 ± 2.75 a
BMF + C	32.22 ± 4.37 b	40.74 ± 13.26 c	8.89 ± 2.22 a
BMF + A + C	44.17 ± 4.53 a	45.93 ± 11.89 b	11.85 ± 3.10 a
Soil preparation: Fertilizers regimes			
Direct seeding: BMF	34.00 ± 15.56 abcd	51.11 ± 15.56 b	4.44 ± 2.22 c
Direct seeding: BMF + A	33.33 ± 17.78 abcd	24.44 ± 17.78 c	6.67 ± 3.85 bc
Direct seeding: BMF + C	21.11 ± 5.88 b	11.11 ± 5.88 d	6.67 ± 3.85 bc
Direct seeding: BMF + A + C	50.00 ± 2.22 ab	22.22 ± 2.22 cd	11.11 ± 8.01 abc
Strip till: BMF	30.00 ± 16.67 cd	28.89 ± 19.75 c	8.89 ± 5.88 abc
Strip till: BMF + A	23.33 ± 10.00 bcd	24.44 ± 4.44 c	6.67 ± 3.85 bc
Strip till: BMF + C	37.78 ± 2.22 abcd	20.00 ± 11.55 cd	6.67 ± 3.85 bc
Strip till: BMF + A + C	44.44 ± 5.88 abc	24.44 ± 11.11 c	11.11 ± 5.88 abc
Tillage: BMF	42.22 ± 5.88 abc	88.89 ± 11.11 a	20.00 ± 7.70 a
Tillage: BMF + A	56.67 ± 10.00 a	88.89 ± 8.01 a	15.56 ± 5.88 ab
Tillage: BMF + C	37.78 ± 5.88 abcd	91.11 ± 4.44 a	13.33 ± 3.85 abc
Tillage: BMF + A + C	40.00 ± 10.18 abc	91.11 ± 5.88 a	13.33 ± 3.85 abc
Soil preparation	0.00 ***	0.00 ***	0.00 ***
Fertilizers regimes	0.00 ***	0.00 ***	0.10 ns
Soil preparation: Fertilizers regimes	0.00 ***	0.00 ***	0.03 **

, * significant at 5 % (0.01 < P < 0.05), and 1 % (P < 0.01), respectively; ns, not significant at P ≤ 0.05. Values with the same letters in front of them are not are not significantly different. BMF, Basal mineral fertilizers 200 kg ha^{-1} of N14P18K18S6B1 + 50 kg ha^{-1} of urea (46%N. A: 200 kg ha^{-1} of calcium phosphate amendment (22P2O5-43CaO-4S). C: 400 kg ha^{-1} of compost.

significantly lower only at the Savalou site. Roger-Estrade et al. (2011) associated the lower biomass observed under direct seeding with less soil porosity, which affects the development of the crop root system. Less below-ground biomass under direct seeding has been also associated with difficulty in rooting due to compact soils under no tillage (Labreuche et al., 2011). In our study, however, the average differences in root biomass in favor of tillage are largely driven by the results of the BMF and BMF+A treatments in both Soaodou and Savalou; when averages are calculated per single treatment (soil preparation × fertilization regime), we observed no significant differences in root biomass between any of the soil preparation and fertilization regimes (Table 4). On the contrary, a positive effect of tillage on the number of roots was only observed at Okpara (Figure 4). Thus, the proposed association between greater root development under tillage than under no tillage suggested by previous studies is not confirmed by our observations.

Other studies reported a neutral or negative effect of direct seeding on above-ground crop biomass compared with that of conventional tillage. A comparative study of the impact of conventional tillage and direct seeding showed that the biomass yields of the different varieties of rice were almost similar to both soil preparation methods (Jiang et al., 2021). Rühlemann and Schmidtke (2015) reported that direct seeding reduced significantly biomass production. Pale et al. (2021) in Burkina Faso also showed that conventional tillage had a more positive impact on millet biomass compared with direct seeding. Büchi et al. (2018) and Adimassu et al. (2019) also reported the highest above-ground biomass with conventional tillage and the lowest in direct seeding (no tillage). Similarly, our results show significant trends of greater biomass production under conventional tillage only when comparing grand means, but less clearly so when comparing individual treatments (soil preparation × fertilization regime; Table 3).

Effect of fertilizers

Under basal mineral fertilization, yield differences between tillage and no tillage tended to be narrow (2% to 10%), whereas they increased, especially in treatments when compost was added (10–25%; Figure 2). Fertilizer regimes affected significantly the seed cotton yields at Soaodou and Savalou when considering average yields. The absence of response to fertilizers on the other sites and treatment combinations can be explained by the quantity of compost (400 kg ha^{-1}) or calcium phosphate amendment (200 kg ha^{-1}) added to the soils. These quantities may not have been sufficiently large to induce short-term increases in seed cotton yields. Some studies showed a significant impact on the yields with the increase in compost (Adugna, 2016). Optimal rates of application to induce changes in yields are in the order of 4 t ha^{-}to 5 t ha^{-1}, but these quantities are not achievable by farmers. Fertilizer regimes did not affect the below-ground biomass at any of the experimental sites or across treatments, but they affected elbow frequencies at Soaodou and Okpara, but not at Savalou. Further studies should explore the relationship among fertilizer regimes, organic matter amendments, and no tillage, especially as this experiment evolves and soils get progressively restored in the next few years and include assessments of carbon sequestration and soil biological activity. The effects of compost and calcium phosphate amendments should be better assessed through a long-term study.

Conclusion

It can be concluded, from the preliminary findings of this study, that direct seeding led to 2–25% lower cotton yields compared with conventional tillage (i.e., a −20 kg ha^{-1} to −500 kg ha^{-1} difference), depending on fertilizer treatment, at all three experimental sites undergoing an early transition to conservation agriculture starting from moderately degraded soils. Such yield differences were wider when compost was added together with mineral basal fertilizers (4–25%) and narrower when only mineral fertilizers were added (2–10%). Contrary to what was hypothesized, the treatments adding compost and calcium phosphate led to better responses under conventional tillage than under no tillage. The observed yield differences can be largely attributed to the poorer rooting (root number and below-ground biomass) associated with no tillage as compared to the other treatments, leading to lower above-ground biomass and seed cotton yields. Increasing fertilizer inputs did not contribute to overcoming such yield declines under CA, and generally, there were no significant differences in productivity, above- or below-ground biomass, and root number across fertilizer regimes at any experimental location. Yet, the effects of soil preparation methods and fertilizer regimes should be assessed over longer periods of time, especially when starting from degraded soils as in this case. Short-term impacts on yields, production costs, or labor use are, however, important because they determine the attractiveness of producers to conservation agriculture and thus its potential for adoption. The impact of soil preparation on seed cotton yields was the widest at Okpara compared to the other sites, where soils are sandier and yields under conventional or strip tillage were substantially greater than the local average. Further research is needed to better understand the causes of such yield penalties and how to avoid them. Yet, considering the need for sustainable practices, in the context of severely degraded soils and poor productivity, such limited yield penalties under CA appear to be a reasonable trade-off. We will continue analyzing the present experiment for the next 5 years to identify cropping systems that may provide both short-term gains and long-term sustainability. From the preliminary results analyzed in this study, it appears that strip cropping may be an alternative yet less effective option to curtail soil degradation, but without yield penalties, and hence perhaps a practicable first step in the transition toward full conservation agriculture.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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