



# Conservation agriculture can enhance maize productivity in high-rainfall regions: Nine-year evidence from Northern Zambia

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## ABSTRACT

Conservation Agriculture (CA) is often perceived to underperform in high-rainfall regions, leading to limited research and promotion in such environments. In Zambia, most CA studies have focused on Southern and Eastern regions, with little emphasis on Northern Zambia, despite its need for improved productivity and sustainability. Understanding CA's performance in high-rainfall areas is critical for sustainable agricultural intensification. This nine-year study in Northern Zambia evaluated the effects of cropping systems and rainfall variability on maize productivity, soil pH, and soil organic carbon (SOC) using a randomized complete block design. Three CA-based cropping systems were compared to two conventional tillage systems. Yearly precipitation showed significant interannual variability, influencing maize grain yield in a complex cubic response pattern, highlighting nonlinear interactions between cropping systems and rainfall. CA-based systems generally outperformed conventional tillage, particularly in moderate to below-average rainfall years, demonstrating resilience under drier conditions. However, conventional ridge and furrow tillage outperformed CA systems during exceptionally high rainfall years, likely due to better drainage. Over time, yield declines indicated soil fertility depletion, though CA-based systems slowed this decline compared to conventional tillage. Rainfall was identified as a primary driver of cropping system performance, with CA-based systems performing better in below-average to moderate rainfall years and tillage-based systems in excessive rainfall years. Soil pH increased significantly under basin planting at 5–15 cm and 30–60 cm depths, while SOC accumulation was highest at 60–90 cm under ridge and furrow tillage. These findings suggest that while CA can enhance maize productivity in high-rainfall regions, site-specific management strategies are needed to mitigate waterlogging and sustain soil fertility. Further research is needed to explore soil-water dynamics and optimize CA practices under varying rainfall regimes.

## 1. Introduction

Climate change is projected to increasingly affect smallholder farmers in southern Africa, exacerbating food insecurity and poverty [1, 2]. Models indicate more intense but erratic rainfall, rising temperatures, and unpredictable growing seasons, including delayed onset and early cessation of rains [3,4]. Some regions will also experience excessive rainfall and flooding, affecting sustainable agricultural production [5,6]. Addressing these threats is critical to ensuring food security in sub-Saharan Africa (IPCC5, 2014; [7]).

Zambia is characterized by three distinct agroecological regions: Region I, with 650–800 mm annual rainfall and predominantly sandy soils; Region II, receiving 800–1000 mm annually with sandy to loamy soils; and Region III, where rainfall exceeds 1000 mm and soils range

from loamy to clayey (Ngoma et al., 2017; Jain, 2007). The Northern Province, part of Natural Region III, experiences high rainfall, with an average of 1500 mm [8], but faces significant challenges in soil fertility management.

Historically, traditional farming systems in the Northern Province included shifting cultivation systems locally called *Chitemene* and *Fundikila* [9,10]. The Chitemene system, a slash-and-burn practice, involves cutting and burning trees to create nutrient-rich ash beds for crop cultivation with subsequent cultivation of pearl millet (*Pennisetum glaucum* (L.) R.Br.) and cassava (*Manihot esculenta* Crantz). While this system allowed for short-term soil fertility restoration, population pressure has significantly reduced fallow periods, making it unsustainable [11,12]. Similarly, the *Fundikila* system, which relies on decomposing grass mounds for nutrient release, has become less viable due to

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labour constraints and increasing weed infestations [13].

Currently, farmers in the Northern Province have adopted hoe tillage and ridge-and-furrow systems, which involve annual soil inversion and residue burning. While these methods can improve drainage under excessive rainfall, they contribute to soil erosion, compaction, and declining fertility over time [14,15]. Additionally, soils in Northern Province are highly acidic ( $\text{pH} < 4.5$ ), leading to phosphorus deficiency and aluminium toxicity, which limit maize productivity [16]. These constraints underscore the urgent need for sustainable soil management strategies tailored to this agricultural region.

Conservation Agriculture (CA) has emerged as a potential solution to enhance soil fertility, improve water-use efficiency, and stabilize crop yields in smallholder farming systems ([17]. CA is based on three main principles: (i) minimum soil disturbance, (ii) permanent soil cover, and (iii) crop diversification through rotations or intercropping [18] amongst other complementary good agriculture practices [19]. While CA has been widely promoted in Zambia's Southern and Eastern Provinces [20,21], its adoption in Northern Province remains limited due to concerns about waterlogging and its effectiveness in high-rainfall conditions [22]. However, studies suggest that CA can improve soil organic matter retention, enhance water infiltration, and reduce nutrient leaching, making it a viable alternative even in higher rainfall regions [23,24]. In other parts of the region, such as in Ethiopia, CA has been tried in high rainfall areas by adapting the CA practices, e.g., from basin planting to permanent ridges [25].

Despite the growing interest in CA in Africa, no comprehensive long-term studies have assessed its performance in high-rainfall environments such as the Northern Province of Zambia. This study aims to fill this knowledge gap by addressing the following research questions: (a) How does maize productivity respond to conventional tillage practices (e.g. conventional ploughing and ridge-and-furrow tillage) and Conservation Agriculture systems in a high-rainfall area? (b) Does rainfall variability in high-rainfall areas affect cropping system performance in maize productivity, and which systems are mostly affected?; and (c) How are different cropping systems influencing soil pH and SOC retention at various soil depths?

We hypothesized that: (a) CA-based systems (Conservation Agriculture) generally outperform conventional tillage practices in high-rainfall areas; (b) Rainfall variability has an influence on cropping system performance with CA-based systems outperforming conventional tillage practices in moderate to below-average rainfall years and vice versa; and (c) CA-based systems lead to increased soil pH and promotion of carbon storage more than conventional tillage practices, contributing to more aerable soils and long-term carbon sequestration. This study provides the first long-term evidence of the performance of CA-based cropping systems in terms of maize productivity in high-rainfall environments in the context of Northern Zambia and southern Africa at large.

## 2. Materials and methods

### 2.1. Study location

The study was conducted at Misamfu Research Station (MiRS), Kasama district, Northern Province of Zambia. The site is located at a latitude of  $-10.17$ , a longitude of  $31.22$ , and an altitude of  $1381$  m above sea level. The station is in a high rainfall area (Natural Region III) with a mean yearly rainfall of  $1353$  mm per annum during the experimental period. The study was established in the 2015/16 cropping year (hereafter referred to as 2016, which also applies to the other years) and it is still ongoing, but for the current study we presented data until the year 2024. Research was conducted for nine consecutive cropping years. The soils are classified as *Ultisols* [26], which are loamy sand with an organic carbon content of  $0.6\%$  and an average annual temperature of  $20.5^{\circ}\text{C}$ .

The traditional farming systems around Kasama are based on the *Chitemene* system [9,10], and cassava was traditionally the predominant

crop in the area, mostly on acidic soils [27]. Increasingly, maize (*Zea mays* L.) has become dominant in this area, supported by the Zambian Government subsidy program called "Farm Input Support Program (FISP)", which heavily promoted maize for food security in the country [28–30]. Other crops grown are beans (*Phaseolus vulgaris* L.) and other legumes. Crops are planted mostly in manual ridge and furrow systems where  $30\text{--}50$  cm tall ridges are created annually at a spacing of  $75\text{--}90$  cm, and crops are planted on top of them. The colonial government introduced this system to improve the drainage of excessive rainwater and to help control weeds (Thierfelder et al., 2013). This study used maize as the test crop and cowpea (*Vigna unguiculata* L. Walp) as an intercrop.

### 2.2. Weather parameters

Daily precipitation was measured using a raingauge installed next to the experimental trial in all years. The measurements were done once per day at 8 a.m. after every rainfall event. Precipitation variability across the years was expressed as a normalized anomaly ( $N_{anomaly}$ ) using the following formula:

$$N_{anomaly} = \frac{X_{year} - \bar{x}}{\sigma} \quad [1]$$

Where  $X_{year}$  is the yearly precipitation,  $\bar{x}$  is the average across the years of experimentation, and  $\sigma$  is the standard deviation of precipitation across the years.

Daily minimum and maximum temperatures were obtained from the NASA Power website (<https://power.larc.nasa.gov/data-access-viewer/>).

### 2.3. Experimental design

The long-term experiment was set as a randomized complete block design with four replications. Five cropping systems (treatments) were randomly assigned to plots within each block by generating random numbers within the desired range and then assigning those plot numbers to the block, ensuring that each cropping system appeared once per block. The randomization was stratified by block to control for field heterogeneity along the slope. Plot positions were determined using the randomization output and implemented accordingly in the field layout. The cropping systems tested were.

1. Conventional tillage with complete soil inversion (CP-MC) (Control 1): Crops were planted on the flat, and crop residues were removed. Maize was intercropped with cowpea.
2. Ridge-and-furrow tillage (RFT-MC) (Control 2): crops were planted in manually dug ridges with crop residue removal. Maize was intercropped with cowpea.
3. Basin planting (BP-MC): Crops were planted in manually dug basins prepared using a hand hoe. Crop residues were retained on the soil surface at a rate of  $2.5\text{--}3.0$  t ha $^{-1}$  and maize intercropped with cowpea.
4. Animal traction rip-line seeding (RI-MC): Crops were planted in rip lines prepared using an ox-drawn Magoye ripper, with  $2.5\text{--}3.0$  t ha $^{-1}$  crop residue retained on the soil surface and maize intercropped with cowpea
5. Dibble stick (DiS-MC): A dibble stick was used to open holes in which crop seed and fertilizer were placed. Crop residues were also retained on the soil surface at a rate of  $2.5\text{--}3.0$  t ha $^{-1}$ . Maize was intercropped with cowpea.

CA-based systems retained  $2.5\text{--}3.0$  t ha $^{-1}$  of maize residues in the first year, with all subsequent residues left in situ after harvest from then onwards. This study regarded the RFT-MC and CP-MC cropping systems as conventional tillage systems and compared them with three CA

cropping systems (BA-MC, RI-MC, and DiS-MC).

Basin planting involved hand seeding of maize in manually dug small planting basins. Basins were dug during the dry winter, usually in September/October of each year. The dimensions of the basins were 15 cm by 30 cm, with a depth of about 25 cm, following the recommendation of the Conservation Farming Unit [31]. The basins were made using a locally crafted hoe with a long handle (locally named Chaka hoe). A maize spacing of 90 cm between rows and 60 cm between plants was observed with the planting of 4 seeds per basin, which was later thinned to achieve a plant population of 44,444 plants ha<sup>-1</sup>.

The RI-MC system involved ripping and hand-seeding maize into furrows opened by a Magoye ripper, which operates at 15–20 cm soil depth and was done after the first effective rains with animal traction. Like the basin cropping system, surface crop residues were applied at a rate of 2.5–3 t ha<sup>-1</sup> and left in situ in subsequent harvests. Maize was planted at a spacing of 90 cm between rows and 25 cm between plants with two seeds planted per station and later thinned to one plant after crop emergence to achieve a target plant population of 44,444 plants ha<sup>-1</sup>.

The direct seeding cropping system (DiS-MC) was planted with a pointed stick, called a dibble stick, at a depth of approximately 10 cm into the soil for planting. Residues were retained as was done in the BA-MC and RI-MC systems. Maize was planted at a spacing of 90 cm by 25 cm with a target population of 44,444 plants ha<sup>-1</sup>.

In all cropping systems except BA-MC, cowpea was planted between maize rows as an intercrop 10–12 days after the emergence of maize at 25 cm between plants to achieve a population of 44,444 plants ha<sup>-1</sup>. In the BA-MC system, cowpea was seeded in basins that were 60 cm apart, with 4 plants per basin to achieve a population of 74,074 plants ha<sup>-1</sup>.

This study used the commercial, long-season hybrid maize variety SC 719 and the cowpea variety Lutembwe (runner type) as test crops throughout the trial period. The basal fertilizer used was Compound D (with the locally recommended blending of N: P: K; 10:20:10) applied at 200 kg ha<sup>-1</sup> in all cropping systems at seeding. Urea (46 % N) was used as a top dressing at a 200 kg ha<sup>-1</sup> split-applied rate at 4 and 7 weeks after planting. Therefore, the nutrient content applied was 112 kg N ha<sup>-1</sup>; 40 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>; 20 kg K<sub>2</sub>O ha<sup>-1</sup>. Liquid lime (98 % calcium carbonate) was applied at a rate of 10 l/ha on all the cropping systems before planting to raise the pH from 4 to an acceptable level of >5.5 to grow maize in the relatively weathered and acidic soils.

We used glyphosate [N-(phosphonomethyl) glycine with 41 % active ingredient] for initial weed control (in CA cropping systems). It was sprayed at a rate of 2.5 l ha<sup>-1</sup>, followed by shallow hand hoe weeding where necessary. The spraying was done before planting. The weed control was done using hand hoes only in the control cropping systems. Weeds were weeded out each time about 50 % of the plot had weeds that were 10 cm in height or circumference.

In some years, cowpea was highly infested by Anthracnose (*Colletotrichum* sp.), a fungal infection of the leaves, which was controlled using Propiconazole (1-[[2-(2, 4-dichlorophenyl)-4-propyl-1, 3-dioxolan-2-yl] methyl]-1, 2, 4-triazole; 14.3 % active ingredient). Similarly, bean leaf beetles (*Oothea mutabilis* Sahlberg) and aphids (*Aphis fabae* L.) attacked the cowpea, and Cypermethrin ([Cyano-(3-phenoxyphenyl) methyl] 3-(2,2-dichloroethenyl)-2, 2-dimethylcyclopropane-1-carboxylate; 25 % active ingredient) was sprayed to combat the attack.

#### 2.4. Crop yield parameters

At physiological maturity (approximately 160 days after planting), maize was harvested from a net plot of 18 m<sup>2</sup> (5 m × 3.6 m). Maize cobs were removed from the stalks, and a subsample of 10 cobs per plot was weighed to determine the fresh weight, air-dried, and then reweighed to determine the dry weight. Grain moisture content was determined at grain shelling, and yield was expressed at 12.5 % moisture content at a kg ha<sup>-1</sup> basis. Maize biomass was weighed in the field, and subsamples were taken, air-dried, and reweighed. Biomass was then expressed in kg

ha<sup>-1</sup>. Cowpea, although part of the cropping systems and planted as intercrops in all cropping systems, was harvested sequentially, thus pods were removed as they matured but the last harvest was usually about 130 days after planting them. However, no further data analysis was done on the yield as the main focus of this paper was on maize performance under high rainfall conditions.

#### 2.5. Soil sampling and chemical analyses

Soil samples were collected from each plot in the years 2020 and 23 from five depths, and these were 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, and 60–90 cm at the end of the growing season. These depths were selected to represent key functional zones in the soil profile. The upper layers (0–30 cm) correspond to the primary rooting zone and are the most sensitive to changes from management practices such as tillage, fertilization, and residue retention. Deeper layers (30–90 cm) were included to assess subsoil nutrient dynamics, potential leaching, and long-term storage of carbon and other elements. This stratification also allows for accurate estimation of depth-weighted nutrient and carbon stocks and aligns with widely used soil sampling protocols in agronomic and environmental research. For each depth, three sub-samples were collected from each plot and mixed to make one composite sample per depth per plot. Standard laboratory methods were employed to analyze the samples for various soil properties. However, the current study focuses solely on SOC and soil pH while the other elements will be reported in other upcoming works. These two elements were selected because the soils in the study region are generally acidic, making crop production difficult, and SOC is generally an important indicator of soil fertility, structure, and water retention, while also playing a key role in mitigating climate change by storing carbon in the soil. Soil pH was determined following the standard calcium chloride (CaCl<sub>2</sub>) method [32]. SOC was measured using the Walkley-Black method, which involves oxidizing a soil sample with potassium dichromate in concentrated sulfuric acid [33]. The amount of dichromate reduced in this reaction corresponds to the oxidizable organic carbon content, and the remaining unreacted dichromate is quantified through back-titration with ferrous sulfate, using diphenylamine as an indicator.

To estimate SOC stocks, soil bulk density measured in each plot for the 0–5 cm depth was used for the 0–5 cm depth, while for other depths, bulk density was obtained from the SoilGrids site (<https://www.soilgrids.org/>) Hengl et al. [34] since direct measurements were not conducted for each depth. SOC stocks (t ha<sup>-1</sup>) were calculated using the following equation [1] from Ellert and Bettany [35]:

$$\text{SOC}_{\text{stock}} = \text{conc} \times \rho_b \times T \times 10,000 \text{ m}^2 \text{ ha}^{-1} \times 0.001 \text{ Mg kg}^{-1} \quad [2]$$

where SOC<sub>stock</sub> represents the SOC mass per unit area (Mg ha<sup>-1</sup>), conc is the SOC concentration (g kg<sup>-1</sup>),  $\rho_b$  is the field bulk density (kg dm<sup>-3</sup>), and T is the soil layer thickness (m).

### 3. Calculations and statistical analysis

#### 3.1. Crop productivity and yield variability

Grain yield and biomass data were checked for outliers using R statistical environment [36], revealing a few extreme values that were evaluated but retained due to their plausible origin from natural variability. Data normality and homoscedasticity were assessed graphically. Mixed-effects models were employed to evaluate the effects of the cropping systems and years on maize grain yield and biomass yield with cropping system and year as fixed effects and blocks within a year and plots within a block as random effects to account for the grouping factors and repeated measures taken across years. Model selection was based on the Akaike Information Criterion [37–39]. Variance explained by fixed and random effects was assessed using marginal (explained by fixed effects without random effects) and conditional (explained by both fixed

and random effects)  $R^2$  values, i.e.,  $mR^2$  and  $cR^2$ , respectively, using the 'MuMIn' package [40]. Significance of fixed effects was tested using  $F$ -tests and where applicable mean comparisons were conducted using adjustment multiple comparisons [41] in 'emmeans' package [42].

A Pearson correlation revealed a strong relationship ( $r = 0.78$ ) between maize grain yield and biomass (Fig. S1), justifying the focus on maize grain yield in further analyses.

Maize grain yield response to the different cropping systems across years was evaluated using 1:1 plots, comparing each cropping system in each replicate to the corresponding controls. Since we had two control cropping systems of interest, we compared CP-MC yield to other CA-based systems, excluding RFT-MC. Next, we compared the RFT-MC control to the remaining cropping systems, excluding CP-MC. Finally, we directly compared the two controls to assess their performance relative to each other. To better understand the responses across the years, we determined the yield advantage of the CA-based cropping systems over the two control cropping systems and the two controls against each other using the mean difference in each replicate in each year using equations (3) and (4):

$$\text{Mean difference (MD)} = \text{Mean}_{CA} - \text{Mean}_{control} \quad [3]$$

$$\text{Mean difference (MD)} = \text{Mean}_{RFT-MC} - \text{Mean}_{CP-MC} \quad [4]$$

Where  $\text{Mean}_{CA}$  is the mean yield of the CA-based cropping systems (BA-MC, DiS-MC, and RI-MC) in each year,  $\text{Mean}_{control}$  is the mean yield of either control 1 (CP-MC) or control 2 (RFT-MC) in each year,  $\text{Mean}_{RFT-MC}$  is the mean yield of control 2 (RFT-MC) in each year, and  $\text{Mean}_{CP-MC}$  is the mean yield of control 1 (CP-MC) each year. Researchers have used this metric previously due to its straightforward interpretation and relevance in comparing potential yield benefits [17]. The yield differences between the cropping systems were exposed to mixed modelling to analyze the effects of the cropping system and year. In the models for the first assessment (Eq. (3)), the cropping system and year were considered fixed effects, while replicates nested into years or plots nested into replicates were considered random effects to account for differences among the replicates across years. For the second assessment (Eq. (4)), only year was used as a fixed effect, while plots nested in replicates were considered random factors to account for plot differences across replicates.

### 3.2. Grain yield response to rainfall and fertility trends

Although some earlier works have established different relationship models for maize grain yield and rainfall, we determined the most appropriate model by comparing linear, quadratic, cubic, and exponential models using the AIC. In this test, the exponential model was fitted using the 'nls2' package (Grothendieck and R Core Team, 2024). The cubic response provided the best fit and was used for subsequent predictions.

To examine long-term fertility trends independent of rainfall, grain yield data were detrended by fitting a linear model against rainfall and analyzing the residuals over time. A simple regression with cropping system as a fixed effect and time as a covariate was used, with random effects included to account for repeated measures within plots. While this approach identifies general fertility trends, it does not isolate the specific drivers behind them, which may also include climate or management variability [43–45].

### 3.3. Relationship between cropping systems and years

Principal Component Analysis (PCA) was used to explore the relationship between cropping systems and years based on maize grain yield using by a singular value decomposition of centered and scaled data matrix using the *prcomp()* function of the 'stats' package in R. Data was scaled to unit variance. At the same time, centering was done to remove

the main effects before calculating the principal components of each cropping system. The results were projected on a PCA biplot using the *biplot()* function, and ellipses that show 95 % confidence were added using the 'ellipse' package [46]. Environmental factors such as total rainfall and average temperature were fitted to the ordination space to aid interpretation of the observed patterns using the *envfit()* function of the 'vegan' package [47].

### 3.4. Soil chemical responses

First, to assess the response of pH to different cropping systems, we analysed the data for each soil depth for the years 2020 and 2023 separately using linear mixed models in R. In these models, the cropping system was considered a fixed effect, while blocks were considered as the random effect to account for the grouping factors.

Second, to assess the effects of cropping systems on SOC and pH at different depths, temporal changes were determined for each cropping system using equation (5) below:

$$\Delta x_k = x_{s1} - x_{s0} \quad [5]$$

Where  $\Delta x_k$  is the temporal change in SOC ( $\text{t ha}^{-1}$ ) or pH for each  $k$ th 'cropping system  $\times$  soil depth' combination,  $x_{s1}$  is the value of the respective element at the second sampling (endline), and  $x_{s0}$  is the value of the respective element at the first sampling (baseline).

The effect of cropping systems on the temporal change values was assessed for each sampling depth using linear mixed models in R. In these models, the cropping system was considered a fixed effect, while blocks were considered as a random effect to account for the grouping factors. In both the first and second analyses, the significance of the fixed effects assessment and mean comparison, where significant differences were detected, were made using the same methods described above. We used this approach because we were interested in considering relative differences between cropping systems at each depth by evaluating how different cropping systems influence SOC retention and pH regulation, identifying depth ranges contributing more to total SOC stocks and optimum soil pH.

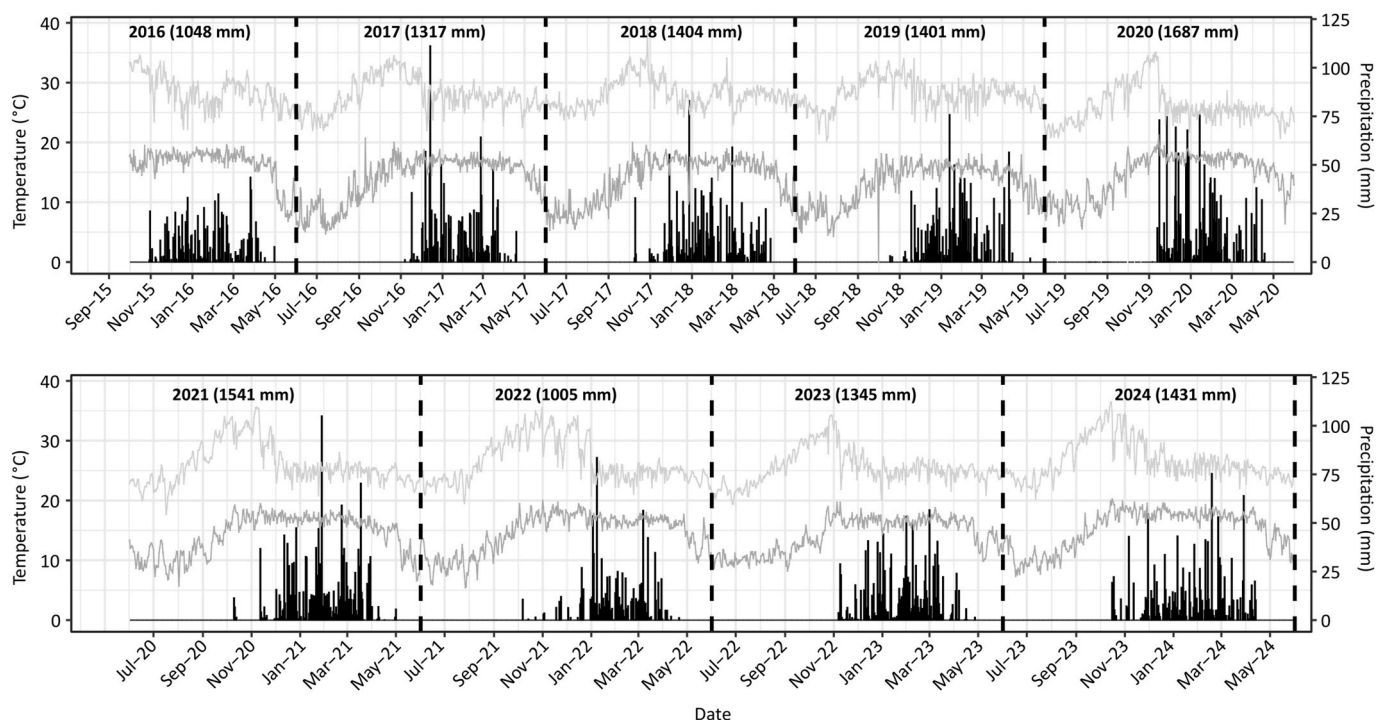
## 4. Results

### 4.1. Weather data

Yearly precipitation was highly variable across the study years and in distribution within the years (Fig. 1). Annual precipitation ranged from 1005 mm in the rainy year of 2022 to 1687 mm in the 2020 rainy year, giving a coefficient of variation (CV) = 16 %. The year 2020 was characterized by consecutive days of more than 60 mm rainfall, which contributed to the high total rainfall. A variability of up to 154 % relative to the experimental period mean was observed in 2020, marking the start of a rare "triple-dip" La Niña weather phenomenon, which stretched to 2023 (Fig. S2). Maximum temperatures reached 39 °C in 2018 and went lower than 5 °C in years such as 2019 (Fig. 1).

### 4.2. Cropping system and rainfall variability effect on maize productivity

The cropping system and year explained most of the variation observed in the maize grain yield and biomass, accounting for 76 % and 65 % of the variance, respectively (Table 1). The interactive effect of the cropping system and year had a significant effect on maize grain yield and biomass ( $p < 0.001$ ) (Table 1). There were clear differences in the performance of the cropping systems across the years in terms of maize grain yield and biomass, with the cropping systems in 2016 performing the best, coinciding with a low rainfall year, while the cropping systems in 2020 performed the least for grain yield (Fig. 2a) coinciding with highest rainfall year. As for maize biomass, the cropping systems in 2020 also performed the least, whilst the highest performances were observed



**Fig. 1.** Daily minimum temperature (light grey line), maximum temperature (dark grey line) and precipitation (vertical black bars) received at the Misamfu Research Station from 2016 to 2024. Daily temperature was presented for the whole year as obtained from the NASA Power site (<https://power.larc.nasa.gov/data-access-viewer/>), while precipitation was only presented from the 1st of October to the 31st of May in each year. The total precipitation for each season is shown in parentheses after the year name label in the plot. The dotted vertical lines demarcate the growing seasons within each year. The coefficient of variation (CV) for the seasonal precipitation = 16 %.

**Table 1**

Significance of fixed effects on grain yield and aboveground biomass yield of maize and total cropping system productivity.

Attribute	Pseudo-R-squared <sup>a</sup>	Source	Degree of freedom	Chi-square	P-value <sup>b</sup>
Grain yield	mR <sup>2</sup> = 0.76; cR <sup>2</sup> = 0.84	System	4	8.0742	0.0889.
		Year	8	305.4667	<2e-16***
		System × Year	32	165.6155	<2e-16***
Biomass	mR <sup>2</sup> = 0.65; cR <sup>2</sup> = 0.72	System	4	3.4332	0.4881
		Year	8	297.8729	<2e-16***
		System × Year	32	91.0982	1.40e-07***

<sup>a</sup> For the pseudo-R-squared, mR<sup>2</sup> represents the marginal R<sup>2</sup>, which is variance explained by the fixed term (cropping system) only, while cR<sup>2</sup> represents the conditional R<sup>2</sup>, which is variance explained by the fixed and the random terms (blocks in years and plots in blocks). The residual variance (not explained by any of the terms) is obtained by subtracting the cR<sup>2</sup> from one;

<sup>b</sup> Asterisks and dots in front of numbers signify the significance level where: 0 \*\*\*\*, 0.001 \*\*\*, and 0.05\*\*.

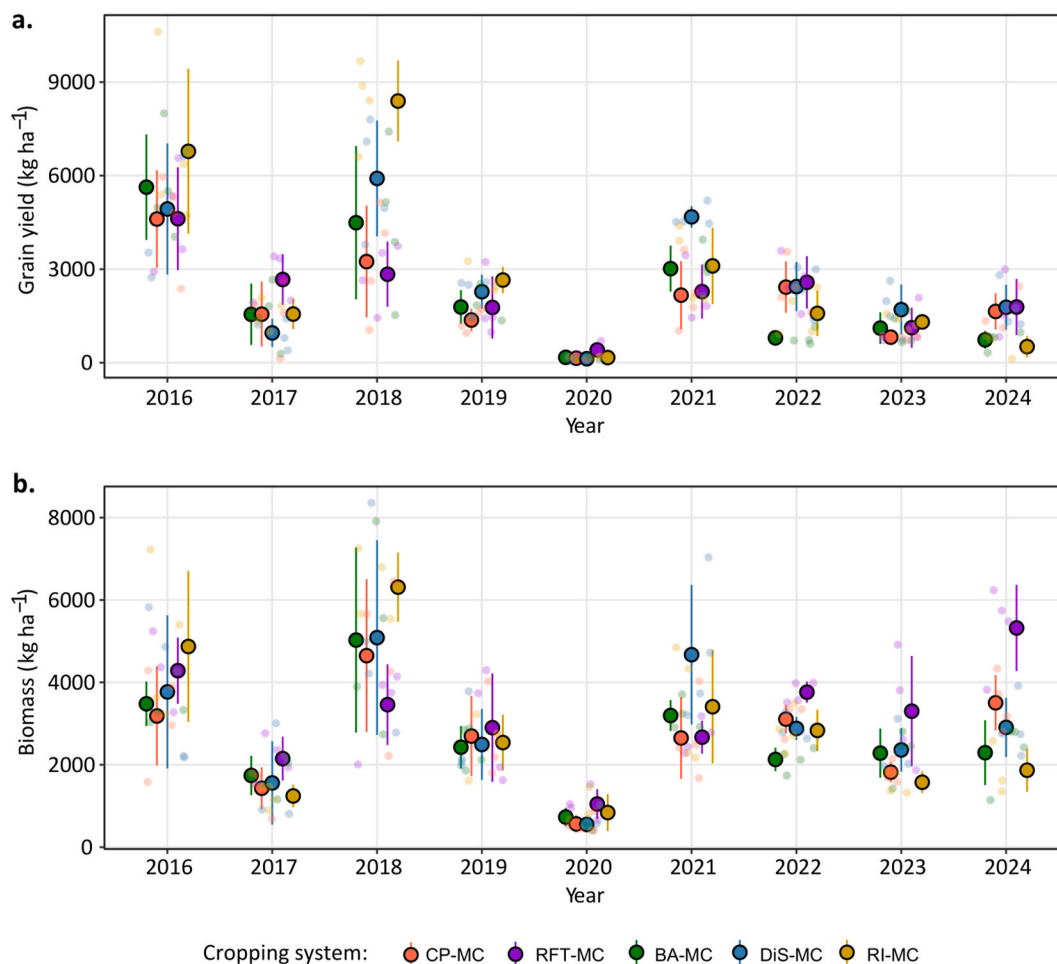
in 2018 (Fig. 2b). In essence, the ripline seeding system (RI-MC) showed highest grain yield and biomass observed in the 2018 year but also showed the least yields in years such as 2024.

Yearly rainfall significantly affected maize grain yield and showed a cubic grain yield response in the overall assessment (Fig. S3). The cubic response showed that yield did not clearly increase or decrease with increasing rainfall. The response showed multiple inflection points, meaning that there was a more complex and nonlinear yield response to rainfall. For example, yield decreased sharply during the first segment as rainfall increased, continued to decrease steadily after the first inflection point, and started to increase again before decreasing again. This

response suggested different responses from the systems that were involved.

Also evident are the differences in fertility trends of the different cropping systems over the years after accounting for the effect of rainfall (Fig. 3). In this assessment, most cropping systems showed a downward trend, meaning fertility (in the broad sense) was likely declining over time. The RI-MC and the CP-MC systems consistently trended downwards, although the slope was steeper for RI-MC, suggesting soil fertility or other yield-determining factors were deteriorating faster in these cropping systems, while the other cropping systems showed a gradual curvilinear fertility trend. The RI-MC system had the highest yield residuals in the early years but declined over time. In contrast, BA-MC, DS-MC, and RFT-MC had lower residuals but remained relatively stable. The BA-MC system showed an increase in fertility until plateauing occurred during the 2020 year and started to decrease, while the DS-MC and RFT-MC systems showed an inverse response. The confidence intervals showed some cropping systems, such as RI-MC, to have wider confidence bands, indicating more variability in yield responses to yearly rainfall.

To understand the response of the CA-based systems compared to the two controls (CP-MC and RFT-MC) and between the two controls within and across the years, we used the 1:1 plots and differences between the cropping system means. Maize yield response was variable when both control systems, CP-MC and RFT-MC, were compared with the CA-based cropping systems (Fig. 4a and c). There were years in which these control systems outyielded the CA-based systems. Still, these years were fewer than those in which CA-based systems were outyielding (Fig. 4a and c). In some years, the CA-based systems attained double the yield of the controls, reflecting an even higher performance. In 45 % of the years and depending on the rainfall year, such as in 2017 and 2022, the yields showed significantly negative responses from the CA-based systems, while in others, such as 2018, yield had highly positive responses (+5000 kg ha<sup>-1</sup>) when compared to the controls, highlighting the



**Fig. 2.** The interactive effects of cropping system and year on maize (a) grain yield and (b) biomass at Misamfu Research Station from 2016 to 2024. The dots represent the mean, and the whiskers represent the standard deviation. The jittered points represent the individual observations for each cropping system in each year. Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop.

variability in response (Table 2, Fig. 4b and d). A comparison between the controls also showed variability in response, with the RFT-MC system outyielding the CP-MC system in most of the years and exhibiting double the yields in others (Fig. 4e). Although insignificant, RFT-MC showed higher potential across most of the years when the differences in performance were considered (Table 2, Fig. 4f).

#### 4.3. Temporal yield dynamics of cropping systems

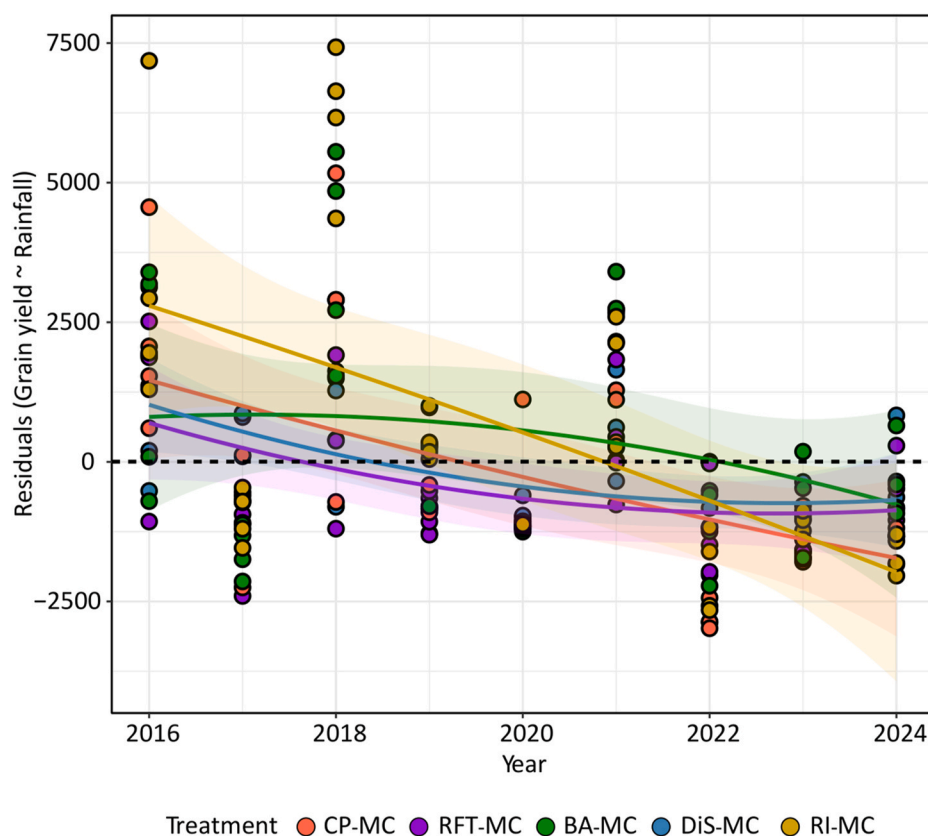
In addition to evaluating crop productivity, it is crucial to investigate the interactions between different cropping systems and temporal variability. We employed Principal Component Analysis (PCA) and corresponding biplots to elucidate these relationships, as presented in Fig. 5. The first principal component (PC1) accounted for 30 % of the total variation, while the second principal component (PC2) explained 26 %, cumulatively capturing a substantial proportion of the observed variability.

The ordination revealed distinct clustering patterns for years and cropping systems, indicating significant temporal and management-related effects. The grouping of years was primarily influenced by rainfall patterns, with years experiencing moderate to below-average rainfall (relative to the long-term average) positioned on one side of the biplot and years with moderate to above-average rainfall on the opposite side. This suggests that rainfall variability was a key driver of temporal differentiation.

The CP-MC cropping system was distinctly isolated within the ordination space, reflecting weak associations with most of the study years, indicating general poor performance across temporal conditions (Fig. 5). In contrast, the RI-MC, BA-MC, and DiS-MC systems showed strong positive associations with years of moderate to below-average rainfall, particularly in 2016, 2018, and 2022, suggesting that these systems responded favourably under such conditions. Interestingly, these conservation agriculture (CA)-based systems clustered closely, implying similar temporal interaction patterns and responses to environmental variables.

Furthermore, the RFT-MC system demonstrated positive associations with years marked by moderate to above-average rainfall. We observed a notable negative interaction between this management system and the CA-based systems, indicating contrasting performance trends across different years, likely driven by divergent sensitivities to climatic factors.

The biplot further highlights the critical influence of total yearly rainfall and temperature as key determinants of yield variability across years. However, rainfall was more important, as indicated by the length of its vector arrow on the ordination space. These findings underscore the complex interplay between cropping system management, climatic variability, and crop productivity.



**Fig. 3.** Fertility trends for different cropping systems at Misamfu Research Station from 2016 to 2024. The fertility trends were modelled using the residuals of grain yield after accounting for the effects of rainfall. Symbols represent the mean residuals of the observed data, the ribbons (uncertainty bounds) are 95 % confidence intervals for those means, and the lines depict the fitted trends. The dashed horizontal line indicates the point where there is no fertility effect. Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop.

#### 4.4. Temporal change of cropping system soil chemical parameters

For cropping system effect on soil pH at different depths, significant differences were only noted in 2020 in the 15–30 cm and the 30–60 cm depths (Table 3). In both depths, the BA-MC system had the highest pH of 3.8 and 4.4, respectively.

For the temporal change assessment, changes in soil pH showed significant differences in pH change between the two sampling times across cropping systems only at the 5–15 cm and 30–60 cm depths, while only marginal differences were observed in the 0–5 cm (Fig. 6a). At 5–15 cm depth, the BA-MC system resulted in the highest increase in pH, whereas both the controls and the DS-MC system had the lowest increase. Similarly, the BA-MC system also had the highest increase in pH at 30–60 cm depth compared to the other systems.

Changes in SOC differed significantly among the cropping systems only at the deepest soil layer, 60–90 cm, where the RFT-MC system resulted in the highest increase compared to the other systems.

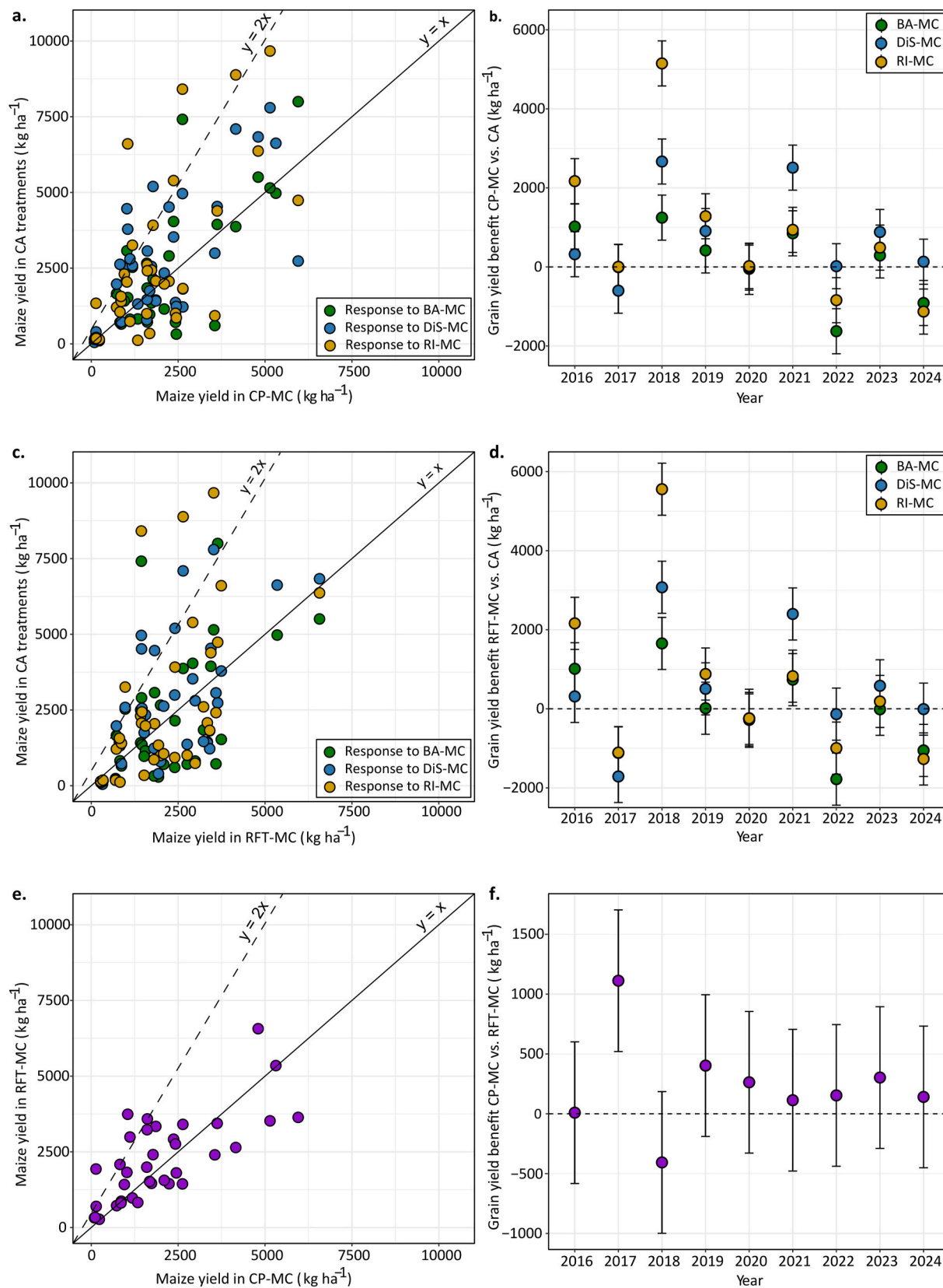
## 5. Discussion

The promotion of CA has been widespread as a resilient cropping system, promising to enhance yields while preserving the environment. However, prior research indicates that CA may face challenges in high-rainfall conditions, particularly in poorly drained soils, due to waterlogging issues [22]. Nonetheless, the increasing encroachment of maize-based systems in Northern Zambia and the necessity to boost yields and protect soil and natural resources, emphasize the need for alternative crop management strategies like CA. This prompted the testing of different CA systems under the high rainfall conditions to

assess which systems could be adapted to the high rainfall conditions.

#### 5.1. Crop productivity, yield variability, and influencing factors over time

This work was carried out over nine years, and in general, the CA-based systems, such as RI-MC, BA-MC, and DS-MC, showed higher yields than the conventional tillage-based systems. The potential of CA to enhance in high-rainfall areas depends on many factors, such as soil type, crop selection, and management practices [22]. The principles of CA (minimum soil disturbance, permanent soil cover, and crop diversification) can improve soil structure, enhance water infiltration, and reduce erosion, which are critical in high-rainfall environments [48–50]. Even though challenges such as waterlogging and nutrient leaching were expected in the CA systems, improved soil structure, adequate drainage, and fertility strategies may have offset their negative effects, especially when rainfall was moderate or slightly above average [51]. Conservation Agriculture enhances water infiltration and drainage primarily through biological processes: minimal soil disturbance preserves soil structure, while permanent organic cover and active soil biota (e.g., roots, earthworms) create stable pores and improve aggregation [52,53]. These biological improvements lead to better infiltration and reduced surface runoff [54]. In contrast, traditional ridge tillage relies on physical manipulation of the soil (raised ridges and furrows) to direct water flow. However, repeated tillage disrupts soil structure and biopores, often leading to compaction, surface crusting, and reduced infiltration over time [55,56]. The retention of maize and cowpea residues in the CA practices has been found to contribute to the improvement of soil fertility as these crop residues decompose quickly under the conditions with a potential increase in soil nutrients at near surface level [57,58].



**Fig. 4.** Maize yield response to tested cropping systems (a, c, e) and maize grain yield benefit of conservation agriculture-based systems relative to the two control treatments in different years from 2016 to 2024 (b & d) and maize grain yield benefit of the RFT-MC control relative to the CP-MC control treatment (f). The error bars represent standard error of mean. Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop.

**Table 2**

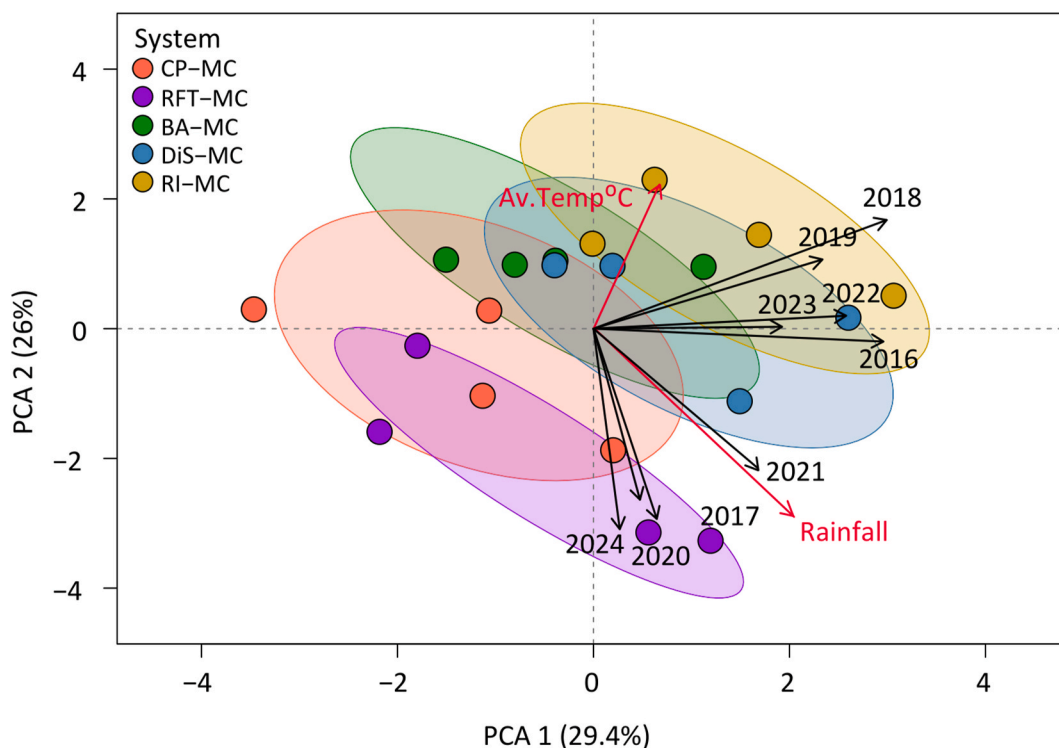
Significance of fixed effects on mean grain yield difference between control treatments and conservation agriculture-based treatments across the years at Misamfu Research Station for the seasons 2016 to 2024.

Attribute <sup>a</sup>	Pseudo-R-squared <sup>b</sup>	Source	Degree of freedom	Chi-square	P-value <sup>c</sup>
CP-MC vs. CA-based treatments	mR <sup>2</sup> = 0.586; cR <sup>2</sup> = 0.666	System	2	3.7058	0.1567787
		Year	8	131.7592	<2.2e-16***
		System × Year	16	43.2465	0.0002565***
RFT-MC vs. CA-based treatments	mR <sup>2</sup> = 0.589; cR <sup>2</sup> = 0.775	System	2	12.493	0.001937**
		Year	8	62.666	1.39e-10***
		System × Year	16	47.993	4.76e-05***
CP-MC vs. RFT-MC	mR <sup>2</sup> = 0.095; cR <sup>2</sup> = 0.1823	Year	8	4.0852	0.8494

<sup>a</sup> Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop.

<sup>b</sup> For the pseudo-R-squared, mR<sup>2</sup> represents the marginal R<sup>2</sup>, which is variance explained by the fixed term (cropping system) only, while cR<sup>2</sup> represents the conditional R<sup>2</sup>, which is variance explained by the fixed and the random terms (blocks in years and plots in blocks). The residual variance (not explained by any of the terms) is obtained by subtracting the cR<sup>2</sup> from one;

<sup>c</sup> Asterisks and dots in front of numbers signify the significance level where: 0 ‘\*\*\*’, 0.001 ‘\*\*’, and 0.05 ‘\*’.



**Fig. 5.** Principal Component Analysis (PCA) biplot of maize grain showing the relationship between cropping systems and seasons at Misamfu Research Station with four field replicates for each cropping system and nine cropping seasons. Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop. The environmental variables rainfall and average temperature (°C) (Av.Temp°C) were projected on the ordination space *a posteriori*.

This is likely to contribute to the improvement of soil fertility and higher crop yields in the long term [59].

The general downward fertility trends observed in most of the cropping systems suggest soil fertility depletion, possibly due to nutrient mining, declining soil organic matter, and acidification (decline in pH leading to phosphorus deficiency and/or an increase in exchangeable Al) [44,60]. Soil organic matter plays a crucial role in maintaining soil fertility by providing essential nutrients to plants and supporting healthy soil microbial activity. In contrast, soil pH directly impacts the availability of nutrients to plants, significantly influencing their growth and overall health by determining which nutrients are soluble in the soil and can be absorbed by the roots [61,62]. Conservation agriculture-based systems (e.g., DS-MC and BA-MC) provided some buffering against fertility decline, reversed fertility loss, and sustained

productivity through several mechanisms. By promoting beneficial microbial communities and enhancing microbial activity, these systems improve nutrient cycling and availability and enhance nutrient mobilization, particularly phosphorus uptake, thus mitigating fertility loss and sustaining productivity [63]. The mulch layer and minimal soil disturbance reduce runoff and leaching, preserving essential nutrients like nitrogen and potassium while maintaining soil moisture during dry spells [48,64]. Improved soil structure and reduced compaction under CA facilitate deeper root penetration, enhancing access to subsoil nutrients [65]. Additionally, crop residue retention ensures a steady supply of organic inputs [66,67]. Moreover, CA practices increase soil resilience against climate variability by improving water infiltration and retention, reducing the risks associated with erratic rainfall and dry spells [49]. By integrating minimum soil disturbance, residue retention, and diverse

**Table 3**  
Soil pH at different depths under contrasting cropping systems in the years 2020 and 2023.

Sampling year	Treatment <sup>a</sup>	Soil depth level				
		0–5 cm	5–15 cm	15–30 cm	30–60 cm	60–90 cm
2020 (Baseline)	CP-MC	3.03a	3.34a	3.48 ab	3.29b	3.46a
	RFT-MC	3.35a	3.72a	3.31b	3.33b	3.27a
	BA-MC	3.24a	3.62a	3.75a	4.39a	3.44a
	DS-MC	3.74a	3.34a	3.29b	3.37b	3.39a
	RI-MC	3.51a	3.85a	3.21b	3.6b	3.5a
	SEM	0.249	0.196	0.142	0.228	0.117
	<i>P</i> -value <sup>b</sup>	0.2621 <sup>ns</sup>	0.1356 <sup>ns</sup>	0.049*	0.001**	0.6796 <sup>ns</sup>
	mR <sup>2</sup>	0.1989	0.2229	0.3324	0.4632	0.1082
	cR <sup>2</sup>	0.2809	0.3955	0.3386	0.5114	0.1082
	2023 (Endline)	CP-MC	3.52a	3.23a	3.35a	3.62 ab
RFT-MC		3.5a	3.5a	3.42a	3.73 ab	3.7a
BA-MC		3.7a	3.48a	3.5a	3.67 ab	3.58a
DS-MC		3.48a	3.33a	3.5a	3.6b	3.73a
RI-MC		3.42a	3.23a	3.38a	3.75a	3.65a
SEM		0.0118a	0.0922	0.0801	0.047	0.0698
<i>P</i> -value <sup>b</sup>		0.5386 <sup>ns</sup>	0.0833 <sup>ns</sup>	0.5578 <sup>ns</sup>	0.0518 <sup>ns</sup>	0.5037 <sup>ns</sup>
mR <sup>2</sup>		0.1408	0.3023	0.11363	0.2792	0.1493
cR <sup>2</sup>		0.1408	0.3023	0.1363	0.4356	0.1493

<sup>a</sup> Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop. For the pseudo-R-squared, mR<sup>2</sup> represents the marginal R<sup>2</sup>, which is variance explained by the fixed term (cropping system) only, while cR<sup>2</sup> represents the conditional R<sup>2</sup>, which is variance explained by the fixed and the random terms (blocks). The residual variance (not explained by any of the terms) is obtained by subtracting the cR<sup>2</sup> from one;

<sup>b</sup> Asterisks and dots in front of numbers signify the significance level where: 0 ‘\*\*\*’, 0.001 ‘\*\*\*’, and 0.05 ‘\*’, while ns means not significant.

cropping systems, CA-based approaches such as DS-MC and BA-MC create sustainable, productive farming systems that counteract soil fertility decline while enhancing long-term crop productivity. Notably, the control cropping system (RFT-MC) exhibited lower yield residuals and demonstrated potential for mitigating fertility decline, displaying a trend comparable to that of the DS-MC system. Although this system likely disrupted soil structure, the use of raised ridges for planting improved soil drainage and mitigated waterlogging effects, resulting in more uniform yields even under high rainfall conditions [68].

Although CA-based systems generally outperformed other cropping systems, their yields were surpassed by the RFT-MC system in years with exceptionally high rainfall. While CA systems are widely recognized for enhancing soil health, moisture retention, and crop productivity, their performance can decline under exceptionally high rainfall conditions and medium-textured soils [69,70]. Excessive soil moisture can lead to waterlogging, limiting oxygen availability for roots and disrupting microbial processes vital for nutrient cycling [71]. Furthermore, reduced soil disturbance and permanent ground cover characteristic of CA may increase infiltration in poorly drained soils, but poor drainage into deeper layers could exacerbate moisture accumulation [69]. In contrast, conventional tillage systems based on ridging or other drainage-enhancing techniques can temporarily mitigate waterlogging effects to a certain extent by having crops planted on the raised ridges. However, conventional tillage systems that involve planting crops on the flat, such as CP-MC, are prone to soil erosion and waterlogging, especially due to poor infiltration caused by poor soil structure leading to nutrient losses and poor yields [64,72]. Thus, yield variability in this high rainfall area was likely caused by the above listed factors such as waterlogging, nutrient leaching, erosion, delayed field operations, and increased pest and disease pressure and their interaction with cropping system management. These factors, combined with potential lodging and lower sunlight due to persistent cloud cover, contribute significantly to yield variability [73].

New research in Northern Zambia is currently exploring permanent ridges and permanent raised beds as an alternative to the annual ridges in RFT-MC which would reduce soil disturbance while benefiting from a more stable cropping system under rainfall variability.

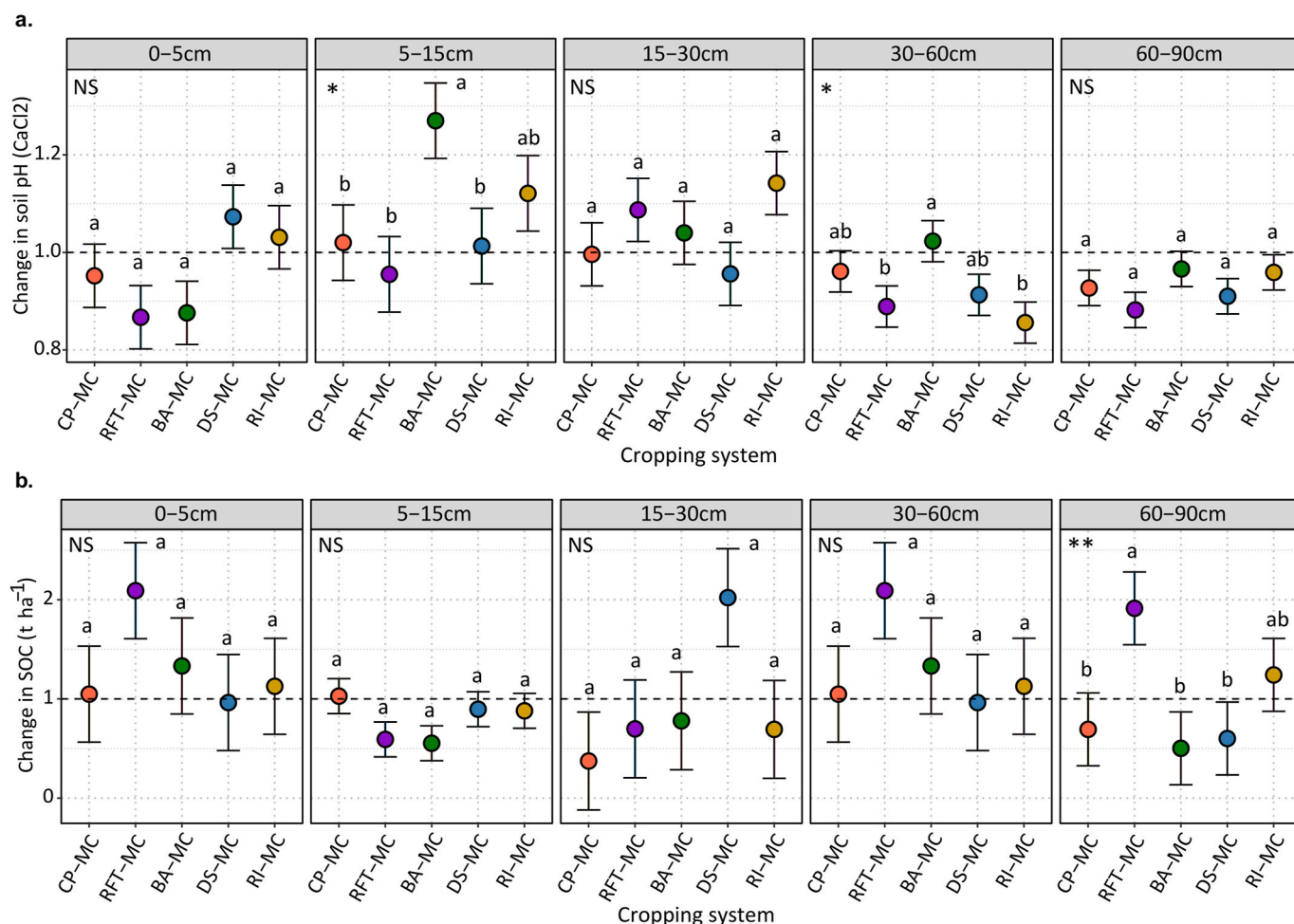
Therefore, we can accept the hypotheses that CA-based systems generally outperform conventional tillage practices in high rainfall areas

in the long term and that rainfall variability influences cropping system performance, with CA-based systems outperforming conventional tillage-based systems mainly in years with moderate to below-average rainfall and vice versa.

## 5.2. Temporal change of cropping system soil chemical parameters

Results indicated that for all the cropping systems, the highest increase in soil pH was recorded for the BA-MC system at the top and middle soil depth layers. CA practices can increase soil pH over time, particularly in acid soils [74,75]. This is important in Northern Zambia where soils are generally acidic and not conducive for maize production. Soil pH is an important indicator of soil health and hence should be managed to enhance crop growth. For example, soil pH strongly influences phosphorus (P) availability by affecting its solubility. In acidic soils (pH < 5.5), P binds with aluminium and iron, while in alkaline soils (pH > 7.5), it forms insoluble compounds with calcium, both reducing plant uptake. The optimal pH range for P availability is 6.0–7.0, where it remains in soluble forms like H<sub>2</sub>PO<sub>4</sub><sup>-</sup> and HPO<sub>4</sub><sup>2-</sup> [76,77]. Cropping systems that improve pH can thus significantly enhance P availability and crop productivity (Brady & Weil, 2016; Havlin et al., 2014; Fageria et al., 2010). The minimal soil disturbance associated with CA reduces soil acidification processes common in conventional tillage systems, such as increased oxidation of organic matter and leaching of basic cations [78]. Additionally, CA promotes organic matter accumulation and microbial activity, enhancing nutrient cycling and buffering soil acidity [78]. Retaining crop residues also facilitates a gradual release of nutrients, including calcium and magnesium, which help to neutralize soil acidity [79].

SOC only differed among the cropping systems in the 60–90 cm soil layer, with the RFT-MC system having the highest increase between sampling periods. This is possible because tillage physically mixes organic matter into the soil profile, facilitating the movement of carbon to greater depths [80]. This mechanical incorporation facilitates the downward movement of organic substrates, allowing microbial communities in subsoil layers to access and process this carbon [81]. As a result, some of the SOC becomes stabilized in the deeper horizons, particularly when conditions such as lower microbial activity, reduced oxygen, and limited disturbance favour slower decomposition and



**Fig. 6.** Soil pH (a) and soil organic carbon (SOC) (b) changes at different depths under contrasting cropping systems. The change was expressed as a ratio of soil samples taken in 2019/20 and 2022/23 seasons. The significances are displayed on the top left corner of each plot, and 'NS' means data were not significantly different, while asterisks mean data were significantly different where '\*\*' and '\*' represent  $<0.01$  and  $<0.05$ , respectively. Abbreviations of cropping systems: CP-MC, conventional tillage with maize-cowpea intercrop; RFT-MC, ridge and furrow tillage with maize-cowpea intercrop; BA-MC, basin planting with maize-cowpea intercrop; DS-MC, direct seeding with maize-cowpea intercrop; and RI-MC, ripping with maize-cowpea intercrop.

enhanced mineral association of organic matter [82]. In contrast, CA practices, which minimize soil disturbance and maintain permanent soil cover, often result in higher SOC concentrations near the surface but may not enhance SOC storage in deeper layers. While this enhances SOC in the upper soil layers due to concentrated microbial activity near the surface, the lack of soil mixing limits the transport of organic matter to deeper layers [83]. Additionally, biological inputs such as root biomass and exudates, which can contribute to deep SOC, may be less spatially distributed compared to the mechanically mixed systems unless deep-rooted crops are used consistently. Studies have shown that while CA, particularly no-tillage systems, increases SOC in the upper soil layers, it may not significantly enhance total SOC storage when deeper soil layers are considered [84,85]. Additionally, the redistribution of organic carbon due to tillage can promote stabilization processes in deeper soil layers [85]. Therefore, the choice between tillage and CA practices should consider the desired distribution of SOC within the soil profile and the farming system's specific environmental and agronomic goals, considering that SOC is positively linked with crop yield and hence an indicator of agricultural resilience [86]. However, the overall impact on SOC distribution and the extent of pH changes depend on soil type, climate, and specific management practices [87,88]. We partially accept the hypothesis that CA-based systems generally lead to increased soil pH and promote carbon storage more than conventional tillage-based systems at all depths, since this was only true for soil pH

and not for SOC. The long-term effects of tillage on mesofauna communities remain unexplored. It is also noteworthy that the use of glyphosate in the CA-based systems may have influenced microbial communities, which play a key role in soil organic carbon (SOC) dynamics, by reducing microbial diversity or altering decomposition rates, factors that can influence the accumulation or turnover of SOC [89]. This may have interfered with SOC measurements.

## 6. Conclusion

Conservation Agriculture is being extensively promoted in sub-Saharan Africa to increase smallholder productivity while conserving natural resources. In Zambia, CA has been established and well-documented in the Southern, Central, and Eastern Provinces. In contrast, few documented studies are known from Northern Province due to the perceived challenges of CA as a water-saving technology under high rainfall. The general narrative has been that CA systems cannot work in high-rainfall areas, although in the central province of Malawi, another high-rainfall area, CA has consistently outperformed conventional systems. We conclude from this study that sustained implementation of CA systems in high-rainfall areas can enhance crop productivity by 12–18 %, especially under annual rainfall of 1300 mm, and maintain soil health in the longer term. Despite initial concerns regarding waterlogging, CA principles, including minimum soil

disturbance, permanent soil cover, and crop diversification, contribute to improved soil structure, enhanced water infiltration, and reduced erosion. These benefits are critical in mitigating the adverse effects of high rainfall and ensuring stable yields even in variable climatic conditions. While CA-based systems generally performed well under the high-rainfall conditions of Northern Zambia, their yield advantages were less pronounced in years with exceptionally high rainfall, where ridge and furrow tillage systems improved drainage and outperformed CA in rainfall exceeding the threshold of 1500 mm. In such extreme rainfall conditions, CA-based systems can be adapted to improve water management and yield. To prevent waterlogging, planting could be done on permanent ridges or raised beds rather than flat ground, which helps channel excess water away from root zones. These permanent raised beds and ridges promote reduced mechanical disturbance of the soil, thus preserving soil structure. Therefore, we confirm that CA systems can be applied in the high-rainfall region of Northern Zambia, but encourage management practices that reduce waterlogging and erosion in years that receive exceptionally high rainfall. Site-specific adjustments based on soil type, slope, and rainfall intensity are essential to maximize the effectiveness of these adaptive measures. A more detailed quantitative analysis is required to elucidate the underlying processes driving the observed responses. This would facilitate a deeper understanding of key factors, such as soil infiltration rate, influencing system performance and soil-water dynamics. In addition, we recommend establishing new CA research on permanent ridges and permanent raised beds, which hold the promise that increased drainage can be achieved while principles of CA are being implemented. Research could also incorporate water-logging tolerant maize varieties to improve the resilience of the system. These will have different characteristics, such as having leaves that remain green during flooding to maintain photosynthesis.

#### CRedit authorship contribution statement

**Blessing Mhlanga:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Kelvin Kalala:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Data curation. **Christian Thierfelder:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that there is no conflict of interest whatsoever regarding the publication of this article.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafr.2025.102082>.

#### Data availability

Data will be made available on request.

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