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Restoring soil nutrient stocks using local inputs, tillage and sorghum-green gram intercropping strategies for drylands in Eastern Kenya

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ABSTRACT

Soil macronutrient and micronutrient availability is particularly critical in semi-arid agro-ecological zones that are characterized by poor soil fertility and low rainfall regimes. An experiment was initiated in Siakago, Embu County to investigate the effects of tied-ridges, conventional tillage and input applications on soil nutrient fertility using a randomized complete block design with a split-split plot arrangement for 4 seasons (2018–2021). The treatments comprised of two main plot tillage systems, three cropping systems allocated to the sub-plots and four soil input management treatments assigned to sub-sub plots. ANOVA was used to test the effects of different treatments including tillage, crop system and soil fertility management using Genstat software. The data was also subjected to Principal Component Analysis procedures using R ("*FactoMineR*" and "*factoextra*") to examine the inter-relationship patterns between different soil fertility parameters and to reduce the data into independent soil fertility components. There were significant main effects due to crop system (Soil Mn), tillage and crop system interaction (SOC and TSN) and soil fertility management (TOC, TSN, Ca, Zn). Soil inputs significantly influenced soil carbon concentrations ($p = 0.002$), with the lowest values observed in the control (0.2 %), followed by sole fertilizer (0.35 %), manure + fertilizer (0.41 %) and the fully decomposed manure treatment (0.61 %). The soil-extracted manganese values recorded significant effects due to crop system, while soil-extracted Zn values were significant due to soil fertility management. Multivariate analysis results revealed the structure of soil nutrient distribution. Tied ridging can improve soil micronutrient availability through reduced soil erosion, conservation of soil organic matter, which can improve soil micronutrient availability. Soil conservation practices such as tied-ridging integrated with organic input applications can enhance multiple nutrient availability for improved crop performance and human nutrition in dryland farming systems where farmers lack soil moisture, technologies and resources to enhance crop nutrient availability.

1. Introduction

Kenya's agricultural sector contributes a major share of the national GDP (gross domestic product, about 33 %). At the same time, over 7 5%of the Kenyan population earns its' livelihood directly from the agricultural sector [1]. In Eastern Kenya, agricultural

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productivity is mainly constrained by several factors, including increasing population density, low soil fertility, and competing land-use enterprises [2]. The situation is exacerbated by land degradation and lack of adequate soil amendments to replenish soil fertility and improve crop productivity [3]. According to FAO [4], Embu County is classified as a "stressed" food security zone because of lack of adequate rainfall and poor soil fertility. This is also a typical challenge in similar agricultural systems of SSA (Sub-Saharan Africa) countries [3].

Appropriate applications of organic manures and inorganic fertilizers in the right amount and the right soil conditions can contribute an important role in enhancing soil fertility and crop production [5–7]. Farmers need to have adequate knowledge regarding soil properties to manage soil fertility and apply the correct type of fertilizers in their fields. This is particularly more critical in semi-arid agro-ecosystems of the SSA region, which are characterized by poverty, high vulnerability to soil degradation, poor agricultural productivity, degradation of soil organic matter, low levels of soil moisture and soil nutrient availability including soil macronutrients and micronutrients.

Several past studies have shown that soil fertility has been declining in the drylands of Eastern Kenya with time because of poor tillage practices and insufficient use of soil inputs coupled with increasing population [8]. Soil fertility and crop performance is influenced by continuous cultivation, which is aggravated by unreliable rainfall in the low-potential agricultural zones [9]. Soil erosion has led to reduced agricultural production in the SSA region, leading to annual crop yield losses of 280 million tons [10]. The poor soil structure and the shallow soil depth makes soil erosion events more severe in the semi-arid farming systems [10]. Soil erosion reduces soil organic matter concentrations, soil aggregate stability and water holding capacity, thus encouraging soil crusting [10]. Integrated soil fertility and water conservation methods such as tied-ridges are some of the options proposed to enhance soil macronutrient and micronutrient conservation. Mo et al. [11] and Pan et al. [12] suggested tied-ridges as a low-input, innovative and high-yield soil water conservation strategy to increase efficiency of crop water use. Tied-ridges are constructed when the furrows are constrained with earth ties at regular intervals to produce micro-catchment basins [13,14]. Despite the technology's high potential to augment retention of soil moisture, soil nutrient conservation and crop productivity, tied-ridge technology has been poorly adopted by small-scale farmers in semi-arid regions [14,15], given the low proportions of adopting farmers. The major reasons for poor adoption of tied-ridging technology includes weak policy environment and lack of knowledge and resources by small-scale farmers to adopt the technology.

Within small-scale semi-arid farming systems, the contributions of common soil fertility management practices on soil micronutrient fertility is not well understood. Soil micronutrients are important for optimum crop growth as well as human health due to their roles in reducing micronutrient deficiencies. Soil micronutrient availability has been poorly studied in the SSA farming systems, due to a much greater focus on soil macronutrients. In addition, several studies have focused on fertilization effects of selected nutrient availability in the foods consumed (especially Zn) while lesser effort is focused on soil management and soil conservation strategies because the relationship between soil micronutrient distribution and environmental factors is not well understood. Thus, more location specific investigations on soil micronutrient availability are needed. Adequate approaches are needed to maintain sufficient quantities of plant-available soil micronutrients to enhance soil fertility, crop yields and human health, particularly in fragile dryland farming systems. The main objectives of the field experiment were as follows: i) to determine the effect of conventional tillage and tied ridges on soil macronutrient and micronutrient availability, and ii) to evaluate the effect of cropping and input application on overall soil fertility parameters in dryland farming systems of Eastern Kenya. The principal hypothesis of the study was that small-scale farmers in dryland zones can improve their soil and macronutrient and micronutrient characteristics using tied-ridges and adequate soil fertility management practices. The study was implemented to fill in knowledge gaps related to soil fertility management factors influencing soil micro-nutrient availability in small-scale dryland ecosystems where farmers have limited knowledge and resources to replenish soil micro-nutrients. By addressing soil micro-nutrients and macro-nutrients, the study aims to harness unique approaches to soil fertility research that are beneficial to improving soil fertility, crop production, food security and nutrition outcomes by exploring the multivariate distribution of soil nutrients as moderated by soil fertility management factors.

2. Materials and methods

2.1. Study site description

This field experiment was installed at the Agricultural Technology Development Centre (ATDC) (S 1.1953511; E 36.9229824), Siakago within Mbeere North sub-County, Embu County for four sequential seasons commencing from October 2018 to February 2021. The agricultural institute falls under agro-climatic zones IV-2 which is semi-arid, with medium potential for crop production. The average annual evaporation ranges from 1550 to 2200 mm while the bimodal annual rainfall pattern ranges between 600 and 1100 mm. The mean annual temperature ranges from 22-24 °C. The rainfall distribution is generally sparse in Mbeere North, falling in two separate cropping seasons. The long rain season typically commences from March through to May, while the short rain season begin from October to January, each year [16]. Approximately 40 % of the annual cumulative rainfall is recorded during March–May and 60 % during October to January [16]. The site has diverse soil types, predominantly comprised of *Rhodic Ferralsols* and *Haplic Lixisols*. The *Rhodic Ferralsols* (the main soil type at the site) are deep, dark red, well-drained, and with friable clay particles [16]. The initial soil characteristics prior to the commencement of the experiment were as follows: soil pH (5.7), total soil N (0.12 %), total soil C (1.19 %), available soil P (7.21 mg/kg), extractable soil Ca (5.04 cmol kg^{-1}) and extractable soil Zn (4.7 cmol kg^{-1}).

2.2. Experimental design

A split-split plot experiment was used arranged in randomized complete block design (RCBD) with three replications. The test crops included green gram (*Vigna radiata*) and sorghum (*Sorghum bicolor*) as sole crops and intercrops. The selected treatments comprised of 2 (two) tillage systems [including tied ridges (TR) and conventional tillage (CT)] which were designated as main plots. Three crop systems (sole green grams, sole sorghum and green gram-sorghum intercrops) were included as the sub plot factors. In addition, four soil fertility input management regimes were used as sub-sub plots. These included no inputs (NIL), full fertilizer (60 kg N & 60 kg P_2O_2 ha^{-1}, FF), farmyard manure (5.0 t ha^{-1} manure, FYM) and integrated fertilizer and manure applications (2.5 t ha^{-1} of manure and 30 kg N & 30 kg P_2O_2 ha^{-1} of chemical fertilizer, HMHF) assigned as the sub-sub plots. The sub-sub plot size was 6mx4m. Farmyard manure was obtained from neighboring farmers at the ATDC, Siakago. Organic and inorganic fertilizer application was done at the time of seeding in the planting holes or tied ridges during rainfall onset. Conventional tillage treatments were tilled using harrowing and hand hoes, following common farmer practices during the preceding dry season to minimize soil compaction. Tied ridges were constructed by digging 15 cm deep furrows with their associated ridges at an interval of 75 cm apart one week before planting manually using a hand hoe. Sole-sorghum was sowed at 75 cm (inter-row) and 25 cm (intra-row) spacing and two plants per hole were maintained irrespective of the tillage system. Sole-green grams were also planted at 60 cm (inter-row) and 15 cm (intra-row) spacing, respectively. For sorghum-green gram intercropping system, one row of green gram was planted between two sorghum rows at 45 cm and 15 cm spacing along the row.

2.3. Field soil sampling and analysis

The zigzag sampling framework was used sample composited soils at plot level (0–20 cm depth) during the beginning and end of the experiment for soil nutrient analysis following the methods outlined in Okalebo et al. [17]. Available soil nutrients (including P, K, Ca, Mg and Mn) were extracted using Mehlich double acid method (0.1 N HCl and 0.025 N H_2SO_4) using a 1:5 soil: volume ratio. Calcium and magnesium were determined with a flame photometer while P, Mg and Mn were determined calorimetrically. To determine total organic carbon (TOC), the soil sample was oxidized using acidified dichromate at 150 °C for 30 minutes followed by calorimetric determination [17]. Nitrogen (N) was analysed by Kjeldahl method [18] method while total phosphorus (P) was analysed according to Olsen and Sommers [19]. Total Potassium (K) was analysed using a flame photometer [17]. Available soil micronutrients (including Fe, Zn and Cu) were extracted using 0.1 M HCl in a 1:10 soil: volume ratio after which they were determined using an Atomic Absorption Spectrophotometer (AAS) [17].

2.4. Data management and analysis

The soil data was captured in an Excel worksheet and subjected to cleaning and checking of outliers using boxplots prior to data analysis. Several descriptive tests were also performed to explore trends. ANOVA was used to test the effects of different treatments including main effects and the interactions of tillage, cropping type and soil fertility management with a Split-split-plot design using Genstat software. Means were separated using the Tukey LSD (0.05) procedure in Genstat. The data was also subjected to PCA procedures using SPSS and R software to examine the inter-relationship patterns between different soil fertility parameters. Several exploratory data analysis procedures including descriptive statistics, correlations and scatter plot matrices were implemented prior to multivariate analysis. Multivariate statistical techniques facilitated the testing of potential correlations between different soil characteristics and soil fertility management practices using R software packages "*FactoMineR*" (for PCA calculations) "*factoextra*" (for plotting). During the procedure, the soil values were standardized prior to multi-variate analysis and confidence ellipses were drawn around the group mean points for different treatment factors (tillage, crop system and soil fertility management).

Table 1
ANOVA model showing the significant main effects and interaction effects for different soil properties.

Parameter	Tillage (1)	Cropping (2)	Tillage:Cropping (2)	Fertility (3)	Fertility:Tillage (3)	Fertility:Cropping (6)	Fertility:Tillage: Cropping (6)
TOC (%)	0.262	0.115	**0.026***	**0.002****	0.93	0.443	0.873
Soil pH	0.788	0.409	0.135	0.202	0.738	0.928	0.873
TSN (%)	0.245	0.12	**0.090.**	**0.000*****	0.753	0.149	0.814
Available soil P (mg kg^{-1})	0.403	0.487	0.812	**0.015** *	0.882	0.493	0.401
Extractable soil K (cmol kg^{-1})	0.637	0.513	0.172	0.433	0.89	0.38	0.086.
Extractable soil Ca (cmol kg^{-1})	0.662	0.63	0.725	**0.035***	0.669	0.652	0.102
Extractable soil Mg (mg kg^{-1})	0.366	0.073.	0.596	0.426	0.979	0.666	0.963
Extractable soil Fe (mg kg^{-1})	0.596	0.643	0.498	0.498	0.675	0.385	0.448
Extractable soil Cu (mg kg^{-1})	0.374	0.349	0.211	0.135	0.491	0.339	0.092.
Extractable soil Mn (mg kg^{-1})	0.765	**0.05***	0.418	0.286	0.758	0.523	0.375
Extractable soil Zn (mg kg^{-1})	0.378	0.238	0.788	**0.045***	0.316	0.781	0.296

Significance codes: 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1. Degrees of freedom (df) are shown for each treatment effect and interaction.

3. Results

3.1. Main effects and interaction effects of tillage, crop system and soil inputs

The results show that there was a significant effect for soil fertility management and an interaction effect between tillage and cropping system for TOC ($p < 0.05$) (Total organic carbon) and TSN (Total soil nitrogen). Soil manganese values recorded significant cropping system effects ($p < 0.05$). Significant main effects were observed for TOC, TSN, available soil P, Calcium, and Zinc due to soil fertility management treatments. In addition, manganese soil concentrations recorded significant main effects due to cropping system (Table 1).

3.2. Treatment effects on soil carbon and total soil nitrogen concentrations

The following section describes the effects of tillage, cropping system, and soil fertility management on soil carbon (Fig. 1A–E) and total soil nitrogen concentrations (Fig. 2A–E).

Soil fertility management treatments significantly influenced soil carbon concentrations, with the lowest mean value recorded in the control plots (0.2 %), followed by fertilizer (0.35 %), half-fertilizer and half-manure (0.41) and the full manure treatment (0.61). There was significant interaction between tillage and cropping systems. The highest mean soil carbon concentration under conservation tillage was recorded in the intercropped plots, followed by green gram and sorghum, while tied ridge plots recorded the highest

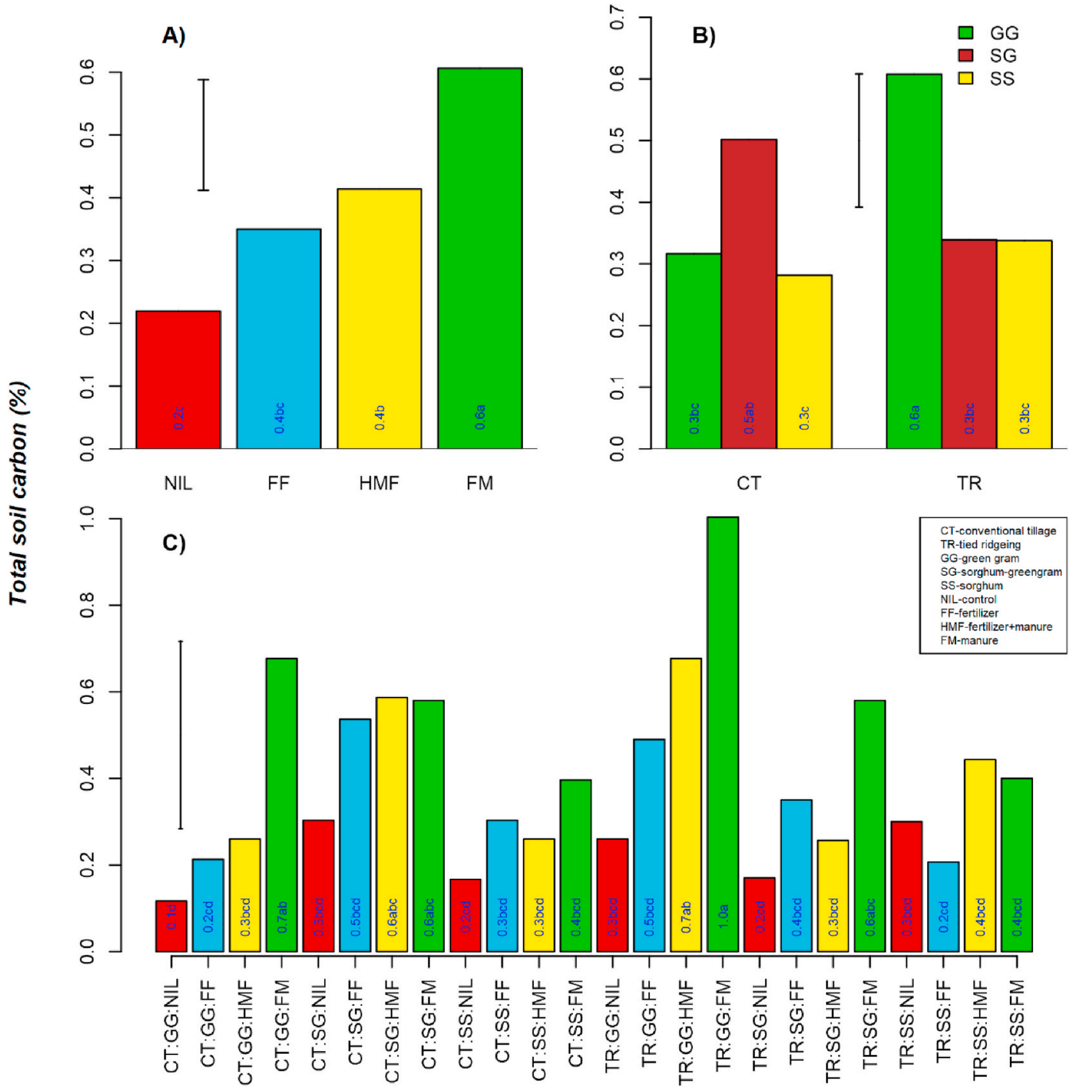

Fig. 1. Soil tillage, crop system, and fertility management effects on soil carbon. Means followed by the same letters are not significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*Cropping, C-Tillage*crop*soil fertility management).

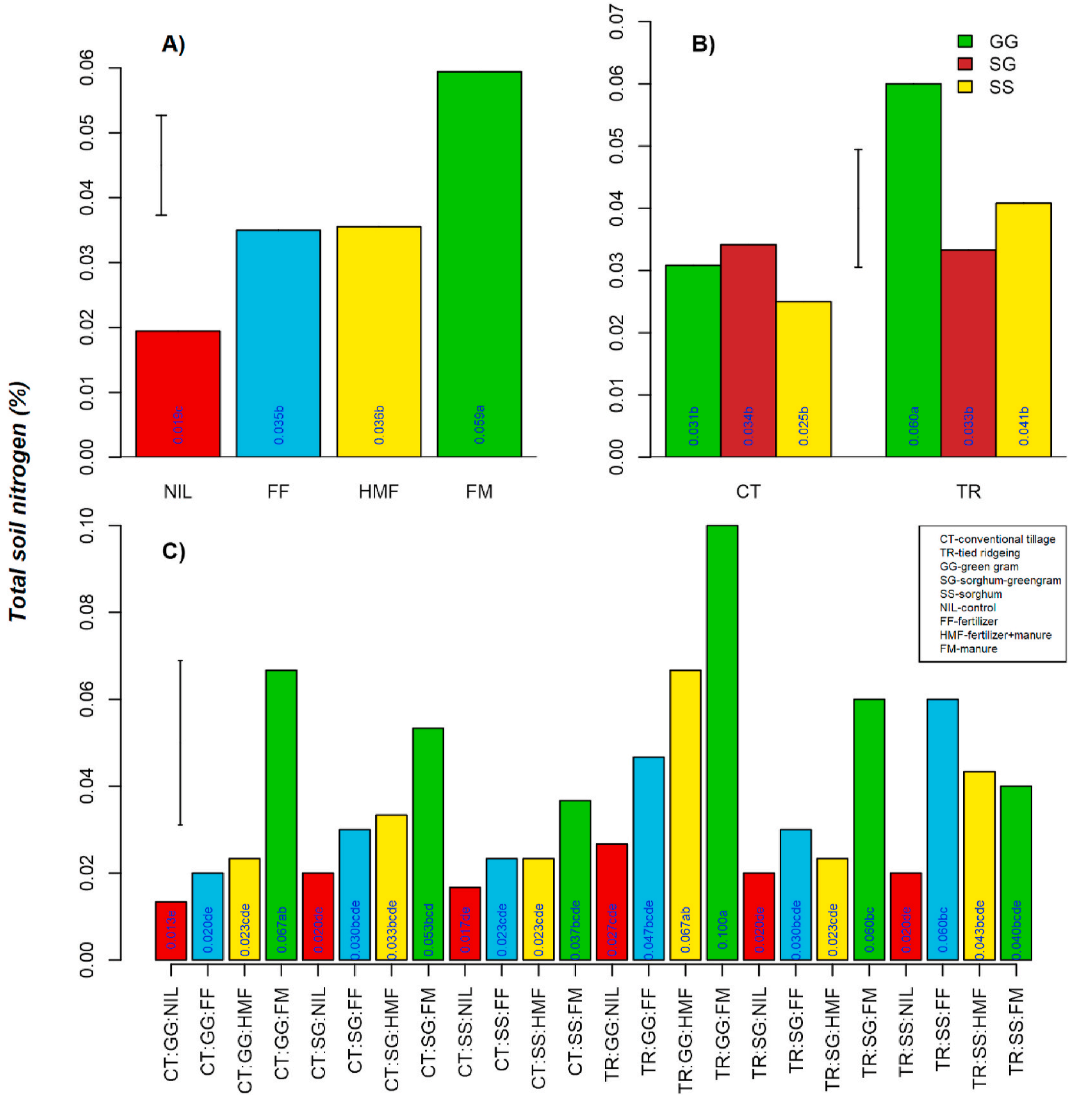

Fig. 2. Soil tillage, crop system, and fertility management effects on total soil N. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*Cropping interaction, C-Tillage*crop*soil fertility management interaction).

soil C under green gram plots. In tied ridging, the highest average soil C concentration was observed in the manure treatment (0.66), while the lowest soil carbon concentration was recorded in the control (0.24 %).

Soil fertility management treatment significantly influenced the soil N distribution ($p = 0.000$) (Fig. 2C), while all other factors and their interactions were not significant ($p < 0.05$). Regarding the crop system (Fig. 2B), the total soil N was highest in the green gram crop system (0.05 %), and was similar for the intercrop and sole sorghum crop (0.03 %). Also, the interaction of tied-ridging and green gram cropping gave the highest total soil N (0.06 %) (Fig. 2D), while the tied-ridging treatment with manure applications resulted in the highest total soil-N concentrations.

3.3. Treatment effects on soil macronutrient concentrations

Soil fertility management treatments significantly influenced the extractable soil P distribution (Fig. 3A–E) ($p = 0.015$). Regarding the crop system, the total soil P was highest in the sorghum (7.27 ppm), and was lowest in the green gram cropping system (6.74 ppm) (Fig. 3B). The manure treatment recorded the highest extractable soil P (7.75), followed by manure + fertilizer (7.29 ppm), fertilizer (7.13 ppm) and the control (5.94 ppm) (Fig. 3C). In relation to the cropping system, sorghum intercropping under tied ridges recorded the highest extractable soil P (7.44 ppm) while this was least in the green gram under conventional tillage (6.39). In all treatments, the crops under conventional tillage recorded the lower extractable soil P, compared to the plots under tied-ridging system (Fig. 3D).

There were significant main effects attributed to soil fertility management for extractable soil Calcium (Fig. 4C). The average soil

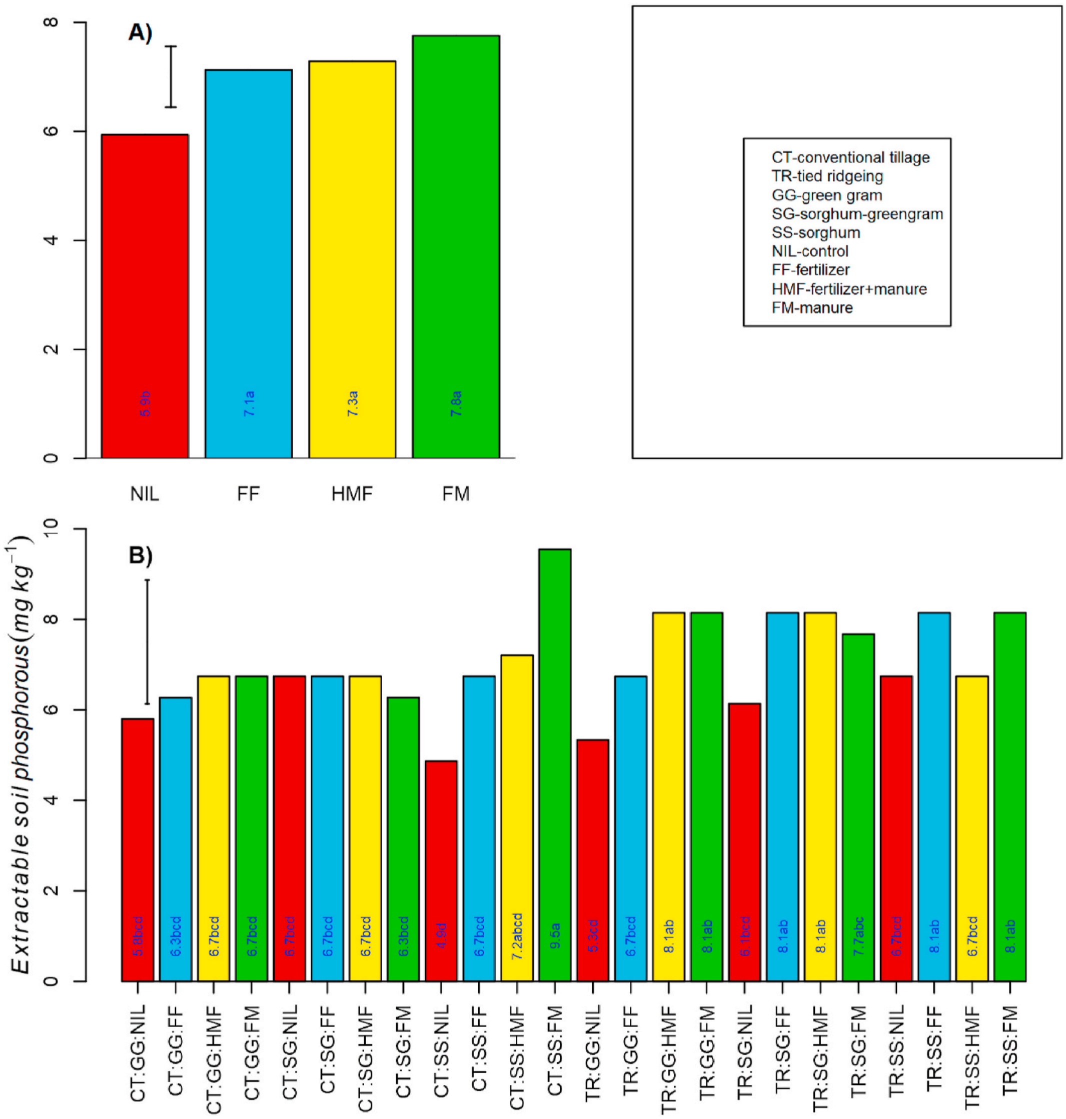

Fig. 3. Soil tillage, crop system, and fertility management effects on soil P. Means followed by the same letters are not significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*crop*soil fertility management interaction).

extractable calcium was highest in the manure + fertilizer treatment (5.3). This was followed by fertilizer (4.95), manure (4.59), while the control recorded the least extractable calcium values. There were significant differences between all soil fertility treatments for extractable soil Ca. Regarding crop system, sorghum-green gram intercrops recorded the highest extractable soil Ca value (4.97), followed by sorghum (4.74) and green gram (4.52). The highest soil extracted Ca was observed in the conventional tillage intercrop (5.24) while this was lowest in green gram tied-ridging system (4.11). In addition, the manure + fertilizer conventional tillage system recorded the highest extracted soil Ca value (5.70), while this was least in the tied-ridging without inputs (4.00).

There were significant main effects attributed to soil fertility cropping system for extractable soil magnesium (Fig. 5B), while other main effects and interactions did not yield significant effects (Fig. 5A, C, D, E). The average soil extractable magnesium was highest in the conventional tillage (1.67) compared to tied ridging system (1.36), but the difference was not significant. In addition, the green gram crop system resulted in the highest Mg levels (1.70), while this was least in the intercropping system (1.17) (Fig. 5B). Significant differences were detected between the manure + fertilizer (1.44) application and the control (1.31) for extractable soil Mg values.

3.4. Treatment effects on soil micronutrient distribution

The soil-extracted Zn values were significant due to soil fertility management (Fig. 5C), while other factors and interactions were not significant (Fig. 5A, B, D, E). The tied-ridging system recorded a lower soil Zn, relative to conventional tillage. For soil fertility management practices, the control was significantly lower in Zn than all other treatments, which were similar (Fig. 5C). In relation to

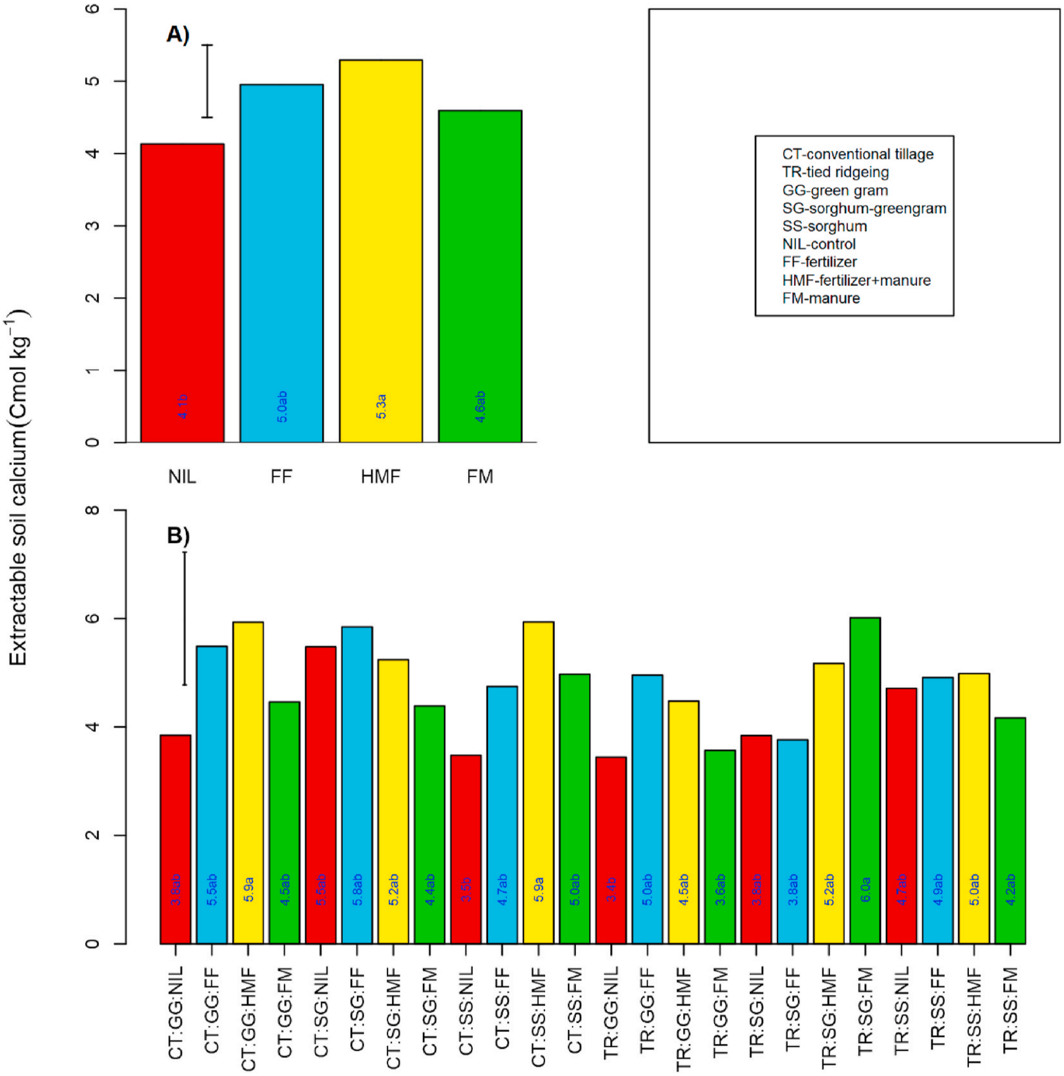

Fig. 4. 4Soil tillage, crop system, and fertility management effects on soil Ca. Means followed by the same letters are not significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*crop*soil fertility management interaction).

cropping system, the green gram system recorded the highest soil Zn (3.99), followed by sorghum (3.70) and the intercrop system (3.34).

3.5. *Multi-variate analysis of soil properties*

Four principal components were extracted from 11 soil fertility parameters in the original soil database (Table 2). The PCA (principal component analysis) model explained 69.4 % of the total variance in soil fertility, while 4 components that had eigen values > 1 were retained in the model for interpretation. The omnibus tests for model adequacy and stability indicated that the multi-variate model was viable due to the high KMO (Kaiser-Meyer -Olkin) measure of sampling adequacy value (0.657). The KMO-MSA value indicated that the soil data was appropriate for multivariate analysis, while the Bartlett's test of sphericity showed that the data was not an identity matrix. The first principal component (factor) comprised of high loadings between available soil K, soil Fe, and negative loadings (correlations) from available soil copper and calcium. The factor was labeled as the soil macronutrients and trace elements factor. The second factor was comprised of high positive loadings from extractable Zn (0.714), extractable Mg (0.682) and extractable Mn with a negative loading (−0.636), which represented a negative correlation with Zn and Mn. Thus, the factor was labeled the soil micronutrient factor. The third factor comprised high and positive loadings (correlations) by soil carbon and soil nitrogen, thus it was labeled the soil organic matter factor. The fourth factor was comprised of soil pH and soil P, thus it was labeled the soil reaction factor.

The biplots (Fig. 6A and B,C,D) display the correlations between different soil parameters during the endline sampling phase at the Siakago experimental site. Points that are close to the average for each variable appear at the origin of the PCA biplot. The loadings plot

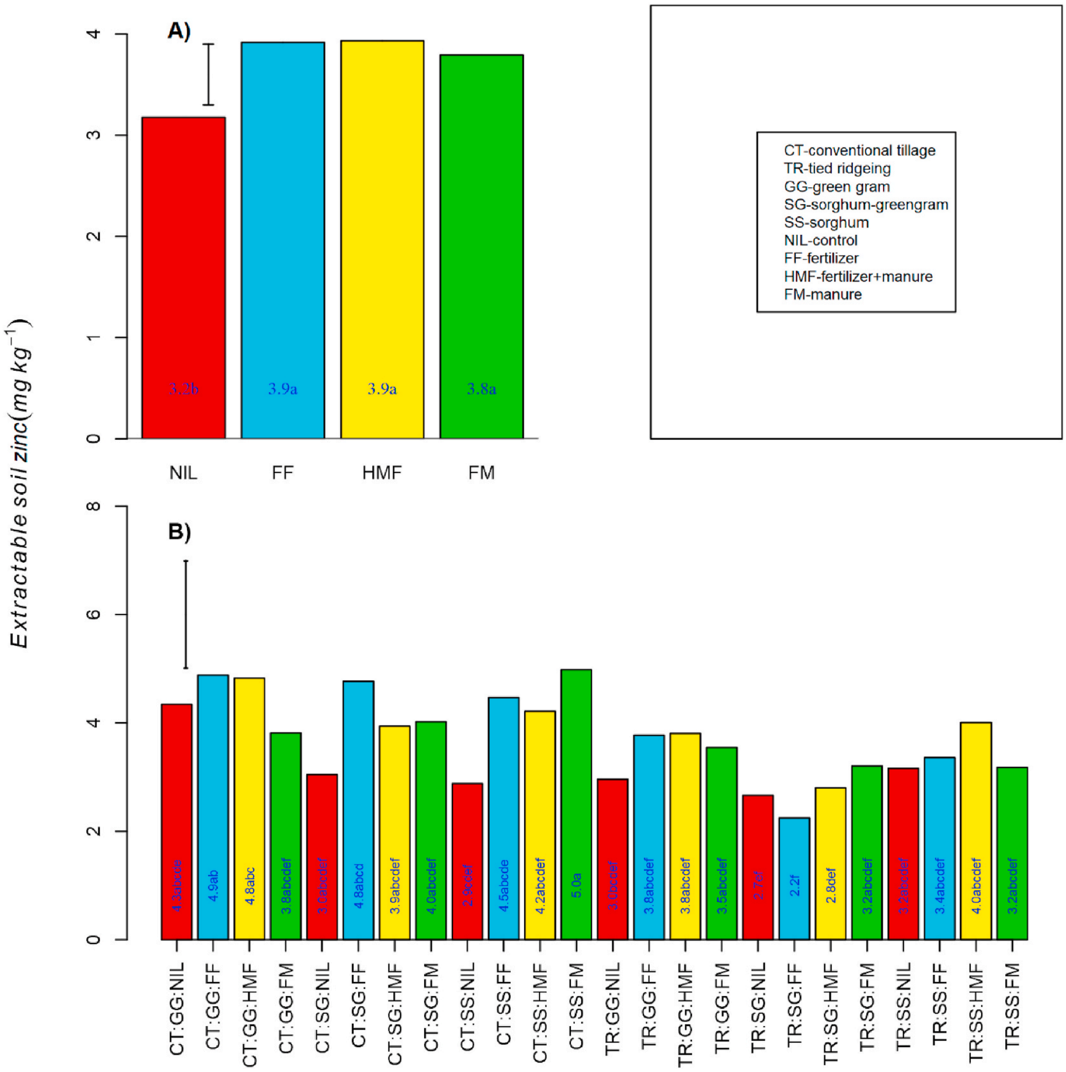

Fig. 5. Soil tillage, crop system, and fertility management effects on soil Zn. Means followed by the same letters are no significant. Least significant differences are presented as error bars (A,-LSD-soil fertility management, B-Tillage*Cropping, C-Tillage*crop*soil fertility management interaction).

show how the original variables contributed to creating the principal component, and strongly correlated variables record approximately the same weight value when they are positively correlated.

4. Discussions

4.1. Effects of soil carbon and nitrogen concentration

Tied ridging recorded higher soil carbon contents relative to conventional tillage by a 16.7 % difference. The findings were in agreement with Kabanza and Rwehumbiza [20] who found that tillage did not influence soil organic matter distribution in Tanzania semi-arid farm systems, significantly. Oduor et al. [21] found that soil conservation strategies and fertility management reduced soil nutrient losses and soil organic carbon, which explained the slight increase in soil carbon under the tied-ridging system. The findings suggest that the effects of tied-ridging on soil carbon and nitrogen distribution could have been clearer with a longer period of experimentation at the dryland site. Soil physical characteristics were modified slowly after establishment of tillage practices, suggesting that long-term tillage experiments (>4 seasons) under similar conditions are needed to elucidate changes in physical characteristics [22]. There was a significant effect of tillage and crop system interaction, with tied-ridging under green gram and tied-ridging under sorghum cropping recording 92 % and 20 % higher soil carbon compared to similar cropping practices under the conventional cropping system. The higher soil carbon values under green gram relative to sorghum was expected because the crop improves soil health and fertility, reduces soil erosion and fixes nitrogen to the soil through biological nitrogen fixation.

Table 2
Four-factor rotated component model of endline soil fertility parameters in Siakago, Kenya.

Soil parameters	Component				Communalities
	1	2	3	4	
K (meq/100g)	0.854				0.740
Extractable soil Fe (mg kg^{-1})	0.827				0.850
Extractable soil Cu (mg kg^{-1})	−0.718				0.808
Extractable soil Ca (cmol kg^{-1})	−0.501				0.461
Extractable soil Zn (mg kg^{-1})		0.714			0.607
Extractable soil Mg (mg kg^{-1})		0.682			0.595
Extractable soil Mn (mg kg^{-1})		−0.636			0.678
Soil C (%)			0.925		0.863
Total soil N (%)			0.871		0.813
Soil pH				0.768	0.646
Available soil P (mg kg^{-1})				0.564	0.570
Eigen values	**3.6**	**1.7**	**1.3**	**1.0**	
% of variance	**32.6**	**15.7**	**11.6**	**9.3**	
Cumulative variance	**32.6**	**48.4**	**60.0**	**69.4**	

KMO measure = 0.657, Bartlett's test of sphericity (Chi-square = 278.5, df = 55, sig = 0.000).
The cut-point for display of loadings was set at 0.4.

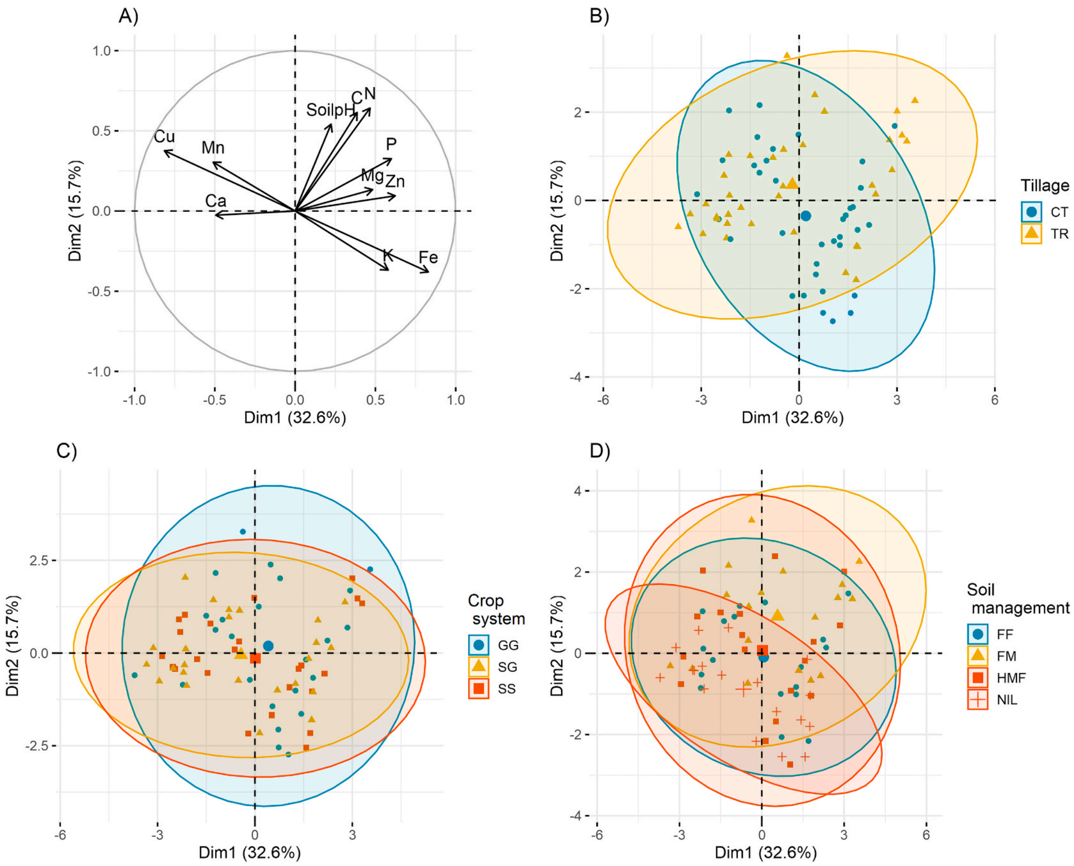

Fig. 6. Principle component biplots for soil parameters (Figure A) and individual plots with confidence ellipses for tillage, crop system and soil fertility management.

There was significant tillage*crop system interaction, with higher total soil nitrogen being observed in tied-ridge green gram plots, compared to the conventional tillage-green gram treatment (94.5 % difference). The findings indicated that tied-ridging contributed to improvements in soil carbon and soil nitrogen concentrations under tied-ridging with green gram cropping after 4 seasons. In addition, the total soil nitrogen recorded the lowest concentrations in the control treatment, while integrated fertilizer and manure recorded the highest total soil N. The improvement in soil organic carbon and total soil nitrogen under the green gram cropping system was expected, because the legume crop fixes atmospheric nitrogen into the soil using biological nitrogen fixation. In addition, the green biomass including the crop residues and leaf fall can improve the soil characteristics. Kumar et al. [23] observed that soil microbiological properties were significantly improved in fields where green-gram was included. This is likely to have improved the soil total carbon and total nitrogen concentrations, particularly under tied-ridge treatments which enhanced conservation of soil nutrients. The findings of the study in relation to tied-ridging in semi-arid areas were consistent with findings of several authors who recorded that tied-ridging and integrated soil fertility management practices were needed to improve soil fertility and crop performance [24].

4.2. Soil pH and macronutrient characteristics

The study findings are consistent with Rasmussen [25] who found that soil tillage practices did not influence soil pH. The results reflect initial soil changes due to treatment effects, and clearer effects could have been manifested with a longer experimental duration which was not the scope of the study. The experiment, however recorded a 7.4 % lower soil pH under conventional tillage, relative to tied-ridging. This result was possibly attributed to higher erosion losses under conventionally tilled plots, which resulted in soil C losses. Soil erosion results in reduced soil carbon, which results in increased soil acidity levels, due to the reduced soil buffering capacity. Lal [26] recorded a decline in soil pH (6.7–5.6) in conservation tillage practices., while in coventional tillage systems, the pH declined from 6.7 to 5.4. The findings indicate that tied-ridging, compared to conventional tillage systems contributed to reduced soil erosion and conservation of soil properties, leading to reduced acidification of the soil. The average soil extractable P under conventional tillage was 9.7% lower, compared to the tied-ridging system. The soil P concentration was higher under tied-ridging mainly because of minimization of soil disturbance under tied-ridging which led to lesser P mobilization and increased levels of residual soil P. The result was in agreement with Gosai et al. [27] who reported greater soil available P in fields with lower tillage intensity including shallow tillage and no-tillage systems.

4.3. Soil micronutrients

Soil micronutrient deficiencies can negatively impact on crop growth, productivity, and quality, thus affecting multiple facets of human health. Micronutrient soil deficiencies are a global problem [28], and effective approaches are needed to enhance soil micronutrient phytoavailability in the agro-ecosystem. Micronutrient deficiencies, usually referred to as 'hidden hunger', can result to profound human health complications. Globally, up to 2 billion persons are at risk of iron (Fe), iodine (I), selenium (Se), zinc (Zn), magnesium (Mg) and calcium (Ca) deficiencies [29]. Large regions of African soils are deficient in soil micronutrient levels and small-scale farmers are limited in soil-to-plant micro-nutrient transfer options, especially in dryland farming systems. Deficiency of soil micronutrients can largely be attributed to geological factors, as well as soil fertility management-related factors [30].

The experiment showed that soil micro-nutrients such as Zn were significantly improved by integrating legumes and including soil conservation management practices. The available soil Zn content was higher in the fertilizer and manure treatment, while it was low in the control treatment. The findings suggest that farmyard manure is an important organic resource for soil micronutrient interventions. Different soil conservation techniques and cropping sequences can lead to variation in soil micronutrients distribution (Fe, Mn, Zn, and Cu).

Soil fertility management influence on soil Zn was partly expected because of the effects of input application practices on soil organic carbon, which influenced the distribution of soil micronutrient availability [31]. The finding was consistent with Kumar et al. [32] who observed an increase in several macronutrients and micronutrients (including potassium, magnesium, iron, manganese, zinc and boron) after mulching soils during a 3-year experiment. Globally, about 33 % of the arable soils are deficient in micronutrients, especially in zinc (Zn) [33]. About 2–3 billion people globally manifest different micronutrient deficiencies, and the problem is more severe in developing countries [34], which have weaker coping strategies for micro-nutrient deficiency. The problem of micronutrient deficiencies is more widespread in the SSA region, compared with several global regions (with at least 2–5 micronutrients simultaneously) [35,36]. Conventional tillage and tied ridging practices can result to different effects on soil micronutrient distribution, including zinc availability.

Zinc is an essential micronutrient for plant physiological development and agronomic performance. Poor soil fertility management practices including conventional tillage can reduce soil zinc availability in soils undergoing continuous cultivation without fallowing. This is because conventional tillage can result in the loss of soil organic matter and nutrients, including micro-nutrients. Conventional tillage systems can lead to compaction of soils, resulting to increased soil bulk density which can reduce soil aeration and water infiltration, limiting zinc availability [37]. Singh et al. [37] reported significant and strong negative correlations between soil bulk density and soil zinc availability ($r = - 0.925–0.929$) under loamy sand, sandy loam and sandy clay loam soils. In addition, high negative correlations were also detected between soil bulk density and soil Iron ($r = -0.931$ -0.981) for the same soil types [37]. Tied ridging with organic soil input integration can improve soil zinc availability through reduced soil erosion, conservation of soil organic matter, soil moisture, improved soil biological properties and reduction of the soil bulk density, which can improve soil micronutrient fertility. The continuous addition of sole synthetic fertilizers without integration soil organic inputs can negatively influence soil characteristics including physical, chemical, and biological characteristics [38]. On the other hand, the regular incorporation of organic residues can significantly improve soil's physical, chemical, and biological properties [39]. Dhaliwal et al. [40] recommended that organic soil amendments including compost, and farmyard manure (FYM), are beneficial in providing some amounts of essential micronutrients for plant growth and development.

4.4. Multivariate pattern of soil characteristics

The PCA analysis reduced the data into four different dimensions, which explained a high proportion of the variability in the original dataset. The first soil component comprised high positive loadings from soil K and available Iron concentrations. The first principal component increased with soil extractable K and Fe principal component scores, suggesting that soil K and soil Iron concentrations were positively correlated. In addition, the soil Cu and soil Ca decreased with increasing PC1 scores, implying that both soil Cu and soil Ca decreased with increasing soil K and soil Fe concentrations. The second principal component was labeled as the soil micronutrient factor, due to high positive correlations between Mg and soil Zn concentrations. PC2 thus increased with increasing soil Zn and soil Mg scores, while soil Mn scores reduced with increasing PC2 scores. The findings imply that the soil Zn and Mg scores were positively correlated, while being negatively correlated with soil Mn concentrations. The PC3 was labeled as the organic matter factor due to high correlations between PC3 and soil carbon and total soil N scores, while PC4 was described by increasing soil pH and soil available P scores. The findings are in agreement with Rastija et al. [41] who observed the positive influence of increasing soil pH (through liming) on soil P availability. Lower values of soil pH implies that the soils are increasing in acidity, thus soil phosphorus reacts with iron and aluminum which makes it unavailable to plants. The multivariate analysis of soil nutrient distribution has implications for integrated soil fertility management strategies because it has revealed the structure of correlations between soil macronutrients and micronutrients. Soil nutrient availability is influenced by soil properties including soil pH and soil organic carbon (SOC) concentration [42].

5. Conclusions

The study findings provide important perspectives related to soil macronutrients and micro-nutrient fertility in semi-arid small-scale farming systems that are characterized by poverty, higher risks of soil degradation, poor agricultural productivity, low soil organic matter content and low levels of soil moisture. Tied-ridging contributed to preliminary increments in the soil organic carbon and nitrogen concentrations, though the time duration of the experiment was not long enough to evaluate tillage impacts on soil organic carbon in the semi-arid farming system. Organic soil inputs including manure applications contributed to improvement in soil Zn concentration, which is a critical micronutrient for plant growth and human health. The experiment has obtained evidence that tied-ridging and organic inputs also contribute to neutralization of soil acidity, which is beneficial in improving the availability of several soil macronutrients and micronutrients. Integration of soil organic inputs combined with adequate soil fertility management strategies including tied-ridges should be promoted in semi-arid farming systems of the SSA region to improve crop productivity and tackle both local and worldwide micronutrient deficiencies in major staple foods. The study recommends improved soil fertility management approaches in dryland farming systems that integrate manure and fertilizers to enhance crop productivity and soil characteristics such as Zinc availability because soil fertility management treatments improved soil zinc concentrations.

Declaration of competing interest

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

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