Soil & Tillage Research 196 (2020) 104473

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Interactive effects of conservation tillage, residue management, and nitrogen fertilizer application on soil properties under maize-cotton rotation system on highly weathered soils of West Africa

Eeusha Nafi[a,*], Heidi Webber[b], Isaac Danso[c], Jesse B. Naab[d], Michael Frei[a], Thomas Gaiser[a]

[a] Crop Science Group, Institute of Crop Science and Resource Conservation, University of Bonn, Katzenburgweg 5, 53115 Bonn, Germany
[b] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374, Müncheberg, Germany
[c] CSIR-Oil Palm Research Institute P.O Box 74 Kusi, Ghana
[d] West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) 06 BP 9507 06, Ouaga 06, Burkina Faso

A R T I C L E I N F O

Keywords:
West Africa
Tillage
Crop residue

A B S T R A C T

Loss of topsoil, enriched with nutrients, reduces soil fertility, and is one of the major impediments to sustainable crop production in West Africa. Appropriate management practices can lead to a stable restoration of land's capacity to provide adequate ecosystem services. Thus, our study aimed to investigate the impact of alternative management practices and their interactions on topsoil (0–20 cm) organic carbon (SOC_d), nutrient stocks [total nitrogen (STN_d), phosphorus (SP_d) and potassium (SK_d)] under a maize-cotton rotation system on highly weathered soils of West Africa. To this end, on-farm trials were set up on four sites in the sub-humid Savanna of West Africa (2 in Benin (St1 and St2), and 2 in Burkina-Faso (St3 and St4)) in a strip-split plot layout, where 2 levels of tillage (contour ridge tillage, Ct and reduced tillage, Rt) were considered as main plot factor, and sub-plot factors included 2 levels of crop residue management (removed, CRr and incorporated, CRi), and 2 levels of N fertilizer (control, N0 and recommended rate, Nr). In 2016, after 5 cycles of annual maize-cotton rotation (2012–2016), the largest pool of soil nutrients was recorded on St3 (Haplic Lixisol, footslope in Benin), while the lowest content was observed on St1 (Ferric Lixisol, footslope in Burkina). When comparing the treatments, we found that Ct combined with CRi improved soil nutrient stocks in upslope sites, St2 (Eutric Plinthosol, upslope in Burkina) and St4 (Plinthic Lixisol, upslope in Benin), which are more prone to erosion. At the same time, footslope sites (St1 and St3) benefited from Rt coupled with CRi. CRi promoted an increase in SP_d and SK_d on all sites except St1 (Haplic Lixisol on footslope). The application of recommended dose of N fertilizer improved STN_d under the Ct system in upslope regions and under the Rt system in footslope regions. However, no significant difference was observed for soil pH among the treatments across all sites. In summary, the efficiency of practices for conservation of soil nutrient stocks was closely related to landscape position of the field, which was correlated with soil moisture, textural class, and gravel content. Consequently, site-adapted tillage practices combined with residue incorporation are crucial for sustainable soil fertility management and crop productivity under maize-cotton rotation in smallholder production systems in West Africa.

1. Introduction

Soil degradation is one of the major challenges that significantly hampers global sustainable crop production. This is particularly severe in the Sudan Savanna region of West Africa, that covers the semi-arid portion of tropical Africa. Low productivity of agriculture is predominantly attributed to widespread soil degradation, and a limited capacity to invest in soil improvement, although the majority of the population depends on agriculture for livelihood. Consequently, crop productivity is hampered and economic growth is affected, contributing to poverty and food insecurity (Tully et al., 2015). Causes of on-going soil degradation in West Africa include inappropriate soil management practices leading to poor soil nutrient supply capacity and limiting crop productivity. One of the most widely studied soil management practices is conservation agriculture (CA). CA consists of the combined use of zero or minimum tillage, crop residue incorporation, and crop rotation with legumes, and has been recommended in several previous studies as a potential approach to improve N stock (Martinsen et al., 2019; Naab

---

* Corresponding author.
E-mail address: eeusha.nafi@gmail.com (E. Nafi).

https://doi.org/10.1016/j.still.2019.104473
Received 12 June 2019; Received in revised form 2 October 2019; Accepted 14 October 2019

et al., 2017; Swanepoel et al., 2018), phosphorus (P), potassium (K) (Tolessa et al., 2014), soil moisture (TerAvest et al., 2015) and minimize soil loss through reducing runoff and erosion processes (Araya et al., 2011; Ghosh et al., 2015). Additionally, incorporation of crop residue is imperative to maintain soil health as it offers positive impacts on SOC, N, P, and K (Alam et al., 2018; Huang et al., 2012; Singh et al., 2018). Crop residue retention has also been demonstrated as an effective way to control soil loss by erosion (Cong et al., 2016), and improve soil water holding capacity and infiltration rate (Desrochers et al., 2019). In spite of the fact that CA has the potential to mitigate the severity of soil nutrient loss caused by conventional cultivation methods, numerous studies hold an opposite view. In particular cases, CA can lead to detrimental effects on soil nutrient stock and reduce crop yield (Jan et al., 2016; Okeyo et al., 2016). Studies conducted in steep-slope regions suggest that the use of contour and/or tied ridge tillage is more effective than CA at limiting soil loss by erosion, thereby maintaining more SOC in topsoil layers and improving crop yields (Gathagu et al., 2018; Mohamoud, 2012). Contour ridge tillage was initially promoted to smallholder farmers in SSA to combat soil degradation in areas with high rainfall intensity (Nyamadzawo et al., 2013). In Northern Ethiopia, Araya and Stroosnijder (2010) reported that crop residues retention with contour/tied ridges increased soil water in the root zone by 13%. On the other hand, Karuma et al. (2014) report potentially noxious effects of tied/contour ridge tillage in a maize-bean cultivation system in Eastern Kenya.

Despite the breadth of previous research, much of it has focused on evaluating the effects of tillage, crop residue incorporation or nitrogen fertilizer application on soil properties in mono cropping systems at single locations (Dossou-Yovo et al., 2016; Kihara et al., 2011; Masvaya et al., 2017). Such studies were often short-term and conducted over 2–3 growing seasons. Accordingly, comprehensive multi-location and multi-factor studies over more than 2 growing seasons on the interactive effects of tillage, crop residue management and N fertilizer application on soil properties are still scarce in the Sudan Savanna Zone of West-Africa. Therefore, the aim of this study was to evaluate the effects of tillage, crop residue management and N fertilizer application on soil nutrient stocks at four representative sites in the Sudan Savanna of West Africa after five years. It was hypothesized that over a 5-years period of continuous cropping i) application of reduced tillage as well as the incorporation of crop residues in a maize-cotton rotation has beneficial effects on topsoil (0–20 cm) properties, SOC, total nitrogen (TN), soil exchangeable phosphorus (P_{CAL}) and potassium (K_{CAL}), and pH compared to current management practices (contour ridge tillage, residue removal and no mineral N application) irrespective of site, ii) SOC and TN are expected to be higher under combined reduced tillage and crop residue retention at all sites; and iii) amounts of less mobile components, P_{CAL} and K_{CAL}, are increased with crop residue retention across all sites.

2. Materials and methods

2.1. Experimental sites

On-farm trials were carried out (Fig. 1) on farmers' fields in Dassari village (10°49´N, 1°04´E) in Atakora Province of the Republic of Benin, and in Dano village (11°10´N, 2°38´W) in the Loba province of Burkina-Faso for five consecutive years (2012–2016). At each location (Fig. 2), two sites were defined based on topographical positions along the slope (footslope and upslope), such that a total of four similar trials were conducted on four different soil types (differed mainly by topography). An average of 3% slope existed between footslope and upslope sites.

Thus, our study consisted of a total of four different sites, where each site shares common weather conditions within the same location but different soil type. The sites were designated as St1 (Dano on Ferric Lixisol at footslope position), St2 (Dano on Eutric Plinthosol at upslope position), St3 (Dassari on Haplic Lixisol at footslope position), and St4 (Dassari on Plinthic Lixisol at upslope position).

2.1.1. Seasonal and spatial variations in temperature and precipitation

The study sites are located in the Sudan-Savanna agro-ecological zone, characterized by a semi-humid climate. The mean rainfall ranges between 900 mm to 1000 mm during May to October, while the mean temperature is 15 °C during the night and 40 °C during the day in the rainy season (Danso et al., 2018a; Kpongor, 2007). The amount of monthly total rainfall during the cotton growing seasons of 2013 and 2015 in Dano was 766 mm and 874 mm, respectively (Fig. 3b). In contrast, Dassari received 777 mm and 973 mm of monthly total rainfall during the cotton growing seasons of 2013 and 2015. Mean monthly cumulative rainfall in Dano and Dassari during the maize growing seasons (2012, 2014 and 2016) were 780 mm and 850 mm, respectively. During the cotton growing seasons at both Dano and Dassari, the average monthly air temperature was 27 °C and 28 °C, respectively (Fig. 3a). Conversely, monthly mean air temperature during the maize growing seasons at both Dano and Dassari was 27 °C. Also, the monthly mean air temperature tended to increase from 2012 to 2016 in Dassari, while in Dano, no such increase was recorded.

2.1.2. Spatial variations in soil properties

According to FAO soil classification system, the major soil types in Dano are Ferric Lixisol (footslope), and Eutric Plinthosol (upslope) with a bedrock type of Andesite; while the soils in Dassari were formed on a parent material of massive Sandstone and classified as Haplic Lixisol (footslope), and Plinthic Lixisol (upslope) (Danso et al., 2018a). These soils differed in many characteristics. Soils in Dano, Ferric Lixisol (FL) and Eutric Plinthosol (EP) had a maximum rooting depth of 75 cm and 65 cm, respectively (Table 1). On the other hand, soils of Dassari, Haplic Lixisol (HL), and Plinthic Lixisol (PL) exhibited a maximum rooting depth of 90 cm and 65 cm, respectively. The total available water capacity (AWC with field capacity at 33 kPa) across the soil profile (up to maximum rooting depth) of HL, EP, PL, and FL were 52.5 mm, 50.6 mm, 42.6 mm, and 29.2 mm, respectively. In addition, these four soil types also varied according to gravel content by mass, exhibiting the following rank: FL (47%) > EP (26%) > PL (24%) > HL (13%) in the topsoil (Table 1).

2.2. Experimental layout and management practices

The experiments started in 2012 at each site, and were conducted for five consecutive growing seasons (2012–2016) under a maize-cotton rotation. A strip-split plot design with four replications was used for statistical analysis. The main plots consisted of two levels of tillage treatment (contour ridge tillage, Ct and reduced tillage, Rt); and the size of each main plot was 30 m long by 10 m wide. Each main plot had sub-plots of 10 m by 5 m, containing random combinations of the two sub-plot treatments. Sub-plot treatments were crop residue management, i.e. with incorporation of crop residues from previous crop (CRi) or without crop residues (CRr), and N fertilizer amount, i.e. no fertilizer (N0) or recommended dose of N fertilizer (Nr) at 45 kg N ha^{-1} for cotton and 60 kg N ha^{-1} for maize. In total, there were 32 plots (8 treatments × 4 replications) at each experimental site (Danso et al., 2018b).

Our study used a short cycle maize variety (*Zea mays* L. cv. Dorke SR) that was generally sown in late June and harvested in mid-October of the same year (every even year, 2012, 2014, and 2016). Cotton (*Gossypium hirsutum* L. cv.FK 97) was sown in mid-June and harvested in mid-October to mid-November of the same year (every odd year, 2013 and 2015) at all sites. Animal drawn moldboard ploughing was used to establish contour ridges in mid-June. Commercial mineral fertilizers, urea (46% N), single superphosphate (12% P_2O_5), and potassium chloride (60% K_2O) were used to provide 60 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} during the maize-growing seasons, and 45 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} during the cotton-

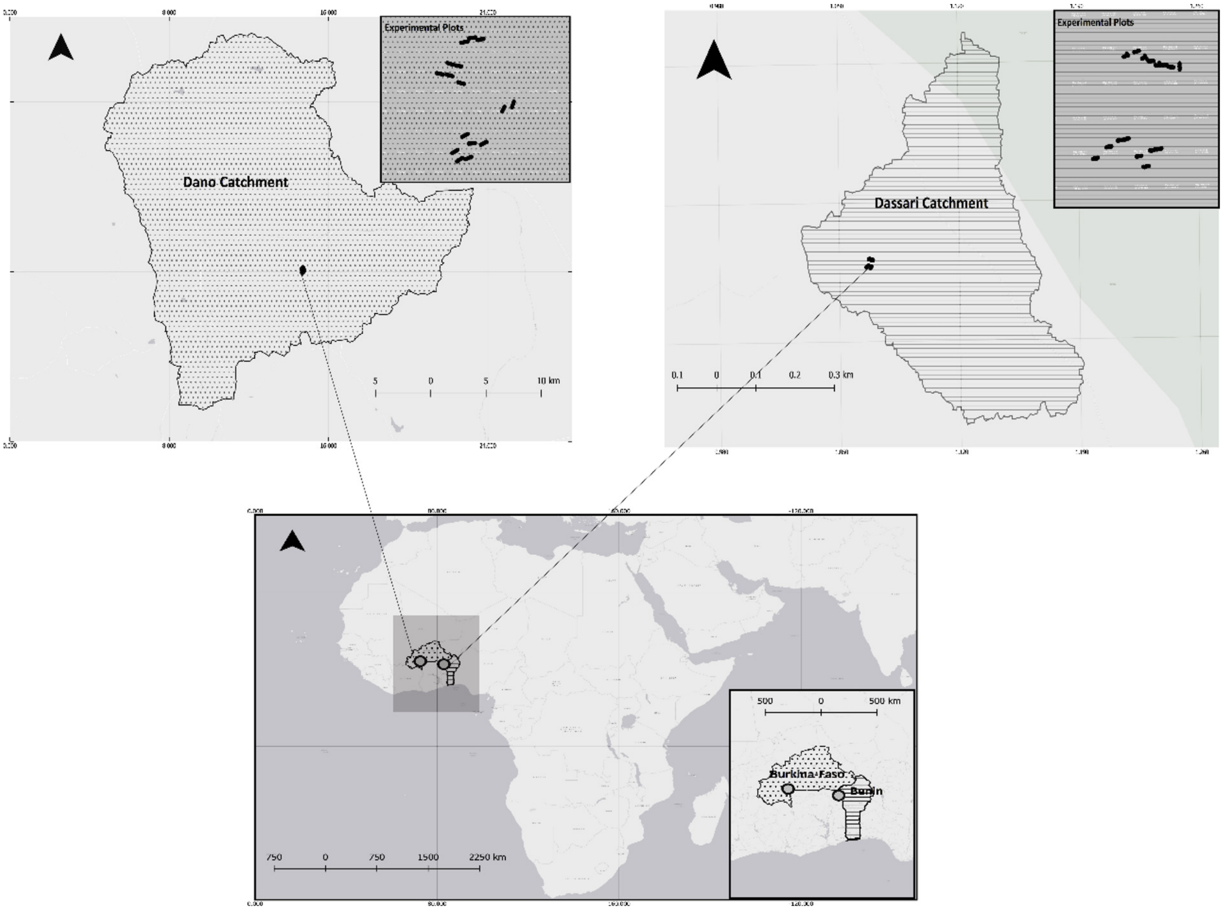

Fig. 1. Locations of study and the corresponding experiment plots.

growing season. All P_2O_5 and K_2O and 50% of N fertilizer was broadcast 25 days after planting and the remaining 50% of N fertilizer was used 45 days after planting. In the control plots, P and K, but no N was applied. At harvest of the previous crop, residues were removed, chopped into pieces and stored until the subsequent growing season. At planting, the previous year's residues were distributed evenly in the sub-plots receiving crop residue retention treatments. Thus, the application rate of residues varied across the tillage and N fertilizer treatments. The C:N ratio of the applied cotton and maize residues were 30 and 70, respectively. Maize and cotton were planted at the recommended density and row spacing (Table 1). Weeds were cleared before implementing tillage operations by applying 2.1 L ha^{-1} glyphosate. Cotton balls were protected from pests by spraying 5–6 times throughout the growing season the pesticide "Super Lambda".

2.3. Soil sampling and analytical methods

To determine soil fertility related properties (pH, OC, TN, P_{CAL}, and K_{CAL}), soils were sampled systematically from five different points using a gouge auger at five different depths, 0–20 cm, 20–40 cm, 40–70 cm, and > 70 cm (depending on the maximum rootable depth) from each sub-plot in August-September, 2016. Collected soil samples were mixed

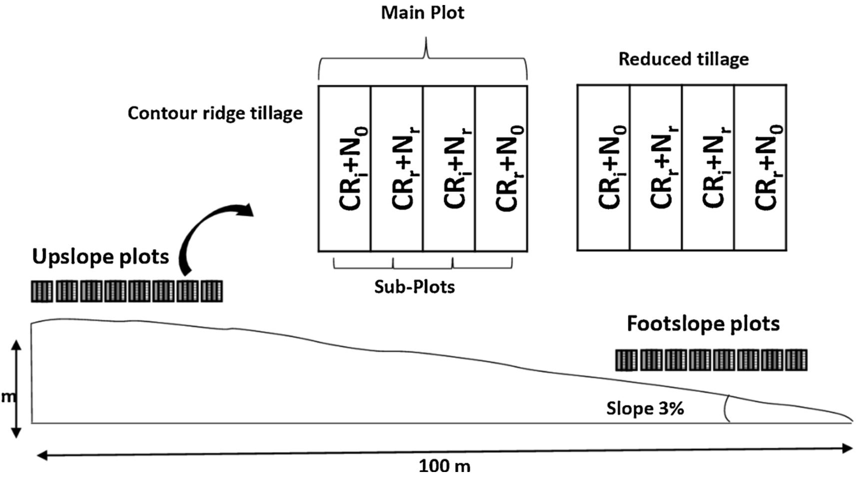

Fig. 2. Experimental design and slope layout (Nr = Recommended rate of nitrogen, N0 = No nitrogen, CRi = residue incorporated, CRr = residue removed).

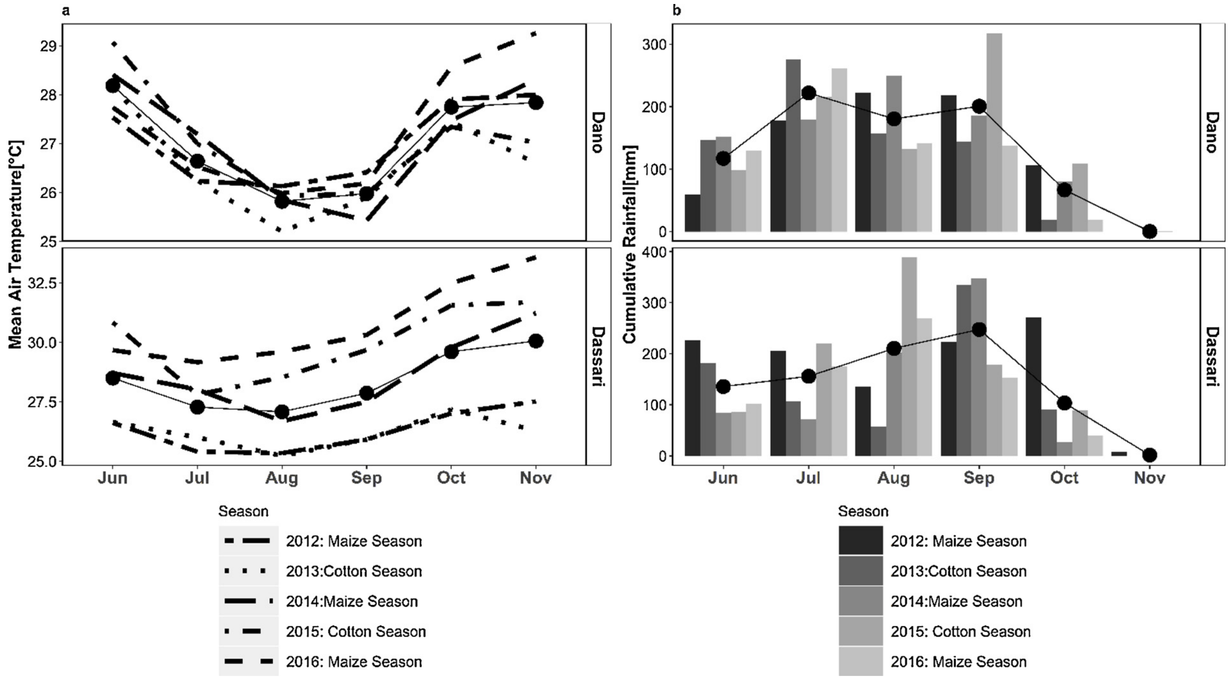

Fig. 3. Climatic conditions during growing seasons of cotton and maize (2012–2016) in experimental sites of Dano and Dassari [a] Mean monthly air temperature (°C), [b] Total monthly rainfall (mm). The black round point indicates the monthly average value over five cropping seasons.

and composited to form a representative sample per sub-plot for each depth. Visible plant residues and other debris were removed from the samples. Soils were then dried at 40 °C, clods were broken by hand, passed through a 2 mm sieve for uniformity, and transferred to the laboratory for chemical analysis.

The residual samples (particle diameter > 2 mm) after sieving were used to measure and calculate soil gravel content following a mass approach suggested by Gardner (1986). SOC and TN was determined using the dry combustion method in a CHN elemental analyser (Fisons NA 2000, Fisons Instruments, Rodano, Milan, Italy), where about 5 mg soils were weighed, settled in silver capsules, combusted in a furnace at a temperature of 1800 °C under a stream of oxygen (Santi et al., 2006). Soil pH was measured using a pH meter after mixing soil with 0.01 M $CaCl_2$ solution in a 1:5 ratio. In order to measure P_{CAL} and K_{CAL}, soils were extracted using calcium acetate lactate (CAL) solution (Schüller, 1969). P_{CAL} was then measured with a photometer, and K_{CAL} determined using atomic absorption spectrophotometry.

2.3.1. Computation of soil nutrient stock

Similarly, soil organic carbon stock/density (SOC_d) was calculated for each layer of the soil, for fine earth particles only, thereby allowing for correction of gravel content. Eq. (3) was followed to calculate soil organic carbon stock (SOC_d, Mg ha^{-1}) using values of % of organic carbon (OC), mass of fine earth materials ($Mass_{fine}$, kg m^{-2}), and % gravel content of the *i* soil layer (cm). Mass of fine earth materials was derived from total soil mass (Eq. 1) and % gravel content as:

$$\text{Masstotal}\ (\text{kg m}^{-2}) = [\text{soil layer thickness (cm)} \times BD_{total} \times 10] \quad (1)$$

Table 1
Major soil characteristics of all four sites in the topsoil (0–20 cm).

Properties	Units (methods)	Location/Topography/Soil types			
		Dano		Dassari	
		Footslope Ferric Lixisol	Upslope Eutric Plinthosol	Footslope Haplic Lixisol	Upslope Plinthic Lixisol
pH	(0.01 M $CaCl_2$)	6.4	6.3	6.6	6.5
Organic C	Mg ha^{-1}	12.5	13.4	16.2	12.3
	(%)	0.5	0.6	0.7	0.5
Total N	Mg ha^{-1}	1.1	1.6	1.9	1.4
	(%)	0.06	0.07	0.07	0.06
CAL P	Mg ha^{-1}	0.03	0.03	0.06	0.06
	(mg kg^{-1})	10	10	20	20
CAL K	Mg ha^{-1}	1.0	1.5	1.8	1.4
	(mg kg^{-1})	60	60	70	60
Sand	%	52.9	32.8	66.4	56.9
Silt	%	43.1	17.1	32.5	40.1
Clay	%	3.0	50.0	1.1	2.0
Texture		Sandy	Sandy clay loam	Sandy Loam	Sandy Loam
Gravel	%	47	26	13	24
Permeability Class		Rapid	Moderately Slow	Moderately Rapid	Moderately Rapid

$$\text{Massfine}\ (\text{kg m}^{-2}) = \frac{(100 - \%\text{gravel content})}{100} \times \text{Mass}_{\text{total}} \quad (2)$$

$$\text{SOCd}_i\ (\text{Mg ha}^{-1}) = \frac{(\text{Mass}_{\text{finei}} \times \%\,\text{OC}_{\text{i}})}{100} \times 10 \quad (3)$$

SOC_d from each soil layer per sub-plot were aggregated to quantify the total SOC_d within the soil profile (up to rooting depth) for each sub-plot.

Similar steps were followed to calculate nitrogen stock (STN_d), available phosphorus stock (SP_d), and available potassium stock (SK_d) by substituting SOC_d value with concentration of nutrients (TN/P_{CAL}/K_{CAL}) in the respective soil layer.

2.4. Statistical analysis

R v 3.5.1 (R Core Team, 2018) in RStudio was used to perform all the statistical analyses. Arithmetic mean, standard error (se), and standard deviation (sd) were calculated independently for all the measured soil attributes using the “summarise” function under the “dplyr” packages (Wickham et al., 2019) and the values were presented as mean and standard error. To analyse the effects of site, tillage, crop residue management, N fertilizer rates and their interactions on measured soil properties, OC, TN, P_{CAL}, K_{CAL}, a mixed linear model for strip-split plot layout was generated according to Gomez et al. (1984) using the “lme” function in the “nlme” package in R (Gałecki and Burzykowski, 2013). Site, tillage, crop residue management, and N fertilizer rate were considered as fixed factors, while the random factors included replication, and replication × tillage interactions. We excluded the effects of crops as the soils were sampled only once after completion of a five continuous annual maize-cotton rotation cycles. Site was a fixed factor in our analysis as the sites represent specific soils among which comparisons were to be made (Piepho et al., 2003). Differences in measured soil attributes among the implemented treatments were examined by Tukey test at $p \le 0.05$ level using the “lsmeans” function (Lenth, 2016). All the figures were produced using the “ggplot2” package (Wickham, 2016).

3. Results

After five years of maize-cotton rotational cropping, all the measured soil attributes (SOC_d, STN_d, SP_d, and SK_d) at 0–20 cm soil depth showed large variation under the influence of different tillage systems, crop residue management measures, and N fertilizer application rates across different experimental sites (Table 3). We conducted an analysis of variance (ANOVA) in order to identify factors significantly affecting the topsoil properties. Topsoil SOC_d significantly varied according to the individual effects of tillage and crop residue, while topsoil STN_d was affected by the single effects of tillage and N fertilizer application. On the other hand, topsoil SP_d and SK_d varied significantly according to only crop residue. Interestingly, we found no treatment effects on topsoil pH. We also observed site-specific effects of the factors (site × factor) on the measured soil traits. A significant effect of site × tillage and site × residue interactions were also observed for topsoil SOC_d, whereas site × tillage and site × N fertilizer interactions were significant for topsoil STN_d. Interestingly, only site × residue interaction effect was recorded for topsoil SP_d and SK_d. No three-way or four-way interactions were observed.

3.1. Changes in topsoil properties

3.1.1. Soil organic carbon stock (SOC_d)

Relative to Rt, Ct increased SOC_d at the surface layer by 8.1% when averaged across sites and treatments (residue and N fertilizer). SOC_d under the Ct system was 31.7% and 15.8% higher than under the Rt system on St2 and St4, respectively, both sites being located on upslope positions (Fig. 4). A significantly higher SOC_d (+28.9%) in the surface soil of St3, which was located footslope, was recorded under the Rt system compared to Ct. Interestingly, no difference in SOC_d between the tillage operations was found on St1 (footslope position). Addition of crop residues to the surface soil significantly increased SOC_d only on sites at the upslope positions, St2 and St4 by 14.1% and 15.8%, respectively (Fig. 5). CRi had no significant beneficial effects on SOC_d at the footslope sites (St1 and St3). CRi led to a 6.8% increase in SOC_d in the surface soil layer when averaged across sites and treatments (tillage and N fertilizer). Our results suggested that SOC_d on sites in the upslope position benefited from CRi and Ct. On the other hand, implementation of Rt together with CRi improved SOC_d in the topsoil layer only on St3 (Table 2).

3.1.2. Soil nitrogen stock (STN_d)

In comparison to Rt, implementation of Ct increased STN_d in the topsoil layer of St2 and St4 by 10.3% and 19.4%, respectively (Fig. 4). Although, there was a small variation in STN_d between Ct and Rt on St1, this difference was not significant ($P > 0.05$). Contrarily, application of Rt instead of Ct increased topsoil STN_d of St3 by 12.7%. Average STN_d in the topsoil layer over all sites was 14% greater under Ct than under Rt (Table 3). After application of the recommended rate of N fertilizer, average STN_d in the topsoil layer increased by 6% (1.6 Mg ha^{-1} vs 1.54 Mg ha^{-1}) compared to the control (Table 3). STN_d increase in the topsoil layer was 7%, 5.8%, and 19.4% with recommended rate of N fertilizer at St2, St3, and St4, respectively (Fig. 6). Top soil STN_d was also significantly affected by soil × tillage × N fertilizer interactions. For example, application of the recommended dose of N fertilizer under the Ct system sharply increased STN_d in the topsoil layer of St2 and St4 (Fig. 7). Rt together with the recommended dose of N fertilizer increased topsoil STN_d on St3. We did not find any difference in topsoil STN_d between tillage and N fertilizer combinations on St1. These results indicated that sites located in upslope positions increased STN_d in the topsoil layer under Ct and judicial application of N fertilizer. Similar to SOC_d, Rt combined with the recommended rate of N fertilizer was beneficial to STN_d only on one of the sites (St3) in footslope position.

3.1.3. Soil phosphorus stock (SP_d)

CRi increased SP_d in the topsoil layer at all sites except St1 (Fig. 5). The order of the topsoil SP_d increase over the sites due to CRi was St1 (+25%) < St2 (+33%) < St3 (+35%) < St4 (+38%). When averaged across sites and treatments, CRi resulted in a 34.8% increase in SP_d in the topsoil layer (Table 3). These results illustrated that CRi improved SP_d in the topsoil layer across all sites.

3.1.4. Soil potassium stock (SK_d)

Due to incorporation of crop residues into the surface soil layer (Table 3), SK_d in the topsoil increased by almost 9.4% when averaged over sites and treatments (tillage and N fertilizer). However, only sites located in upslope positions had significantly higher SK_d with CRi. CRi resulted in an increase of 14.3% and 10.8% in SK_d in the topsoil layer of St2 and St4, respectively (Fig. 5). However, such an effect was not significant when crop residues were applied to sites located at the footslope position. These results indicate that incorporation of crop residues into soils of upslope sites showed marked positive effects on topsoil SK_d, while such effects were smaller and not significant on sites in footslope positions.

3.1.5. Soil pH

The pH of the topsoil layer varied from 6.3 to 6.6. Sites at Dassari had the highest average topsoil pH of 6.6 (St3) and 6.5 (St4), while sites at Dano, St2 and St1 had average topsoil pH of 6.3 and 6.4, respectively.

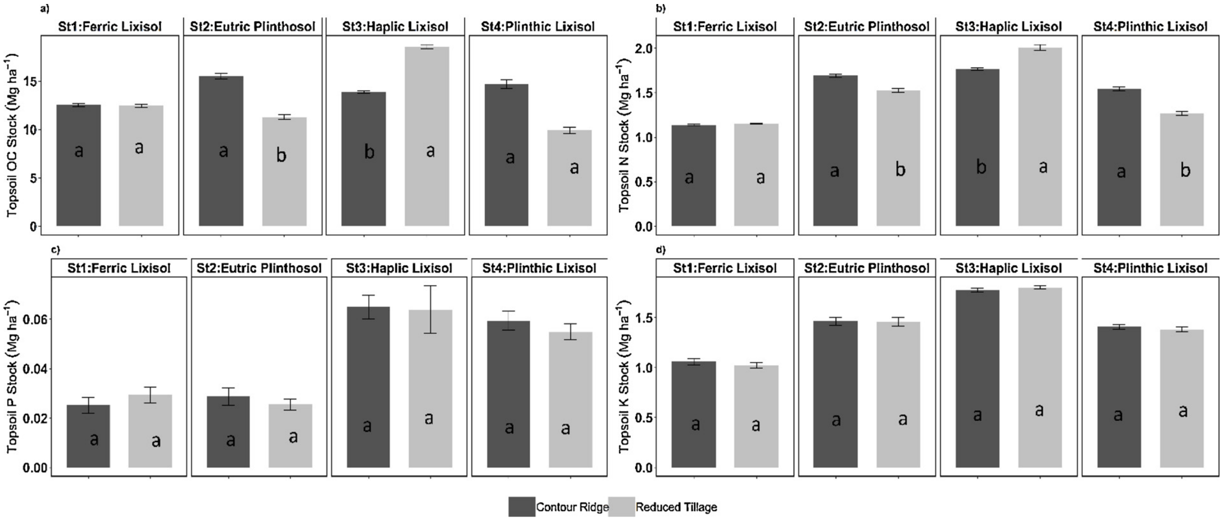

Fig. 4. Topsoil soil organic carbon stock (Mg ha^{-1}) [a], topsoil soil nitrogen stock (Mg ha^{-1}) [b], topsoil soil phosphorus stock (Mg ha^{-1}) [c], and topsoil potassium stock (Mg ha^{-1}) [d] as affected by contour ridge tillage and reduced tillage in four sites. Each bar is a mean of 16 values (1 tillage × 2 crop residue × 2 N fertilizer × 4 replications). Vertical bars indicate mean standard error (±). Bars belonging to same variable within a soil group followed by same letter (s) are not significantly different at P ≤ 0.05 level according to Tukey test.

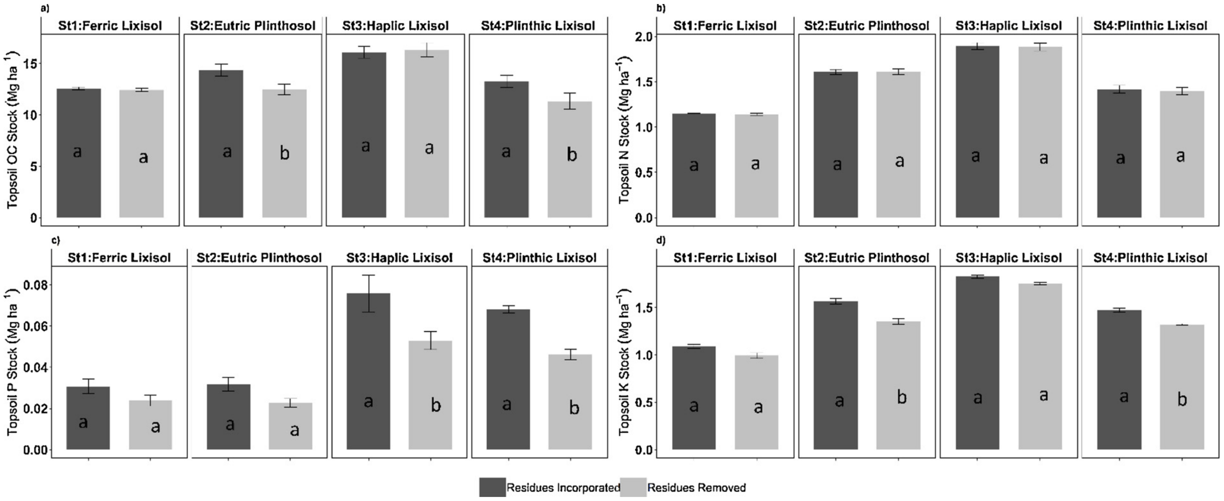

Fig. 5. Topsoil soil organic carbon stock (Mg ha^{-1}) [a], topsoil soil nitrogen stock (Mg ha^{-1}) [b], topsoil soil phosphorus stock (Mg ha^{-1}) [c], and topsoil potassium stock (Mg ha^{-1}) [d] as affected by crop residue retention in four sites. Each bar is a mean of 16 values (1 crop residue × 2 tillage × 2 N fertilizer × 4 replications). Vertical bars indicate mean standard error (±). Bars belonging to same variable within a soil group followed by same letter (s) are not significantly different at P ≤ 0.05 level according to Tukey test.

4. Discussion

his study adds to the understanding of the combined effects of tillage, crop residues, and N fertilizer application on major soil chemical properties under maize-cotton rotations in highly weathered soils of West Africa. The evidence gathered aids in addressing the questions, i) how the observed topsoil attributes (0–20 cm) respond to different management practices and how they vary across locations differing by climatic and soil conditions; and ii) how the combined effects of these management practices contribute to the conservation of soil fertility.

4.1. Effects of tillage operations

or the soils considered in our study, Ct over 5 years improved SOC$_d$ in both the topsoil and over the entire soil profile compared to Rt when averaged across soil types and treatments. This is consistent with the findings from a study conducted in Luvisols with a gentle slope (1–3%) in Southern Mali under semi-arid climate by Traoré et al. (2004) who found a significant positive impact of Ct implementation on crop yield, SOC$_d$, and soil water content. Ct prevents the rainwater from moving footslope which in turn provides the rainwater with more time to infiltrate and increases soil water storage (Traore et al., 2017). Increase in soil water storage can be expected to stimulate crop biomass production and consequently root biomass when water is otherwise limiting (Nunes et al., 2018; Thierfelder et al., 2013; Wolka et al., 2018). Higher above and below-ground biomass is one possible explanation of the greater SOC$_d$ in both topsoil and the entire soil profile (Berhongaray et al., 2019). Additionally, it is well documented that the adoption of Ct could be an effective measure to control the loss of topsoil through erosion (Hatfield et al., 1998; Lal, 1990; Wolka et al., 2018).

In our study, about 14% higher topsoil STN$_d$ under Ct was observed compared to Rt when averaged across soil types and treatments. This is explained by the fact discussed above that Ct increased on average SOC$_d$ and the close relationship between SOC$_d$ and STN$_d$ in all arable soils. According to Dai et al. (2018), implementation of Ct in red clay soils with 5° to 25° slope under subtropical monsoon climatic conditions

Table 2
Crop characteristics and management practices.

Crop characteristics/ Management Practices	Descriptions	
	Maize	Cotton
Variety	Dorke SR	FK 37
Sowing	mid-June	mid-June
Harvesting	mid-October	mid-October - mid-November
Planting density (plants ha^{-1})	62,500 plants ha^{-1}	83,333 plants ha^{-1}
Inter-row spacing (m)	0.8 m	0.8 m
Intra-row spacing (m)	0.4 m	0.3 m
Physiological Maturity (days)	94-108	124-150
N Fertilizer (kg ha^{-1})	60 kg ha^{-1}	45 kg ha^{-1}
P Fertilizer (kg ha^{-1})	60 kg ha^{-1}	60 kg ha^{-1}
K Fertilizer (kg ha^{-1})	60 kg ha^{-1}	60 kg ha^{-1}
Tillage	Contour ridges were developed by using animal drawn moldboard ploughs	
Fertilizer Application	All the P and K and 50 % nitrogen was broadcasted 25 days after planting and the rest 50 % of nitrogen was applied 45 days after planting	
Weeding	2.1liter ha^{-1} glyphosate was applied prior to tillage operations and manual hoe weeding as needed during the growing season	
Pest Management	“Super Lambda” was sprayed 5-6 times to protect the cotton bolls	

resulted in approximately 97% reduction in total N loss. Generally, the underlying mechanism is that Ct across the slope increases surface roughness and acts as a barrier that reduces run-off velocity, traps sediments, and increases soil water infiltration, thereby controlling sediment loss during the period of intensive rainfall (Lal, 1990; Liu and Huang, 2013; Liu et al., 2014, 2011; Quinton and Catt, 2006).

Moreover, the present study has shown significant interactions between tillage and site with respect to the effect on SOC_d and STN_d. Ct significantly improved SOC_d and STN_d on two out of four sites, St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari). At the same time, Rt contributed to significantly higher SOC_d and STN_d on St3 (Haplic Lixisol, footslope in Dassari) compared to Ct. As mentioned earlier, soil erosion risk was probably lower on the footslope site St3, and the site might even benefit from eroded sediments from upslope. On the same experimental site (St3), Danso et al. (2018b) stated that the average biomass production was greatest under Rt compared to Ct. Another possible contribution of Rt to higher SOC_d compared to Ct could be related to reduced disruption of soil aggregates. Minimum soil mechanical disturbance due to Rt likely results in restricted SOC oxidation, which is the primary source of SOC loss from tropical soils (Nandan et al., 2019). Therefore, increased biomass production as well as improved soil aggregate stability resulting from minimum soil disturbance could have contributed to increased SOC input under the Rt system in St3. Implementation of Rt also markedly improved STN_d only on St3, which is consistent with the higher SOC_d that occurred only on this site.

4.2. *Effects of crop residue retention*

Consistent with our expectations and other studies (Ghimire et al., 2017; Han et al., 2018; Xu et al., 2019a, b), greater SOC_d in the topsoil was detected with crop residues returned to the field when averaged over all sites (Table 3). Application of crop residue as a surface mulch is

Table 3
Mean effects (single main effects) and summary of ANOVA output of generalized linear mixed model for the effect of sites, tillage, crop residue, and N fertilizer on soil nutrient stocks on topsoil layer (0–20 cm).

Sites/Factors/Levels	SOC_d (Mg ha^{-1})	STN_d (Mg ha^{-1})	SP_d (Mg ha^{-1})	SK_d (Mg ha^{-1})	pH
Sites					
St1: Ferric Lixisol (FL)	12.5 ± 0.1 c	1.1 ± 0.01 d	0.03 ± 3 b	1.0 ± 0.01 d	6.4 ± 0.03 b
St2: Eutric Plinthosol (EP)	13.4 ± 0.1 b	1.6 ± 0.01 b	0.03 ± 3 b	1.5 ± 0.01 b	6.3 ± 0.03 b
St3: Haplic Lixisol (HL)	16.2 ± 0.1 a	1.9 ± 0.01 a	0.06 ± 3 a	1.8 ± 0.01 a	6.6 ± 0.03 a
St4: Plinthic Lixisol (PL)	12.3 ± 0.1 c	1.4 ± 0.01 c	0.06 ± 3 a	1.4 ± 0.01 c	6.5 ± 0.03 a
Tillage					
Reduced Tillage (Rt)	13.1 ± 0.1 b	1.5 ± 0.09 b	0.04 ± 3 a	1.4 ± 0.01 a	6.4 ± 0.02 a
Contour Ridges (Ct)	14.2 ± 0.1 a	1.5 ± 0.07 a	0.04 ± 3 a	1.4 ± 0.01 a	6.5 ± 0.02 a
Crop Residue					
Residues Removed (CRi)	13.2 ± 0.1 b	1.5 ± 0.08 a	0.04 ± 3 b	1.4 ± 0.01 b	6.4 ± 0.02 a
Residues Incorporated (CRr)	14.1 ± 0.1 a	1.5 ± 0.08 a	0.05 ± 3 a	1.5 ± 0.01 a	6.4 ± 0.02 a
N Fertilizer					
Control (N0)	13.6 ± 0.1 a	1.5 ± 0.08 b	0.04 ± 3 a	1.4 ± 0.01 a	6.5 ± 0.02 a
Recommended N (Nr)	13.6 ± 0.1 a	1.6 ± 0.08 a	0.04 ± 3 a	1.4 ± 0.01 a	6.4 ± 0.02 a
Analysis of Variance					
Site (St)	**< .0001** ***	**< .0001** ***	**< .0001** ***	**< .0001** ***	**< .0001** ***
Tillage (T)	**< .0001** ***	**< .0001** ***	ns	ns	ns
Residue (R)	**< .0001** ***	ns	**< .0001** ***	**< .0001** ***	ns
Nitrogen (N)	ns	**< .0001** ***	ns	ns	ns
St:T	**< .0001** ***	**< .0001** ***	ns	ns	ns
St:R	**< .0001** ***	ns	**0.0351** *	**0.0249** *	ns
T:R	ns	ns	ns	ns	ns
St:N	ns	**< .0001** ***	ns	ns	ns
T:N	ns	**0.0022** **	ns	ns	ns
R:N	ns	ns	ns	ns	ns
St:T:R	ns	ns	ns	ns	ns
St:T:N	ns	**0.0003** ***	ns	ns	ns
St:R:N	ns	ns	ns	ns	ns
T:R:N	ns	ns	ns	ns	ns
St:T:R:N	ns	ns	ns	ns	ns

The values are presented as lsmean ± standard error. For each main treatment effect, values within a column followed by same letters are not significantly different at $P \leq 0.05$. The amount of nitrogen fertilizer for cotton was 45 kg ha^{-1} and for maize was 60 kg ha^{-1}.
*, **, and *** denote the significance of the factor at $P \leq 0.05$, 0.01, and 0.001, respectively; ns, not significant at $P \leq 0.05$.
SOC_d = soil organic carbon stock, STN_d = soil nitrogen stock, SP_d = soil phosphorus stock, SK_d = soil potassium stock.

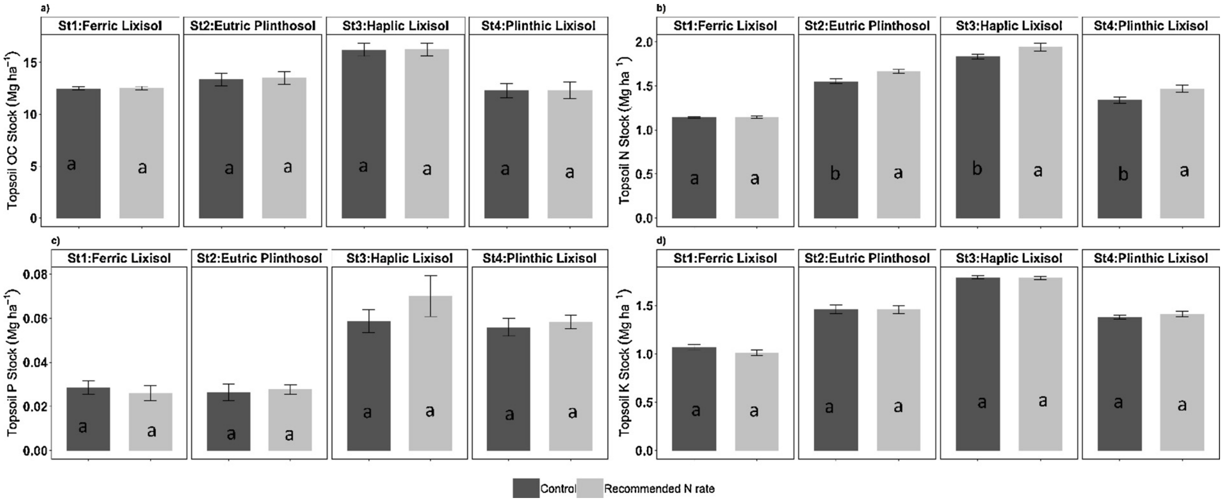

Fig. 6. Topsoil soil organic carbon stock (Mg ha^{-1}) [a], topsoil soil nitrogen stock (Mg ha^{-1}) [b], topsoil soil phosphorus stock (Mg ha^{-1}) [c], and topsoil potassium stock (Mg ha^{-1}) [d] as affected by N fertilizer applications in four sites. Each bar is a mean of 16 values (2 crop residue × 2 tillage × 1 N fertilizer × 4 replications). Vertical bars indicate mean standard error (±). Bars belonging to same variable within a soil group followed by same letter (s) are not significantly different at P ≤ 0.05 level according to Tukey test.

one of the most prominent measures to rebuild SOC stock in dryland soils of West Africa, although our results showed that this effect was site-dependent.

The decomposition of added high quality cotton residue (C:N ratio 30) might have promoted microbial growth (Srinivasan et al., 2012; West and Post, 2002), whereas returning low quality maize residues (C:N ratio 70) might have added more recalcitrant SOC. This is consistent with the findings from Ghosh et al. (2016) who observed increased stable SOC pool by adding cereal residues with high content of less decomposable lignin. However, our results contradict findings by Wang et al. (2015) who reported rapid decomposition rate of maize residues that had smaller C:N ratio and lower lignin content.

In agreement with previous studies, SP_d was also improved with CRi in our experiments. On a Vertisol in India, application of wheat residue markedly reduced soil P adsorption and increased both bicarbonate-extractable inorganic and organic P (Reddy et al., 2014). Moreover, soil phosphatase is the most common enzyme in soil that accelerates the transformation of organic P into the available form (Nannipieri et al., 2011). CRi can increase phosphatase activity in the topsoil layer (Akhtar et al., 2018; Yang et al., 2016) causing greater soil P availability. Another probable explanation could be that the rapid decomposition of previously added cotton residues released a considerable amount of organic acids, thereby solubilizing inorganic P (Laboski and Lamb, 2003). Oxidation of added residues releases some organic ligands that physically block the adsorption sites by forming complex compounds (Agbenin and Igbokwe, 2006). CRi also increased SK_d in the topsoil, although an interaction with the sites was observed. As demonstrated by Wei et al. (2015) and Yang et al. (2018), soil available K

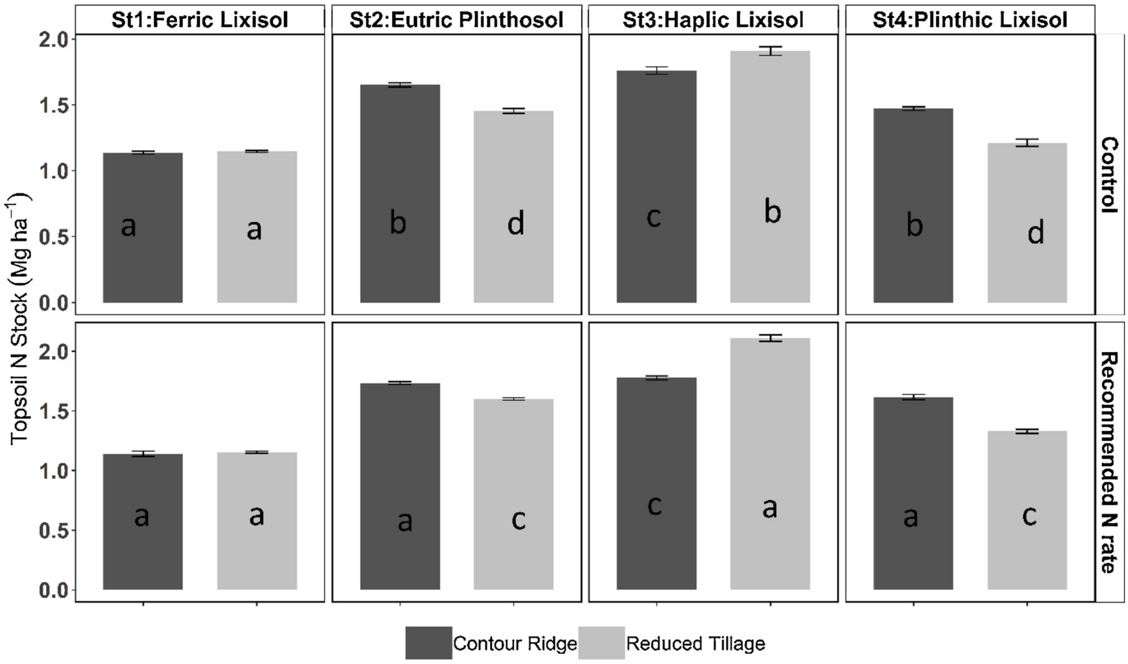

Fig. 7. Topsoil soil nitrogen stock (Mg ha^{-1}) as affected by N fertilizer (control and recommended rate) and tillage interactions (N × T) in four sites. Each bar is a mean of 8 values (2 crop residue × 1 tillage × 1 N fertilizer × 4 replications). Vertical bars indicate mean standard error (±). Bars within a soil group followed by same letter (s) are not significantly different at P ≤ 0.05 level according to Tukey test.

in the topsoil increases as a result of CRi. Findings from China by Zhao et al. (2014) demonstrated that CRi could be an ideal measure for increasing the level of both soil available and slowly available K.

Our study also demonstrated a significant interaction of sites and crop residue management on soil chemical properties. It appeared that improved SOC_d, SK_d, and SP_d were recorded under CRi in all sites (soil types) except St1 (Ferric Lixisol, footslope in Dano). Addition of crop residues to the soil is an effective measure to limit soil erosion, sediment concentration in the runoff, and runoff discharge (Abrantes et al., 2018; Keesstra et al., 2019). During the period of intensive rainfall, crop residues act as a barrier that protect soil particles from detachment by raindrop impact and loss by water erosion (Brant et al., 2017; Edwards et al., 2000). Accordingly, we assume that crop residue retention exerts strong control over surface run-off that could result in improved soil nutrient stock at St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari), as these sites are located in upslope positions and are more prone to erosion. In addition, increased physical protection of soil organic matter through improved soil aggregate stability triggered by CRi could have increased SOC_d on St2, St3 and St4. In contrast to St3 (Haplic Lixisol, footslope in Dassari), St1 (the footslope site in Dano) had much higher gravel content in the topsoil and contributed to much lower crop biomass production. Scant soil cover and rapid oxidation of existing soil organic matter as well as lower quantity of fine earth to stabilize SOC due to high gravel content could be a possible explanation of poor SOC_d with CRi on St1. Lower crop residue production in St1 compared to St2 and St4 resulted in lower release of mobile P and K and therefore CRi did not improve SK_d and SP_d compared to CRr on this site. In addition, P and K could have been subjected to more rapid leaching losses on St1 due to higher hydraulic conductivity with greater gravel content (47%).

4.3. Effects of N fertilizer application

Average total aboveground biomass with the recommended rate of N fertilizer was approximately 27% higher compared to no N fertilizer application as evidenced from Danso et al. (2018a). Improved crop biomass production contributes to increased organic matter input to the soils by aboveground litter and root exudates. Steady decomposition of large amounts of maize litter with high C:N ratios causes immobilization of mineral N added through synthetic fertilizer (Chen et al., 2014; Gentile et al., 2009; Kaleeem Abbasi et al., 2015). Few studies confirmed that N fertilizer application stabilizes soil organic matter, preserves native and stable organic matter, and immobilizes N, which in turn increase soil TN content (Hagedorn et al., 2003; Ren et al., 2014). Collectively, these assumptions can explain why, averaged over all sites, higher STN_d was recorded with the application of recommended rates of mineral N fertilizer. However, our study revealed a significant interaction of mineral N fertilizer with site and tillage on STN_d. Ct with N fertilizer application had significant effects on STN_d in St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari) while higher STN_d was recorded under Rt combined with N fertilizer application in St3 (Haplic Lixisol, footslope in Dassari). As shown in before implementation of Ct might have acted as a barrier to surface runoff in upslope soils, reducing soil erosion and mitigating mineral N loss added as synthetic fertilizer. However, on footslope sites and in particular on St3, N fertilizer application combined with Rt was related to increased residue production, higher SOC_d and consequently higher N immobilization of the added N fertilizer.

The lack of significant increase in SOC_d under N fertilizer application in this study is in agreement with many other studies (Chen et al., 2014; Mahal et al., 2019; Poffenbarger et al., 2017). This might be due to the fact that inorganic N inputs can accelerate soil organic matter decomposition by increasing soil microbial biomass and enzymatic activities. Further, no significant changes in SP_d and SK_d content were observed with the application of N fertilizer. Addition of N fertilizer stimulates crop growth, increases biotic P and K demand, and concurrently promotes P and K uptake by the crops which decreases SP_d and SK_d (Apthorp et al., 1987; Káš et al., 2016; Yang et al., 2015).

Collectively, with respect to our hypothesis that implementation of Rt along with CRi increases SOC_d and STN_d across sites, we found only partial support. Rt combined with CRi was effectively increasing SOC_d and STN_d only on one out of four sites (St3, Haplic Lixisol, footslope in Dassari) while Ct along with CRi was beneficial for conservation of SOC_d and STN_d on St2 (Eutric Plinthosol, upslope in Dano) and St4 (Plinthic Lixisol, upslope in Dassari). Regarding the second hypothesis that CRi increases SP_d and SK_d across sites, we found that SP_d and SK_d were higher with CRi on all sites except St1 (Ferric Lixisol, footslope in Dano). However, soil pH was unaffected by the implemented management practices. Overall, the findings of our study suggest the potential of Ct along with CRi in building-up of soil nutrient stocks in upslope soils (St2 and St4), while Rt combined with CRi could be more effective on footslope soils like St3

5. Conclusions

Our study helps to understand alternative management effects on soil fertility and crop production in different soils of West Africa, and may be used in the development of site-specific agronomic practices aiming to reduce negative impacts of soil degradation on soil properties and agronomic productivity. Our experiment demonstrated that in a gently undulated region subject to soil degradation through runoff and erosion, implementation of contour ridge tillage along with crop residue retention in upslope areas maintained soil fertility and sustained crop productivity. On the other hand, in footslope areas, adoption of reduced tillage with crop residue retention could be more beneficial. We emphasized that water retention capacity of the soils, which strongly affects water supply to the crops, is one of the most prominent factors influencing the conservation of SOC_d, STN_d, and SK_d across sites. We recommend additional simulation-based studies in order to predict the long-term effect of the management practices tested in this paper as well as the effect of future climate change.

Declaration of Competing Interest

No conflict of Interest

Acknowledgements

The authors thank all the people who helped to carry out the field work and providing logistical support. This research was funded by the German Federal Ministry of Education and Research (BMBF) within the WASCAL program (Funding number FKZ 01LG1202A), the Eiselen Foundation Fiat Panis (Ulm), Stiftung Fiat Panis, and Center for Development Research (ZEF).

References

Abrantes, J.R.C.B., Prats, S.A., Keizer, J.J., de Lima, J.L.M.P., 2018. Effectiveness of the application of rice straw mulching strips in reducing runoff and soil loss: laboratory soil flume experiments under simulated rainfall. Soil Tillage Res. 180, 238–249. https://doi.org/10.1016/J.STILL.2018.03.015.

Agbenin, J.O., Igbokwe, S.O., 2006. Effect of soil–dung manure incubation on the solubility and retention of applied phosphate by a weathered tropical semi-arid soil. Geoderma 133, 191–203. https://doi.org/10.1016/J.GEODERMA.2005.07.006.

Akhtar, K., Wang, W., Ren, G., Khan, A., Feng, Y., Yang, G., 2018. Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong. China. Soil Tillage Res. 182, 94–102. https://doi.org/10.1016/J.STILL.2018.05.007.

Alam, M.K., Bell, R.W., Haque, M.E., Kader, M.A., 2018. Minimal soil disturbance and increased residue retention increase soil carbon in rice-based cropping systems on the Eastern Gangetic Plain. Soil Tillage Res. 183, 28–41. https://doi.org/10.1016/J.STILL.2018.05.009.

Apthorp, J.N., Hedley, M.J., Tillman, R.W., 1987. The effects of nitrogen fertilizer form on the plant availability of phosphate from soil, phosphate rock and mono-calcium phosphate. Fertil. Res. 12, 269–283. https://doi.org/10.1007/BF01315111.

Araya, T., Cornelis, W.M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., Deckers, J., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. Soil Use Manag. 27https://doi.org/10.1111/j.1475-2743.2011.00347.x. no-no.

Brant, V., Kroulík, M., Pivec, J., Zábranský, P., Hakl, J., Holec, J., Kvíz, Z., Procházka, l., 2017. Splash erosion in maize crops under conservation management in combination with shallow strip-tillage before sowing. Soil Water Res. 12, 106–116. https://doi.org/10.17221/147/2015-SWR.

Chen, B., Liu, E., Tian, Q., Yan, C., Zhang, Y., 2014. Soil nitrogen dynamics and crop residues. A review. Agron. Sustain. Dev. 34, 429–442 https://doi.org/10.1007/s13593-014-0207-8ï.

Cong, P., Yin, G., Gu, J., 2016. Effects of stubble and mulching on soil erosion by wind in semi-arid China. Sci. Rep. 6, 29966. https://doi.org/10.1038/srep29966.

Dai, C., Liu, Y., Wang, T., Li, Z., Zhou, Y., 2018. Exploring optimal measures to reduce soil erosion and nutrient losses in southern China. Agric. Water Manage. 210, 41–48. https://doi.org/10.1016/J.AGWAT.2018.07.032.

Danso, I., Gaiser, T., Webber, H., Naab, J., Ewert, F., 2018a. Response of Maize to Different Nitrogen Application Rates and Tillage Practices Under Two Slope Positions in the Face of Current Climate Variability in the Sudan Savanna of West Africa. Springer, Singapore, pp. 41–58. https://doi.org/10.1007/978-981-10-4796-1_3.

Danso, I., Webber, H., Bourgault, M., Ewert, F., Naab, J.B., Gaiser, T., 2018b. Crop management adaptations to improve and stabilize crop yields under low-yielding conditions in the Sudan Savanna of West Africa. Eur. J. Agron. 101, 1–9. https://doi.org/10.1016/J.EJA.2018.08.001.

Desrochers, J., Brye, K.R., Gbur, E., Mason, R.E., 2019. Infiltration as affected by long-term residue and water management on a loess-derived soil in eastern Arkansas, USA. Geoderma Reg. 16, e00203. https://doi.org/10.1016/J.GEODRS.2019.E00203.

Dossou-Yovo, E.R., Ampofo, E., Igue, A.M., Sintondji, L.O., Agbossou, E.K., 2016. Tillage, Rice Straw Mulch and Nitrogen Fertilization Effects on Upland Rice Yield in Northern Benin 6, 107–117.

Edwards, L.M., Volk, A., Burney, J.R., 2000. Mulching potatoes: aspects of mulch management systems and soil erosion. Am. J. Potato Res. 77, 225–232. https://doi.org/10.1007/BF02855790.

Gałecki, A., Burzykowski, T., 2013. Linear Mixed-Effects Models Using R. Springer, Verlag New York. https://doi.org/10.1007/978-1-4614-3900-4_1.

Gardner, W.H., 1986. Water Content, in: Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 493–544. https://doi.org/10.2136/sssabookser5.1.2 ed.c21.

Gathagu, J.N., ang, a., Mourad, K.A., Sang, J., 2018. Effectiveness of Contour Farming and Filter Strips on Ecosystem Services. Water (Switzerland) 10. https://doi.org/10.3390/w10101312.

Gentile, R., Vanlauwe, B., van Kessel, C., Six, J., 2009. Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. Agric. Ecosyst. Environ. 131, 308–314. https://doi.org/10.1016/J.AGEE.2009.02.003.

Ghimire, R., Lamichhane, S., Acharya, B.S., Bista, P., Sainju, U.M., 2017. ScienceDirect Tillage, crop residue, and nutrient management effects on soil organic carbon in rice-based cropping systems: a review. J. Integr. Agric. 16, 1–15. https://doi.org/10.1016/S2095-3119(16)61337-0.

Ghosh, B.N., Dogra, P., Sharma, N.K., Bhattacharyya, R., Mishra, P.K., 2015. Conservation agriculture impact for soil conservation in maize–wheat cropping system in the Indian sub-Himalayas. Int. Soil Water Conserv. Res. 3, 112–118. https://doi.org/10.1016/J.ISWCR.2015.05.001.

Ghosh, P.K., Hazra, K.K., Venkatesh, M.S., Singh, K.K., Kumar, N., Mathur, R.S., 2016. Potential of crop residue and fertilizer on enrichment of carbon pools in upland soils of Subtropical India. Agric. Res. 5, 261–268. https://doi.org/10.1007/s40003-016-0215-9.

Gomez, K.A., Gomez, A.A., Gomez, K.A., 1984. Statistical Procedures for Agricultural Research. Wiley.

Hagedorn, F., Spinnler, D., Siegwolf, R., 2003. Increased N deposition retards mineralization of old soil organic matter. Soil Biol. Biochem. 35, 1683–1692. https://doi.org/10.1016/J.SOILBIO.2003.08.015.

Han, X., Xu, C., Dungait, J.A.J., Bol, R., Wang, X., Wu, W., Meng, F., 2018. Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: a system analysis. Biogeosciences 15, 1933–1946. https://doi.org/10.5194/bg-15-1933-2018.

Hatfield, J.L., Allmaras, R.R., Rehm, G.W., Lowery, B., 1998. Ridge tillage for corn and soybean production: environmental quality impacts. Soil Tillage Res. 48, 145–154. https://doi.org/10.1016/S0167-1987(98)00141-X.

Huang, G.B., Luo, Z.Z., Li, L.L., Zhang, R.Z., Li, G.D., Cai, L.Q., Xie, J.H., 2012. Effects of stubble management on soil fertility and crop yield of rainfed area in Western Loess Plateau, China. Appl. Environ. Soil Sci. 1–9. https://doi.org/10.1155/2012/256312.

Jan, A., Hussain, N., Ostergaard, L., 2016. Spring wheat response to nitrogen, tillage and cropping system under rainfed condition. Cogent Biol. 2, 1167653. https://doi.org/10.1080/23312025.2016.1167653.

Kaleeem Abbasi, M., Mahmood Tahir, M., Sabir, N., Khurshid, M., 2015. Impact of the addition of different plant residues on nitrogen mineralization–immobilization turnover and carbon content of a soil incubated under laboratory conditions. Solid Earth 6, 197–205. https://doi.org/10.5194/se-6-197-2015.

Karuma, A., Mtakwa, P., Amuri, N., Gachene, C.K., Gicheru, P., 2014. Tillage effects on selected soil physical properties in a maize-bean intercropping system in Mwala District, Kenya. Int. Sch. Res. Not., 497205. https://doi.org/10.1155/2014/497205.

Káš, M., Mühlbachová, G., Kusá, H., Pechová, M., 2016. Soil phosphorus and potassium availability in long-term field experiments with organic and mineral fertilization. Plant Soil Environ. 62, 558–565. https://doi.org/10.17221/534/2016-PSE.

Keesstra, S.D., Rodrigo-Comino, J., Novara, A., Giménez-Morera, A., Pulido, M., Di Prima, S., Cerdà, A., 2019. Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. CATENA 174, 95–103. https://doi.org/10.1016/J.CATENA.2018.11.007.

Kihara, J., Bationo, A., Mugendi, D.N., Martius, C., Vlek, P.L.G., 2011. Conservation Tillage, Local Organic Resources, and Nitrogen Fertilizer Combinations Affect Maize Productivity, Soil Structure and Nutrient Balances in Semi-arid Kenya, in: Innovations As Key to the Green Revolution in Africa. Springer, Netherlands, Dordrecht, pp. 155–167. https://doi.org/10.1007/978-90-481-2543-2_14.

Kpongor, D.S., 2007. Spatially Explicit Modeling of Sorghum (Sorghum Bicolor (L.) Moench) Production on Complex Terrain of a Semi-arid Region in Ghana Using APSIM. University of Bonn, Germany.

Laboski, C.A.M., Lamb, J.A., 2003. Changes in soil test phosphorus concentration after application of manure or fertilizer. Soil Sci. Soc. Am. J. 67, 544. https://doi.org/10.2136/sssaj2003.5440.

Lal, R., 1990. Ridge-tillage. Soil Tillage Res. 18, 107–111. https://doi.org/10.1016/0167-1987(90)90053-G.

Lenth, R.V., 2016. Least-squares means: the r package lsmeans. J. Stat. Softw. 69, 1–33. https://doi.org/10.18637/jss.v069.i01.

Liu, H., Huang, Q., 2013. Adoption and continued use of contour cultivation in the highlands of southwest China. Ecol. Econ. 91, 28–37. https://doi.org/10.1016/J.ECOLECON.2013.03.015.

Liu, Q.J., Zhang, H.Y., An, J., Wu, Y.Z., 2014. Soil erosion processes on row sideslopes within contour ridging systems. CATENA 115, 11–18. https://doi.org/10.1016/J.CATENA.2013.11.013.

Liu, X., Zhang, S., Zhang, X., Ding, G., Cruse, R.M., 2011. Soil erosion control practices in Northeast China: a mini-review. Soil Tillage Res. 117, 44–48. https://doi.org/10.1016/J.STILL.2011.08.005.

Mahal, N.K., Osterholz, W.R., Miguez, F.E., Poffenbarger, H.J., Sawyer, J.E., Olk, D.C., Archontoulis, S.V., Castellano, M.J., 2019. Nitrogen fertilizer suppresses mineralization of soil organic matter in maize agroecosystems. Front. Ecol. Evol. 7, 59. https://doi.org/10.3389/fevo.2019.00059.

Martinsen, V., Munera-Echeverri, J.L., Obia, A., Cornelissen, G., Mulder, J., 2019. Significant build-up of soil organic carbon under climate-smart conservation farming in Sub-Saharan Acrisols. Sci. Total Environ. 660, 97–104. https://doi.org/10.1016/J.SCITOTENV.2018.12.452.

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017. Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. Soil Tillage Res. 168, 125–132. https://doi.org/10.1016/J.STILL.2016.12.007.

Mohamoud, Y.M., 2012. Effect of contour ridging on runoff and soil loss. Afr. J. Agric. Res. 7, 6115–6124. https://doi.org/10.5897/AJAR11.2307.

Naab, J.B., Mahama, G.Y., Yahaya, I., Prasad, P.V.V., 2017. Conservation agriculture improves soil quality, crop yield, and incomes of smallholder farmers in North Western Ghana. Front. Plant Sci. 8, 996. https://doi.org/10.3389/fpls.2017.00996.

Nandan, R., Singh, V., Singh, S.S., Kumar, V., Hazra, K.K., Nath, C.P., Poonia, S., Malik, R.K., Bhattacharyya, R., McDonald, A., 2019. Impact of conservation tillage in rice–based cropping systems on soil aggregation, carbon pools and nutrients. Geoderma 340, 104–114. https://doi.org/10.1016/J.GEODERMA.2019.01.001.

Nannipieri, P., Giagnoni, L., Landi, L., Renella, G., 2011. Role of phosphatase enzymes in soil. In: Bünemann, E., Oberson, A., Frossard, E. (Eds.), Eds.), Phosphorus in Action. Springer, Berlin, Heidelberg, pp. 215–243. https://doi.org/10.1007/978-3-642-15271-9_9.

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J., Ryan, M., 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328, 30–43. https://doi.org/10.1016/J.GEODERMA.2018.04.031.

Nyamadzawo, G., Wuta, M., Nyamangara, J., Gumbo, D., 2013. Opportunities for optimization of in-field water harvesting to cope with changing climate in semi-arid smallholder farming areas of Zimbabwe. Springerplus 2, 100. https://doi.org/10.1186/2193-1801-2-100.

Okeyo, J.M., Norton, J., Koala, S., Waswa, B., Kihara, J., Bationo, A., 2016. Impact of reduced tillage and crop residue management on soil properties and crop yields in a long-term trial in western Kenya. Arid. Soil Res. Rehabil. 54, 719. https://doi.org/10.1071/SR15074.

Piepho, H.P., Buchse, A., Emrich, K., 2003. A hitchhiker's guide to mixed models for randomized experiments. J. Agron. Crop Sci. 189, 310–322. https://doi.org/10.1046/j.1439-037X.2003.00049.x.

Poffenbarger, H.J., Barker, D.W., Helmers, M.J., Miguez, F.E., Olk, D.C., Sawyer, J.E., Six, J., Castellano, M.J., 2017. Maximum soil organic carbon storage in Midwest U.S. Cropping systems when crops are optimally nitrogen-fertilized. PLoS One 12, e0172293. https://doi.org/10.1371/journal.pone.0172293.

Quinton, J.N., Catt, J.A., 2006. The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn Erosion reference Experiment on sandy soil at Woburn. Engl. Soil Use Manage. 20, 343–349. https://doi.org/10.1111/j.1475-2743.2004.tb00379.x.

R Development Core Team, 2018. R: a Language and Environment for Statistical Computing. https://doi.org/ISBN: 3-900051-07-0. .

Reddy, D.D., Kushwaha, S., Srivastava, S., Khamparia, R.S., 2014. Long-term wheat residue management and supplementary nutrient input effects on phosphorus fractions and adsorption behavior in a vertisol. Commun. Soil Sci. Plant Anal. 45, 541–554. https://doi.org/10.1080/00103624.2013.867043.

Ren, T., Wang, J., Chen, Q., Zhang, F., Lu, S., 2014. The effects of manure and nitrogen fertilizer applications on soil organic carbon and nitrogen in a high-input cropping system. PLoS One 9, e97732. https://doi.org/10.1371/journal.pone.0097732.

Santi, C., Certini, G., D'Acqui, L.P., 2006. Direct determination of organic carbon by dry combustion in soils with carbonates. Commun. Soil Sci. Plant Anal. 37, 155–162.

https://doi.org/10.1080/00103620500403531.

Schüller, H., 1969. Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. Zeitschrift für Pflanzenernährung und Bodenkd. 123, 48–63. https://doi.org/10.1002/jpln.19691230106.

Singh, G., Bhattacharyya, R., Das, T.K., Sharma, A.R., Ghosh, A., Das, S., Jha, P., 2018. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. Soil Tillage Res. 184, 291–300. https://doi.org/10.1016/J.STILL.2018.08.006.

Srinivasan, V., Maheswarappa, H.P., Lal, R., 2012. Long term effects of topsoil depth and amendments on particulate and non particulate carbon fractions in a Miamian soil of Central Ohio. Soil Tillage Res. 121, 10–17. https://doi.org/10.1016/J.STILL.2012.01.014.

Swanepoel, C.M., Rötter, R.P., van der Laan, M., Annandale, J.G., Beukes, D.J., du Preez, C.C., Swanepoel, L.H., van der Merwe, A., Hoffmann, M.P., 2018. The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. Soil Tillage Res. 183, 72–82. https://doi.org/10.1016/J.STILL.2018.05.016.

TerAvest, D., Carpenter-Boggs, L., Thierfelder, C., Reganold, J.P., 2015. Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. Agric. Ecosyst. Environ. 212, 285–296. https://doi.org/10.1016/J.AGEE.2015.07.011.

Tolessa, D., Du Preez, C.C., Ceronio, G.M., 2014. Effect of tillage system and nitrogen fertilization on the pH, extractable phosphorus and exchangeable potassium of Nitisols in Western Ethiopia. Afr. J. Agric. Res. 9, 2669–2680. https://doi.org/10.5897/AJAR2013.7779.

Traoré, K.B., Gigou, J., Coulibaly, H., Doumbia, M.D., 2004. Contoured ridge-tillage increases cereal yields and carbon sequestration. In: 13th Int. Soil Conserv. Organ. Conf. Brisbane, 4-8 July 2004.

Traore, K., Sidibe, D.K., Coulibaly, H., Bayala, J., 2017. Optimizing yield of improved varieties of millet and sorghum under highly variable rainfall conditions using contour ridges in Cinzana. Mali. Agric. Food Secur. 6, 11. https://doi.org/10.1186/s40066-016-0086-0.

Tully, K., Sullivan, C., Weil, R., Sanchez, P., Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The state of soil degradation in Sub-Saharan Africa: baselines, trajectories, and solutions. Sustainability 7, 6523–6552. https://doi.org/10.3390/su7066523.

Wang, J., Wang, X., Xu, M., Feng, G., Zhang, W., Yang, X., Huang, S., 2015. Contributions of wheat and maize residues to soil organic carbon under long-term rotation in north China. Sci. Rep. 5, 11409. https://doi.org/10.1038/srep11409.

Wei, T., Zhang, P., Wang, K., Ding, R., Yang, B., Nie, J., Jia, Z., Han, Q., 2015. Effects of wheat straw incorporation on the availability of soil nutrients and enzyme activities in semiarid areas. PLoS One 10, e0120994. https://doi.org/10.1371/journal.pone.0120994.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Sci. Soc. Am. J. 66, 1930. https://doi.org/10.2136/sssaj2002.1930.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer, New York, New York, NY. https://doi.org/10.1007/978-0-387-98141-3_1.

Wickham, H., Francois, R., Henry, L., Müller, K., 2019. Package ‘dplyr’. A Grammar of Data Manipulation. R Packag. Version 0.8.0.1. pp. 1–88.

Xu, J., Han, H., Ning, T., Li, Z., Lal, R., 2019a. Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. F. Crop. Res. 233, 33–40. https://doi.org/10.1016/J.FCR.2018.12.016.

Xu, X., An, T., Zhang, J., Sun, Z., Schaeffer, S., Wang, J., 2019b. Transformation and stabilization of straw residue carbon in soil affected by soil types, maize straw addition and fertilized levels of soil. Geoderma 337, 622–629. https://doi.org/10.1016/J.GEODERMA.2018.08.018.

Yang, K., Zhu, J., Gu, J., Yu, L., Wang, Z., 2015. Changes in soil phosphorus fractions after 9 years of continuous nitrogen addition in a Larix gmelinii plantation. Ann. For. Sci. 72, 435–442. https://doi.org/10.1007/s13595-014-0444-7.

Yang, S., Wang, Y., Liu, R., Xing, L., Yang, Z., 2018. Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district. Sci. Rep. 8, 9458. https://doi.org/10.1038/s41598-018-27776-5.

Yang, X., Li, Z., Cheng, C., 2016. Effect of conservation tillage practices on soil phosphorus nutrition in an apple orchard. Hortic. Plant J. 2, 331–337. https://doi.org/10.1016/J.HPJ.2016.11.005.

Zhao, S., He, P., Qiu, S., Jia, L., Liu, M., Jin, J., Johnston, A.M., 2014. Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. F. Crop. Res. 169, 116–122. https://doi.org/10.1016/J.FCR.2014.09.017.