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Long-Term Organic Inputs Determine Soil Productivity Better in Sorghum-Cowpea Rotation Than in Sorghum Monoculture

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Abstract

Information on long-term fertilization combined with crop rotation can contribute to better management of West African Lixisols. There is little information on how long-term organic inputs influence soil chemical properties under cereal monoculture versus a rotation with a legume. Here, we investigated how fertilization regimes with emphasis on organic inputs influence soil chemical properties in sorghum monoculture compared to sorghum-cowpea rotation. The long-term field trial of Saria in Burkina Faso, which has been in operation since 1960, was used for this purpose. Soils were sampled at the 0-20 cm depth to determine their organic C, total N, total P, mineral N, available P, pH_{water}, exchangeable basic cations, and cation exchange capacity. The best soil properties were exhibited with the application of 40 t ha^{-1} of manure. Recycling of sorghum residues combined with mineral fertilization led to a decrease in mineral N and available P but maintained a higher level of total N and P compared to exclusive mineral fertilization. Organic inputs determined soil properties and sorghum yield better ($R^2 = 0.89$) in rotation than in monoculture. Our results show that a better productivity of the studied Lixisol requires an application of manure at more than 5 t ha^{-1} combined with mineral fertilization. In addition, a rotation including a legume and a regular recycling of crop residues is necessary.

Keywords: long term organic inputs, legumes, soil properties, lixisol

1. Introduction

In Sub-Saharan Africa, in addition to the pejoration of climate conditions, crop yields are limited by the inappropriate management of soils. Indeed, the soils in this area are generally nutrient depleted and have a very low organic matter content and a fragile structure (Bado & Bationo, 2018). In Burkina Faso for instance, the Lixisols, which represent about 40% of the total surface area are known to be low in clay, nitrogen, phosphorus and organic matter. It is established that practicing agriculture on those soils without appropriate fertilizer inputs lead to a drastic yield decline over years (Mando et al., 2005, Bationo et al., 2012). The fertilizer inputs, mostly mineral, are very low because of limited physical and economical access by the farmers (Klutse et al., 2018). In addition, those soils have a low cation exchange capacity (Thiam et al., 2019). In this context, organic inputs are essential to improve their functioning, and hence their productivity (Bationo & Buerkert, 2001).

Long-term field trials are known to be useful tools for studying changes in soil properties and productivity. The study of Adams et al. (2016) on a 16 years old trial on millet production in Niger showed that the combined application of crop residue or manure up to 2.7 t ha^{-1} with mineral fertilizer buffered soil pH and led to changes in the forms of C and functional groups of N in soil organic matter but did not improve soil organic C. Soma et al. (2018) showed a significant increase of soil available P by about 64% after 32 years of sorghum cultivation with a yearly application of 10 t ha^{-1} of compost and manure and highlighted very little effect of sorghum straw on soil P forms compared to manure and compost. Mando et al. (2005) showed that application of manure maintains soil C and N at levels that are similar to those measured on neighboring fallow plots and increases sorghum grain yield up to 70% compared to the control without fertilization. In addition to the relevance of organic inputs, crop rotation is also a key practice to improving nutrient use efficiency and soil productivity in the African low inputs systems. Crop rotations including legumes are particularly relevant for these systems as they allow to benefit from a low cost nitrogen supply from the atmosphere. Indeed, in the western area of Burkina Faso, Bado et al. (2012) showed that long term crop rotation including groundnut allows more mineral nitrogen release in the soil and increases nitrogen use efficiency compared to continuous sorghum cropping. They also showed a decrease of soil organic C in all crop rotations excepted for rotation including a natural fallow. The benefits of crop rotation, including legumes, in African cropping systems were also highlighted by Alvey et al. (2001), who showed that soil P availability and P uptake by cereals was up to 62 times higher than under continuous cereal cropping.

While the effects of fertilization and crop rotation on soil properties and productivity in low-input cereal/legume systems have been documented, there is little information on how organic inputs influence soil chemical properties in monoculture versus rotation with a legume. Such information can be gathered from the long-term Saria field trial, implemented on a Lixisol since 1960 in the Central West region of Burkina Faso in sub-Saharan Africa. The trial investigates the effects of different mineral and/or organic input regimes on soil productivity combined with crop rotations. It has already been used in numerous studies to highlight the importance of organic inputs and crop rotation in maintaining sorghum yields through improved chemical, physical and biological soil properties (Lompo et al., 2008; Ouandaogo et al., 2016; Traoré et al., 2016; Adams et al., 2020; Ouandaogo et al., 2021).

This study aims to determine how rotation between sorghum and cowpea and long-term organic and/or mineral fertilizers influence soil chemical properties and what are the relations between those properties. We hypothesize that long-term organic inputs control the chemical properties of the Lixisol and grain yields of sorghum better when sorghum is cropped in rotation with a legume than in monoculture. We first present and analyze the effects of long-term fertilization regimes and crop rotations on soil chemical properties, and then analyze the relationship between soil organic carbon and selected chemical properties and sorghum grain yield under monoculture versus in rotation with cowpea.

2. Method

2.1 Study Site

The study was conducted at the research station of the "Institut de l'Environnement et de Recherches Agricoles (INERA)" in Burkina Faso, located at the Center area (12°16′ N and 2°9′ W). The data were collected from the ongoing long-term field trial, established since 1960 at this research station. The trial was implemented on a Lixisol containing 3 to 5 g kg^{-1} of total C, 0.3 to 0.5 g kg^{-1} of total N and less than 15% of clay, essentially composed of kaolinite.

2.2 Experimental Design

The experimental design was a split-splot with 6 replicates, 6 main treatments and 3 subtreatments. The main treatments were: i) control without any fertilizer addition, ii) low mineral fertilization plus recycling of sorghum residues (fmr), iii) low mineral fertilization plus low rate of cow manure (fmo), iv) exclusive low mineral fertilization (fm), v) high mineral fertilization plus high rate of cow manure (FMO), vi) exclusive high mineral fertilization (FM). The subtreatments were: i) continuous sorghum, ii) rotation sorghum-cotton, iii) rotation sorghum-cowpea. For this study the six main treatments (fertilization regimes) and 2 subtreatments (continuous sorghum and rotation sorghum-cowpea) of 4 replicates were considered. The manure was applied every second year at the rates of 5 t ha^{-1} and 40 t ha^{-1} for the fmo and FMO treatments respectively. The plots were ploughed annually up to 20 cm of depth. The manure supplies 90-10.5-150 kg ha^{-1} and 720-84-1200 kg ha^{-1} of N-P-K with the low rate and the high rate respectively. The sorghum residue supplies 10-6.2-32 kg ha^{-1} of N-P-K (Adams et al., 2020). The low rate of mineral fertilizer corresponds to 37-23-14 kg ha^{-1} of N-P_2O_5-K_2O and the high rate to 60-23-44 of kg ha^{-1} of N-P_2O_5-K_2O. Sorghum receives additional N through urea (46% N) while cowpea receives only the complex NPK fertilizer.

2.3 Soil Sampling and Chemical Analysis

Soil samples were taken at the end of the cropping season of 2011. Each sample was a composite of three samples taken with an auger on the diagonal of the plot at from 0-20 cm layer. The soil samples were then air dried and sieved at 2 mm. The soil organic carbon content was determined according to Walkley and Black (1934). The total N and P contents were determined after a wet digestion with H_2SO_4 solution, as described in Novozamsky et al. (1983) and a measurement using an automatic colorimeter (SKALAR SAN plus SYSTEM). Available phosphorus was extracted according to the Bray and Kurtz (1945) and then, its content determined with the automatic colorimeter. The soil cation exchange capacity (CEC) was determined from extraction with

1N ammonium acetate at pH 7.0. The exchangeable basic cations were determined by Atomic Absorption Spectrometry from the solution of the extractions. Soil pH was determined, using the electrometric method, in a soil solution with soil and water ratio of 1/2.5. Soil mineral nitrogen content was determined using an automatic colorimeter.

2.4 Statistics and Data Analysis

The data of soil properties were analyzed using two-way ANOVA considering fertilization regimes and crop rotations as factors after checking for normal distribution. The Student-Newman-Keuls post hoc test for differences in means was performed with Genstat Discovery 4 software. The principal component analysis was performed with the software canoco 5 (Ter Braak & Šmilauer, 2018) to summarize variability of soil chemical properties across the crop rotation and fertilization regimes. Regression analyses between soil organic C and graphs were performed with Sigmaplot 12 considering only treatment receiving organic matter (fmr, fmo, FMO).

3. Results

3.1 Soil Organic C and Total N and P

The fertilization regimes led to significant changes in soil organic C and total N and P while crop rotation led to changes only in soil available P (Table 1). Whether in monoculture or in rotation, the highest soil organic carbon content was obtained with the FMO followed by the fmo. The exclusive mineral fertilization whether at low (fm) or high (FM) rate and the combined low mineral fertilization and sorghum residue application (fmr) slightly increased soil organic C content which showed the lowest value. Whether, in monoculture or in rotation, soil total N increased with the fmo and FMO but not with the fmr compared to the control. In the monoculture, soil total P increased with all the fertilization regimes while in the rotation, only FMO and FM led to significant increases. Significant interactions between the rotation and fertilization regimes were observed for soil organic C and total N but not for total P.

Table 1. Soil organic C, total N and total P as affected by long term crop rotation and fertilization regimes

Crop rotation	Fertilization	Organic C	Total N	Total P
		g kg^{-1}	------------ mg kg^{-1} -------------	
Sorghum-Sorghum	**Control**	1.49^{e}	180^{d}	119^{c}
	fmr	2.14^{d}	190^{d}	162^{b}
	fmo	3.54^{b}	370^{b}	176^{b}
	fm	2.57^{c}	280^{c}	187^{b}
	FOM	6.46^{a}	610^{a}	292^{a}
	FM	2.52^{c}	210^{d}	184^{b}
Sorghum-Cowpea	**Control**	1.88^{d}	190^{c}	129^{c}
	fmr	2.22^{c}	200^{c}	138^{c}
	fmo	3.07^{b}	310^{b}	166^{c}
	fm	2.41^{c}	250^{c}	169^{c}
	FOM	6.86^{a}	680^{a}	283^{a}
	FM	2.55^{c}	220^{c}	175^{b}
P value	Rotation	0.339	0.891	0.042
	Fertilization	< 0.001	< 0.001	< 0.001
	Rotation × Fertilization	< 0.001	0.003	0.959

3.2 Soil Available P and Mineral N

The fertilization regimes as well as crop rotation led to significant changes in soil available P and mineral N (Table 2). Whether, in monoculture or in rotation, all the fertilization regimes increased soil available P compared to the control. The application of manure combined with mineral fertilizer (fmo and FMO) led to the highest soil available P. With the continuous sorghum cropping, all the fertilization regimes except for the fmo treatment led to an increase of soil mineral N. The highest increases of soil mineral N was obtained with the exclusive mineral fertilization (fm and FM) followed by the fmr and FMO treatments. Significant interactions between the crop rotation and fertilization regimes were observed for soil available P and mineral N as well.

Table 2. Soil available P and mineral N as affected by long term crop rotation and fertilization regimes

Crop rotation	Fertilization	Available P (Bray)	Nmin
		mg kg^{-1}	
Sorghum-Sorghum	**Control**	4.60^{e}	9.44^{c}
	fmr	18.90^{d}	15.00^{b}
	fmo	33.80^{b}	10.35^{c}
	fm	26.00^{c}	17.91^{a}
	FOM	48.30^{a}	14.82^{b}
	FM	20.00^{d}	15.46^{b}
Sorghum-Cowpea	**Control**	4.40^{e}	8.65^{d}
	fmr	11.60^{d}	10.41^{c}
	fmo	22.00^{b}	13.68^{b}
	fm	17.60^{c}	7.69^{e}
	FOM	35.10^{a}	15.24^{a}
	FM	16.30^{c}	8.09^{e}
P value	Rotation	< 0.001	< 0.001
	Fertilization	< 0.001	< 0.001
	Rotation × Fertilization	< 0.001	< 0.001

3.3 Soil Cation Exchange Capacity and pH

Whether, in monoculture or in rotation, the fertilization regimes led to changes in soil cation exchange capacity and acidity (Table 3). The crop rotation induced significant changes in soil CEC and slightly in soil pH. The application of manure led to an increase of soil CEC compared to the control in both cropping systems. In the rotation plots, the exclusive mineral fertilization led to increases of the soil CEC while in the continuous cropping no significant increases were observed. Whether in monoculture or in rotation the fertilization regimes, except for FMO treatment led to soil acidification. The application of high rate of manure (FMO) led to the highest soil pH in both cropping systems. No significant interactions were observed between rotation and fertilization regimes both for soil CEC and soil pH.

Table 3. Soil cation exchange capacity and pH as affected by long term crop rotation and fertilization regimes

Crop rotation	Fertilization	CEC	pHwater
		cmol kg^{-1}	
Sorghum-Sorghum	**Control**	1.63^{d}	5.35^{b}
	fmr	2.08^{cd}	3.95^{d}
	fmo	2.78^{b}	4.62^{c}
	Fm	2.28^{cd}	4.04^{d}
	FOM	3.67^{a}	5.93^{a}
	FM	2.39^{cd}	3.85^{d}
Sorghum-Cowpea	**Control**	2.26^{d}	4.80^{b}
	fmr	2.39^{d}	3.97^{d}
	fmo	3.52^{b}	4.37^{c}
	Fm	3.04^{c}	4.04^{d}
	FOM	4.51^{a}	5.88^{a}
	FM	3.53^{b}	3.91^{d}
P value	Rotation	0.003	0.091
	Fertilization	< 0.001	< 0.001
	Rotation × Fertilization	0.323	0.126

3.4 Relationships Between Soil Chemical Properties

Principal component analysis (Figure 1) showed a clustering of 4 soil fertility management practices, namely i) high rate of combined mineral and organic fertilization (FMO) ii) no fertilization (control), iii) low rate of combined organic and mineral fertilization (fmr, fmo) and iv) exclusive mineral fertilization (fm, FM). The two principal components explained 82% of the total variance, with PC1 explaining 60% and PC2 22%. The first axis determined by the application of the high rate of combined organic and mineral fertilization was strongly positively correlated with soil organic C, exchangeable bases and total N and P and slightly with soil pH, mineral N and available P. The second axis was strongly correlated on its negative side with H^+, exchangeable Al^{3+} and slightly with mineral N and available P. This axis was slightly correlated on its positive side with the soil pH. Figure 2 showed that soil organic matter determined soil chemical properties as available P and the sum of exchangeable basic cations better in rotation than in continuous sorghum cropping. Similarly, sorghum grain yield was significantly determined by soil organic matter in rotation, whereas in monoculture, no significant relation was observed (Figure 3).

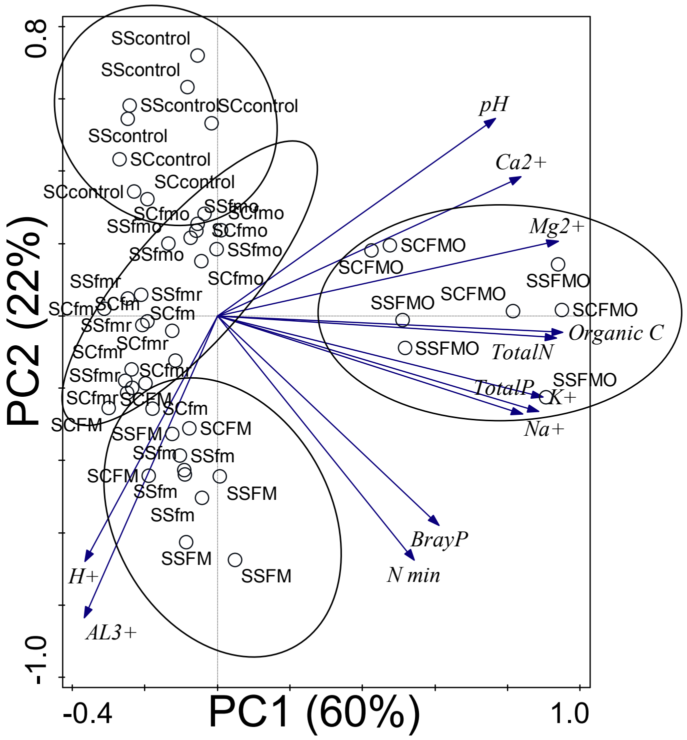
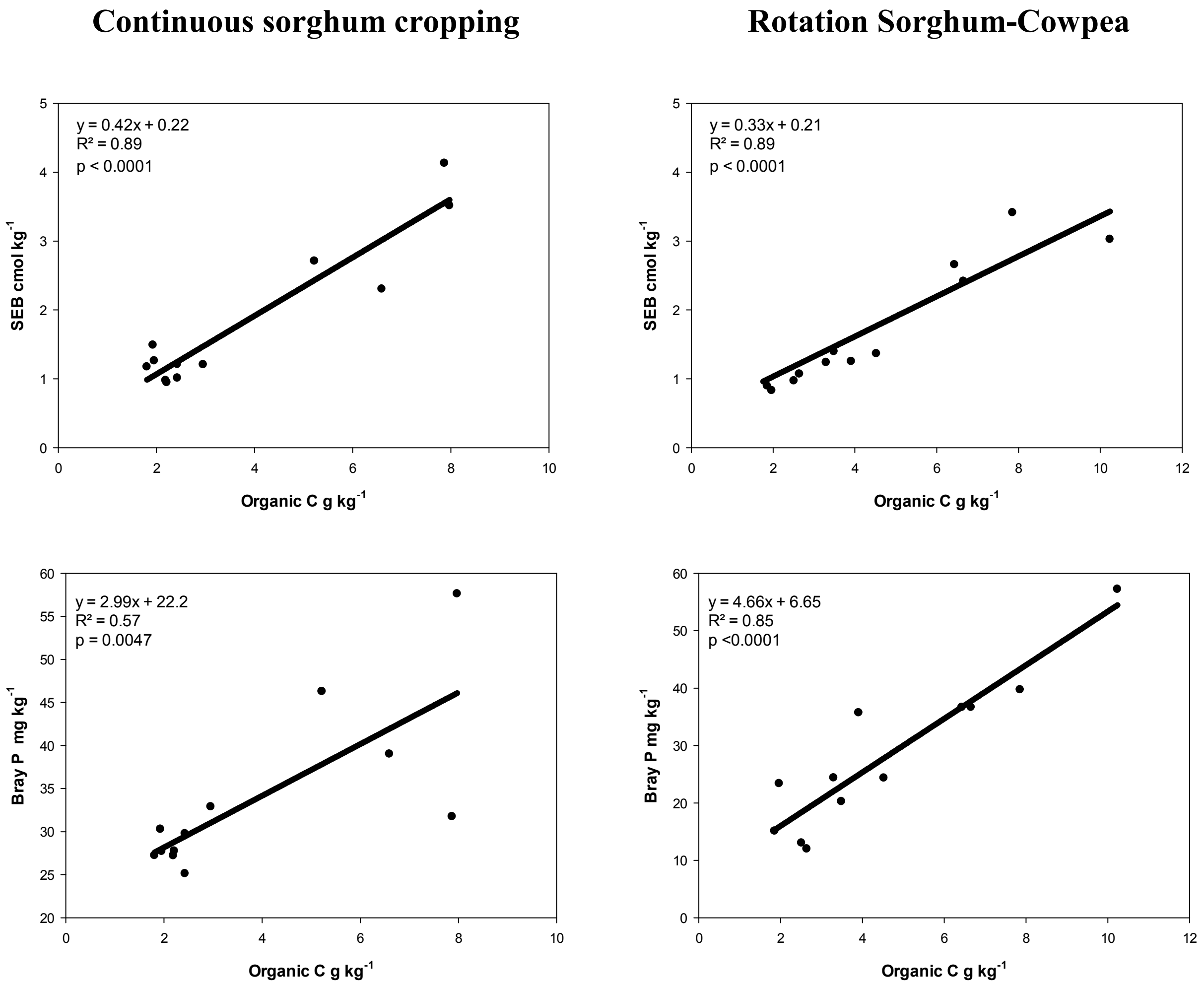
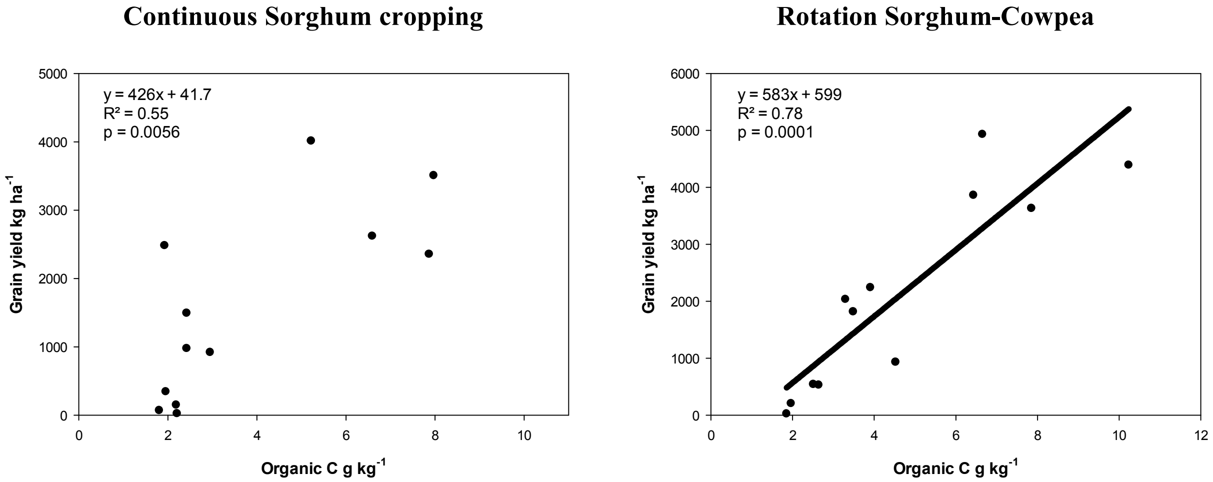


Figure 1. Principal component analysis of soil chemical properties (small circles represent fertilization regimes and crop rotation, arrows represent soil chemical properties, big circles show the clusters)


Continuous sorghum cropping

Rotation Sorghum-Cowpea

Figure 2. Relations between soil organic C and Sum of exchangeable basic cations and available P (Bray P) crop rotation and organic amendment


Continuous Sorghum cropping

Rotation Sorghum-Cowpea

Figure 3. Relations between soil organic C and sorghum grain yield under crop rotation and organic amendment

4. Discussion

4.1 Changes in Soil Properties

The application of 5 t ha^{-1} of manure or the recycling of sorghum residue did not allow soil buffering as highlighted by the pH decrease with these treatments compared to the control. This is in line with results obtained in previous studies on the same trial (Adam et al., 2020). Given the low clay content of the studied soil (about 12%, data not shown) soil buffering requires high rate of organic matter to provide enough humic acid for improving the cation exchange capacity. The application of 5 t ha^{-1} or recycling of sorghum straw every second year cannot obviously fully play this role. The comparison between exclusive mineral fertilization (fm and FM) and combined mineral fertilizer and manure application (fmo and FMO) highlights the ability of manure to increase soil available P. These results point out the fast mineralization or organic matter in tropical soils (Campos et al., 2020) and also the fact that manure contains a significant amount of water soluble P (Soma et al., 2018). One could at first sight link the increase of soil organic C with the exclusive mineral fertilization to an increase of below ground biomass as highlighted in (Chowdhury et al., 2021). However, such an increase was less expected in our nutrient-depleted soil where plants might tend to grow more roots to increase their nutrient uptake when no fertilizer is added and the reverse when fertilizer is added (Achat et al., 2012; Chowdhury et al., 2021). The most likely hypothesis for this organic C increase linked to mineral fertilization would be a negative priming effect caused by N fertilization (Zang et al., 2016).

The decrease of soil available P and mineral N with the recycling of sorghum straw (fmr treatment) in comparison to the low exclusive mineral fertilization (fm) might be explained by an immobilization of P as organic forms by soil microbes. This might limit nutrient losses via lixiviation when not taken up by the crops. Ouandaogo et al. (2021) reported for instance from the same trial, an increase of soil microbial biomass with the straw treatment up to 60 time of that of the control. In addition, Traoré et al. (2016) investigating microbial nutrient limitation using soil from the same trial showed that carbon is the primary limiting factor of microbial growth. It could then be hypothesized that sorghum straw is a better source of carbon for soil microbes than manure, which would provide carbon in a more stable form. Su et al. (2020) highlighted for instance that some cellulolytic fungi and specific bacteria were positively correlated with particulate organic carbon derived from straw. Whereas the recycling of sorghum straw might improve soil biological properties this cannot obviously sustain soil productivity given its low effect on soil available nutrients and cation exchange capacity. With regard to the different effects manure and sorghum residues may have on soil properties, it would therefore be wise to conclude that good management of carbon depleted tropical soils requires inputs of crop residues as well as manure. Simultaneous or alternating application of these two types of organic matter would therefore be advisable.

4.2 Changes in Soil Properties due to Crop Rotation

The decrease in mineral N due to rotation is related to the fact that less N is applied when cowpea is grown. Indeed, sorghum receives additional N as urea (50 kg ha^{-1}) while for cowpea only the complex NPK fertilizer is applied. Nitrogen supply by only the cowpea roots (as leaves and grains are exported) through symbiotic fixation cannot obviously offset for this lack of N. The decrease in soil total and available P can be explained by the high demand for P by cowpea which led to a depletion of this nutrient over time. The high demand for P by legumes is well documented. Giacometti et al 2021 showed for instance that a 9-years rotation including legumes led to a significant decrease of soil Olsen P compared to continuous corn cropping and cereal based rotation. One would expect a decrease in soil pH in the rotation plots due to the release of protons from cowpea (Lazali et al., 2017). This can only be seen by comparing the pH of unfertilized plots in monoculture (pH 5.3) with those in rotation (pH 4.8). In the fertilized plots with no or less application of organic matter, it seems that the continuous application of urea under monoculture of sorghum has brought the soil acidity to a level similar to that of the rotation plots. The soil CEC is an important property that has a strong influence on nutrient availability and more often linked to the soil pH (Aschi et al., 2017). In our study the ability of a rotation involving a legume as cowpea to improve soil CEC was clearly shown. The increase in soil CEC by legume cultivation can be explained by an accumulation of organic C thanks to their ability to protect soil organic matter with their extensive root systems through aggregates formation and stabilization (Oliveira et al., 2019). Our results show that such an accumulation of organic C is not really very noticeable, especially in the plots receiving organic amendment probably because of a dilution effect. Furthermore, these results clearly show that the effect of crop rotation on soil organic C depends on the fertilization regimes as shown by the positive interaction between these two factors. Thus, the increase in soil CEC under exclusive mineral fertilization occurring only in the rotation plots could be a combination of different effects, namely the previously mentioned negative priming effect of mineral fertilizer and the protection of organic matter over time due to the extended root system of cowpea.

4.3 Relationship Between Soil Properties and Importance of Organic Inputs in Relation to Crop Rotation

The organic amendment is essential for the proper functioning of the studied lixisol, as shown by the relationships between soil organic carbon and other soil chemical properties. This is in line with numerous studies which highlighted the importance of organic inputs in tropical soils as a source of nutrients and their ability to improve soil cation exchange capacity and other physical and biological related properties (Bationo & Buerkert, 2001). The principal component analysis clearly shows that manure applied at 40 t ha^{-1} over time has led to an accumulation of basic ions that are well determined by soil organic matter. This analysis also highlights that calcium is an important element from manure that allow avoiding soil acidification probably by binding protons and Al^+ (Wong et al., 1998). On the contrary, the exclusive long term mineral fertilization at high rate led to a depletion of soil organic matter and to a release of protons and exchangeable aluminum leading to soil acidification (Nguyen & Tran, 2019). Regression analyses show that cowpea, as a legume, has the capacity to improve the productive function of soil organic matter as shown by the best correlations between organic carbon and other soil chemical properties and sorghum grain yield in the rotation plots compared to the continuous sorghum plots. This could be explained by a better stabilization of this organic matter due to legume cropping as reported (Yao et al., 2019) thus creating an environment conducive to a balanced nutrition of sorghum.

5. Conclusion

The long-term effects of organic inputs and legume rotation were highlighted. The results showed that the application of manure at a rate of 40 t ha^{-1} improves soil properties and prevents soil acidification. The recycling of sorghum residues in presence of mineral fertilization decreases mineral N and P availability while maintaining higher total N and P compared to the exclusive mineral fertilization probably due to microbial immobilization. This might be beneficial in limiting nutrients losses. In view of the different effects that these types of organic matter may have on soil properties, their simultaneous or alternating application might be beneficial for a sustained productivity of the studied Lixisol. Our analysis also showed that a rotation involving a legume crop as cowpea is an excellent way to protect soil organic matter and to better express its capacity to improve soil productivity.

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