Agriculture, Forestry and Fisheries
2023; 12(1): 1-7
http://www.sciencepublishinggroup.com/j/aff
doi: 10.11648/j.aff.20231201.11
ISSN: 2328-563X (Print); ISSN: 2328-5648 (Online)

Carbon and Nutrients Dynamics Along a Lixisol Profile as Affected by Long-Term Organic and Mineral Fertilization

Dohan Mariam Soma*, Delwendé Innocent Kiba, Ouakoltio Youssouf Abidine Traoré, Zacharia Gnankambary, François Lompo, Papaoba Michel Sedogo

Département Gestion des Ressources Naturelles et Systèmes de Production, Institut de l'Environnement et de Recherches Agricoles, Ouagadougou, Burkina Faso

Email address:

Soma_mariam1@yahoo.fr (Dohan Mariam Soma)

*Corresponding author

To cite this article:

Dohan Mariam Soma, Delwendé Innocent Kiba, Ouakoltio Youssouf Abidine Traoré, Zacharia Gnankambary, François Lompo, Papaoba Michel Sedogo. Carbon and Nutrients Dynamics Along a Lixisol Profile as Affected by Long-Term Organic and Mineral Fertilization. *Agriculture, Forestry and Fisheries*. Vol. 12, No. 1, 2023, pp. 1-7. doi: 10.11648/j.aff.20231201.11

Received: November 28, 2022; **Accepted**: December 16, 2022; **Published**: January 10, 2023

Abstract: Lixisols in sub-Saharan Africa are known to be deficient in nutrients and organic matter and therefore long-term studies could provide appropriate solutions for their better management. This study was conducted at the long-term field trial of Saria established since 1960 in the Centre West region of Burkina Faso. In plots where sorghum and cowpea were grown in rotation, we assessed the effects of long term organic and mineral fertilization on soil carbon and nutrient dynamics. The soil chemical properties, namely total C, N, P and pH, were measured along the profile down to 40 cm. We calculated available P stocks for the 40-60, 60-80 and 80-100 cm horizons and N and P balances for two cropping seasons. With an application of 40 t ha^{-1} of manure every second year, soil carbon stock was maintained but the risk of P losses was high (about 50 kg ha^{-1} of available P found in the 80-100 cm horizon). In the contrast 5 tha^{-1} of manure every second year did not maintain soil carbon stock but led to low amount of P in the horizon 80-100 cm (< 10 kg ha^{-1}). When water soluble mineral fertilizer was applied solely, the uptake of P and K was more with cowpea than with sorghum, leading to a negative K budget. On the contrary when manure was added, the uptake of P and K was more with sorghum than with cowpea and their budgets were positives.

Keywords: P Availability, Organic Matter, Crop Rotation, Lixisol, Long-Term Field Trial

1. Introduction

In sub-Saharan Africa, the management of soils to maintain their productivity at a good level is a real challenge. Indeed, soils in this region have generally low nutrient contents [1], and their productivity declines rapidly after a few years of cultivation due to their very fragile structure, combined with inappropriate fertilizer inputs. It is well established that substantial application of organic and mineral fertilizers is necessary to maintain good crop yields on these soils [2]. Whereas mineral water soluble fertilizers are known sources of nutrients for the cropping systems, their access to smallholder farmers remain limited because of the limited financial resources [3]. Smallholders more often use organic resources such as manure and composts when they are available. Indeed, the availability of these organic resources is often limited when livestock and crop productions are not well integrated [4]. Phosphorus is one of the most limiting nutrients in these cropping systems [5]. In addition to water-soluble mineral fertilizers and organic resources, this nutrient can be sourced from rock phosphates. However, the use of these rock phosphates is limited because of the low solubility of their P and therefore a low P availability for crops when applied to the soils [6].

The low access to financial resources for improved soil management on farms in sub-Saharan Africa and the fragility of these soils require rational use of fertilizers and a better understanding of nutrient use efficiency. In Burkina Faso, in addition to the mineral fertilization consisting of the application of major nutrients (N, P, K), a dose of 2.5 $tha^{-1}year^{-1}$ dry matter of organic fertilizer was recommended to compensate for the annual mineralisation of soil organic matter, regardless of the soil type or the quality of the available organic fertilizers [7-9]. The effects of these fertilisation strategies were studied on the total content, availability and use efficiency of P [6, 10], soil organic matter fractions [11] and soil chemical and biological properties in general [12, 13]. While these studies have provided recommendations for better management of these soils to improve crop yields, few have examined the fate of applied nutrients in the soil profile after long-term fertilization mostly on phosphorus known to be a non-renewable resource. Given the sandy texture of soils in Sub Saharan Africa [14], repeated application of fertilizers depending on the doses could lead in the long term to an accumulation of nutrients deep in the soil outside the crop roots zone. The long term field trial established at Saria in Burkina Faso since 1960, offers an opportunity to investigate different mineral and/or organic input strategies on the properties and productivity of a Lixisol under various cropping systems (continuous sorghum cropping, sorghum-cotton rotation, sorghum-cowpea rotation). Since the establishment of this trial in 1960, many studies were conducted in the continuous sorghum and sorghum-cotton rotation and very few in the sorghum-cowpea rotation.

The main objective of this study was to understand the effects of organic and/or mineral inputs on the carbon and nutrients dynamics along the profile of a Lixisol under sorghum-cowpea rotation. We hypothesized that the application of manure at low rate (5 tha^{-1} every second year) does not maintain soil carbon stock given the high mineralization often occurring in tropical soils while high rate (40 t ha^{-1} every second year) does and leads to positive nutrient budgets but increased P accumulation in deep soil horizons.

2. Material and Methods

2.1. Description of the Study Area

The study was conducted at the agricultural research station of the "Institut de l'Environnement et de Recherches Agricoles (INERA)", located in the Centre West region of Burkina Faso (12° 16' N, 2° 9' W, 300 m asl). This area receives an average of 800 mm of rainfall per year, distributed between May and October. The rainiest months are generally July, August and September. The minimum temperature is around 18°C in December and the maximum can reach 45°C in April. The average potential evapotranspiration is about 2000 mm. The soils are classified as Lixisols [15]. These soils are sandy with a very fragile structure and low total P (about 200 mg kg^{-1}) and available P of about 4 mg kg^{-1} Bray P [10]. The characteristics of those Lixisol profiles (Table 1) under about 40 years of fallow were described [14]. The slope is between 0 and 1% and the ferruginous hardpan is located at about 150 cm depth. Soil clay content (mainly kaolinite) decreases from the upper horizon (10 cm) to the deep horizon (158 cm) as well as Fe and Al content. The total carbon content is between 5 and 1 g kg^{-1} from the upper horizon (10 cm) to the deep horizon (158 cm). The pH is acidic and around 5.5.

Table 1. *Selected chemical and physical properties of a Lixisol from the Centre West area of Burkina Faso. (Hien 2004).*

	0-10	**10-27**	**27-57**	**57-87**	**87-120**	**120-158**
	Soil horizon (cm)					
Clay (%)	11.6	17.2	38.9	36.2	31.8	31.1
Total C (g kg^{-1})	5.25	3.23	2.94	1.86	1.74	1.07
pH (water)	5.5	5.4	5.2	5.3	5.2	5.4
Fe (%)*	0.54	0.69	1.38	2.60	2.67	2.18
Al (%)*	0.06	0.09	0.23	0.33	0.32	0.27

*Extraction with Citrate-Bicarbonate-dithionite

2.2. Description of the Long Term Field Trial of Saria

The long-term field trial of Saria was set up in 1960 to study the effects of long-term application of organic amendments and water-soluble mineral fertilizers on soil fertility in different cropping systems. The field trial covers an area of 9672 m^2 (162.2 m × 60 m) and consists of a plot design divided into six blocks. The sub-plots have an area of 84 m^2 (10 m × 8.4 m). The distance between two blocks is 2 m. Six fertilisation treatments are tested as the main factor: 1) control (no nutrient addition since 1960), 2) low mineral fertilization (33 kg N, 10 kg P and 11 kg K ha^{-1} added as water-soluble mineral fertilizer) and recycling of sorghum residues every second year "fmr", 3) low mineral fertilization "fm", 4) low mineral fertilization plus low rate manure application "fmo" where in addition to "fm" 5 t ha^{-1} of manure is added every second year, 5) high mineral fertilization "FM" (56 kg N, 10 kg P and 26 kg K ha^{-1} added as water-soluble mineral fertiliser) and 6) high mineral fertilization plus high rate manure application "FMO" where, in addition to "FM", 40 t ha^{-1} of manure is added every second year. Three cropping systems are tested as a secondary factor: 1) continuous sorghum, 2) sorghum-cotton rotation and 3) sorghum-legume rotation. Our study was conducted only in the sorghum-legume (cowpea) rotation considering five fertilization treatments: control, fmo, fm, FMO and FM.

2.3. Plant and Soil Sampling

For each sub-plot, straw weights were measured and a sub-sample was taken for moisture determination. The straw and grain harvested were air-dried for about two weeks and for each sub-plot, composite samples were taken, oven-dried at 60°C and packed in plastic bags for chemical analysis. For each subplot, sub-samples of soil were taken at 5 points on six horizons: 0-10, 10-20, 20-40, 40-60, 60-80 and 80-100 cm, immediately after the sorghum harvest. The 5 subsamples from each horizon were then mixed, yielding one composite sample per horizon and six composite samples per subplot. The composite samples were then air-dried, sieved to 2 mm and packed in plastic bags for chemical analysis.

2.4. Soil Analysis

Soils from the first three sampled horizons, 0-10, 10-20 and 20-40 cm were analysed for their total C, N, P, inorganic P, available P contents and pH. Soil total C and N were measured on ball-milled samples with a CN analyser (Flash EA, 1112 series, Italy). Soil total P was measured with the method of total digestion [16]. The method consists in heating at 360°C during 2.5 hours using a digestion block (Tecator), 200 mg of dry soil in to 4.4 ml of a solution containing concentrated sulphuric acid, hydrogen peroxide, selenium and lithium sulphate. The solutions after digestion were made up to 250 ml with distilled water and an aliquot was taken for the measurement of P concentration in colorimetry with the malachite green method [17]. Soil inorganic P was measured according to Bowman & Moir [18]. According to this method, 3 g of dry soil was shaken in 30 ml NaOH (0.25 M)-EDTA (0.05 M) solution during 16 hours. The extracts were then filtered through 0.8 µm nitrocellulose membranes and the P concentration was measured with the malachite green method. Soil available P was measured according to Bray & Kurtz [19]. Soil pH was measured on a suspension of 1 g of soil in 10 ml of distilled water with a pH meter (ORION model 720A, USA).

2.5. Plant Analysis

Plant material (grain and straw) were crushed with centrifuge mill and analyzed for their N, P and K contents. N content was determined with a CN analyser on ball-milled samples. P content was measured in colorimetry with the malachite green method after ignition of 200 mg of dry material at 550°C during 3 hours in an electrical furnace, followed by an extraction with 2 ml HNO_3 (14M) made up to 200 ml with distilled water and a filtration through 0.2 µm nitrocellulose membrane. The extracts were also used for the determination of K contents with inductively coupled plasma mass spectrometer (ICP-MS; Agilent 7500 ce, USA).

2.6. Calculation of P Stocks and N, P and K Budgets

The stocks of available P (Bray-1 P) was calculated for the horizons 40-60, 60-80 and 80-100 cm, considering soil apparent densities of 1.75, 1.70, 1.71, 1.63, 1.66 g cm-^{3} respectively for the treatments control, fmo, fm, FMO and FM measured in the continuous sorghum cropping subplots of the trial, on 40 cm of depth [14]. We assumed that the soil apparent density is not significantly affected by the crop rotation and do not change significantly after 40 cm. The N, P and K budgets were estimated for a cropping cycle of two years (2009 and 2010) in each subplot using the equation: Nutrient Budget (kg ha -1) = Nutrient inputs – Nutrient ouputs. In this equation the inputs for a given nutrient are the addition of this nutrient in kg ha^{-1} with water soluble mineral fertilizers in 2009 and 2010 and manure in 2010. For the N budget the total quantity of N fixed in 2009 by cowpea was considered. This total quantity of N fixed was the sum of N fixed in the aboveground material (grains and straw) and the roots [20]. The outputs of a given nutrient in kg ha^{-1} was calculated as the amount of the nutrient in kg ha^{-1} taken up by the plant, obtained from the nutrient concentration in the grains and straw multiplied by the corresponding dry matter produced in kg ha^{-1}.

2.7. Statistical Analysis

The data were analysed with the software SAS 9.2. Soil data were subjected to one-way ANOVA. For each sampled horizon the fertilization treatment was considered as the independent factor and for each fertilization treatment the sampled horizon was considered as the independent factor. Plant data as they were not normalized were subjected to transformation prior to one-way ANOVA considering the fertilization treatment as the independent factor. In this case, for parameters with negative values (eg. nutrient budget) or values below 1 (nutrient uptake), a constant was added to all the values of those parameters to move the minimum value of the distribution to 1 prior to the ln transformation. All the means were compared using the Newman-Keuls test at 95% of confidence level when a significant factor effect was observed.

3. Results and Discussion

3.1. Soil Carbon, Nutrients and pH

There was a significant effect of the fertilization treatments in soil total C, N, P, inorganic P and pH in the horizons 0-10, 10-20 and 20-40 cm, excepted for total C in the horizon 20-40 cm (Table 2). Regarding the sampling horizon, significant effect was observed on soil total element contents and soil pH excepted for total C in the fmo and FM treatments, soil total N in the fmo treatment, soil total P in the control, fm and FM treatments and soil pH in the fm and FM treatments.

The fact that ploughing was limited to the top 20 cm of soil explains why there was no effect of manure on soil carbon content beyond this horizon. This result indicates that there was not a significant leaching of organic matter from the upper to the deep horizons despite the sandy texture of the Lixisol. It was reported that soil total C on the 0-20 cm was 6.20 g kg^{-1} in 1960 at the implementation of the trial [21]. It appears then that only the addition of 40 t ha^{-1} of manure every second year allows maintaining soil total C content, while cropping without fertilization or with exclusive water soluble mineral fertilizers addition leads to losses of about half.

In the horizons 0-10 cm and 10-20 cm, the highest soil total P contents were measured in the FMO treatment and the lowest in the control. The quantity of P added in the FMO treatment probably exceeds the needs of sorghum and cowpea, explaining the high soil available P as well as the high stock of available P in deep soil horizons measured after crop harvest. Given the very sandy texture of the Lixisols, the addition of high rate of manure may lead in the long term, to increased risks of P losses and therefore to groundwater pollution and to a net loss of an important resource for agricultural production.

Table 2. *Total C, N, P, and inorganic P contents and pH as affected by fertilization treatments along soil profile in the long term field trial of Saria in Burkina Faso.*

Treatment	Horizon	Total N	Total P	NaOH Pi	pH
	cm	mg kg $^{-1}$			
control		140±25.8	70.1±14.0	16.1±3.14	6.2±0.3
fmo		320±138	149±38.1	68.4±15.3	5.8±0.1
fm	0-10	169±27.8	111±18.9	53.8±8.55	5.8±0.9
FMO		518±64.3	218±48.1	108±29.2	6.7±0.1
FM		186±46.9	111±29.6	47.0±15.3	5.3±0.4
p value (treatment)		*<0.0001*	*<0.0001*	*<0.0001*	*0.0009*
control		138±34.4	66.0±13.9	12.9±1.86	6.7±0.5
fmo		208±33.4	119±22.7	53.2±12.1	6.1±0.2
fm	10-20	134±22.9	103±31.3	44.2±16.2	5.3±0.2
FMO		364±89.7	202±30.2	100±17.3	7.2±0.1
FM		155±39.6	89.8±17.9	32.9±8.80	5.4±0.3
p value (treatment)		*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
control		196±42.7	83.1±15.3	8.84±1.66	6.4±0.2
fmo		214±26.4	100±6.99	19.6±3.92	6.4±0.3
fm	20-40	207±26.9	96.8±20.3	17.2±4.85	5.4±0.2
FMO		267±28.5	143±22.0	48.8±14.7	7.4±0.1
FM		221±20.5	89.9±13.4	15.1±4.27	5.3±0.3
p value (treatment)		*0.0039*	*<0.0001*	*<0.0001*	*<0.0001*
	control	*0.0183*	*0.1364*	*0.0003*	*0.0714*
	fmo	*0.2097*	*0.0554*	*<0.0001*	*0.0853*
p value (horizon)	*fm*	*0.0009*	*0.5996*	*0.0001*	*0.3621*
	FMO	*<0.0001*	*0.0054*	*0.0004*	*<0.0001*
	FM	*0.0266*	*0.1854*	*0.0004*	*0.9760*

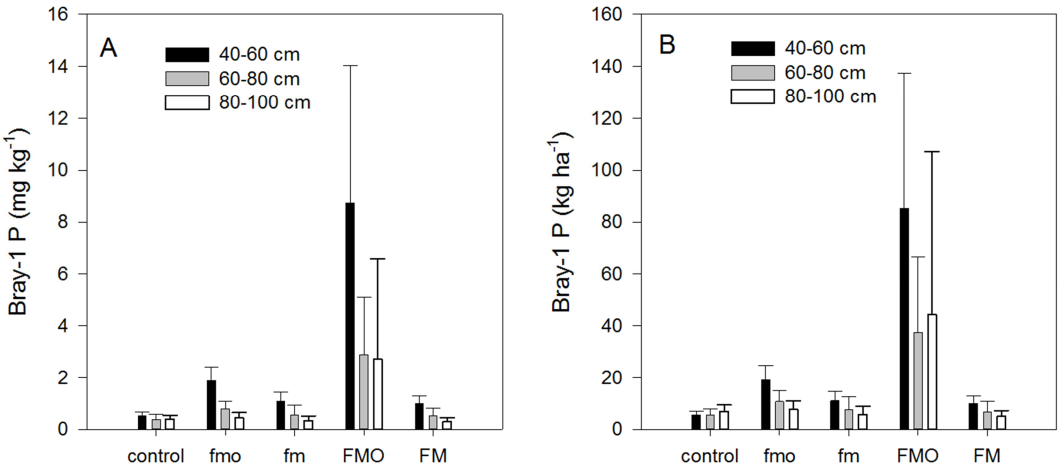

Figure 1. *Available Bray-1 P (A) and stock of available Bray-1 P (B) along soil profile as affected by fertilization in the long term field trial of Saria in Burkina Faso.*

The results also showed that manure also supplies a large amount of mineral elements such as inorganic P. The significant increase of inorganic P above the 20 cm horizon is probably explained by a lixiviation of the phosphate ions mostly when large amount of manure was applied. The increase of inorganic P with the application of manure is related to the fact that manure contains nutrients in available form and also that in tropical conditions organic matter after application on the soil is rapidly mineralized leading to nutrients release [22]. For instance, it was reported that a yearly mineralization rate of 3.5% in the long term field trial of Saria [14]. For another another long term field trial in the same area, comparing different types of organic amendments, it was highlighted that mineralization occurs both in the particulate and fine organic matter fractions [11]. Considering the assumption of a high mineralization rate and a possible priming effect as usually observed when mineral fertilizers are applied [23], we expected a significant decrease in total soil C in the fm and FM treatments compared to the control. However, this was not highlighted with our results. We believe that the mineral fertilizers, even when added alone, may have contributed to a higher production of root biomass compared to that obtained in the control treatment, which probably contributed to the total soil C content. In addition, the contribution of senescent leaves to soil carbon could be higher in the fm and FM treatments compared to the control due to a higher production of above-ground biomass. The lowest soil pH was measured in the FM treatment (between 5.3 and 5.4) and the highest in the FMO treatment (between 6.7 and 7.4) for all the three horizons. It is known that the exclusive application of water-soluble mineral fertilizer, mainly urea, leads to a decrease in soil pH [24]. Our results showed that only the FMO treatment led to significant differences in soil pH between the three sampled horizons (0-10, 10-20 and 20-40 cm) with the highest value observed in the deepest horizon. A possible transfer of Ca, Mg and K from the manure into the deep horizons during the long cultivation period in this sandy Lixisol is a potential explanation for this pH increase.

3.2. Nutrient Uptake and Budgets

There was a significant effect of fertilization treatments on cowpea and sorghum N, P and K uptake (Table 3). As well as on soil surface N, P and K budgets (Figure 2).

Our results showed that without fertilizer addition or exclusive water soluble mineral fertilizer addition the uptake of P and K with cowpea are higher than those with sorghum. The contrary was observed with the application of manure at 5 or 40 t ha^{-1} every second year. Cowpea certainly develops strategies which could be root system development, association with mycorrhiza or acidic substrates exudation for mobilizing more nutrients [25] when their amounts are low in the soil solution. It might be also that manure contains micronutrients [26] which may provide specifically better growing conditions for sorghum increasing therefore P and K uptake. Finally, sorghum could be more sensitive compared to cowpea to the degraded soil structure observed during the study period and more pronounced in the control plots and those receiving exclusive water soluble mineral fertilizers.

The positive balances of N, P and K in the FMO treatment indicate an accumulation of nutrients suggesting a risk of nutrient losses. The results suggest that manure is an important source of K as its application has allowed limiting K depletion in the fmo and FMO treatments compared to the fm and FM treatments, where negative K balances were obtained. The addition of N via N_2 fixation by cowpea has probably limited N depletion in the control treatment, leading to a positive N balance. The K depletion in the fm and FM treatments could be the main factor limiting sorghum and cowpea yields. It seems that the applied rate of K did not meet sorghum and cowpea requirement, leading in the long term to yield decrease.

Table 3. *Cowpea and sorghum N, P and K uptake as affected by fertilization in the long-term field trial of Saria in Burkina Faso.*

Treatment	Cowpea			Sorghum		
	N	P	K	N	P	K
	kg ha^{-1}					
control	36.0±13.6	2.74±1.17	15.6±6.15	10.8±2.71	1.29±0.49	8.53±2.87
fmo	71.3±31.8	7.80±3.75	34.1±13.8	72.8±20.7	14.9±3.70	54.7±28.3
fm	64.8±20.4	6.21±1.85	29.6±7.29	14.2±11.4	2.21±1.97	11.8±9.86
FMO	150±37.1	17.3±4.42	135±41.5	155±32.5	38.3±11.9	300±92.9
FM	74.6±19.6	7.66±2.01	43.5±15.8	23.8±11.6	3.41±1.76	24.0±13.5
p value	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*

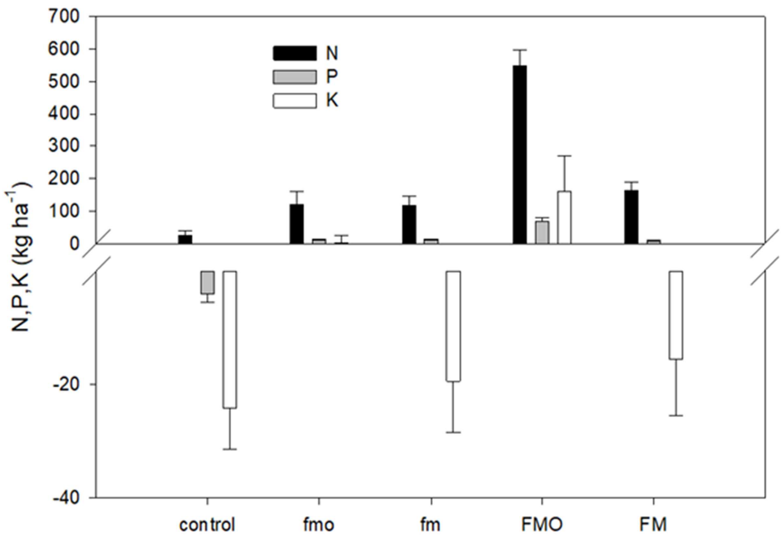

Figure 2. *Soil N, P and K surface budgets as affected by fertilization treatments after 50 years of cropping in the long term field trial of Saria in Burkina Faso.*

4. Conclusion

On the studied Lixisol, the application of 40 t ha^{-1} of manure every two allow maintaining soil organic matter content and reaching sorghum and cowpea yield potentials but lead to high risk of P losses. In contrast, the application of 5 tha^{-1} every second year, despite this rate leads to lower risks of nutrient losses, it cannot allow maintaining soil organic matter. We conclude that optimal rate of manure to be applied every second year on the Lixisol is probably higher than 5 t ha^{-1} but probably lower than 40 t ha^{-1}.

Acknowledgements

The authors thank Sanon Martin and Coulibaly Dofinita, technicians from INERA who helped with the collection of data.

References

[1] Rakotoson, T., Tsujimoto, Y., & Nishigaki, T. (2022). Phosphorus management strategies to increase lowland rice yields in sub-Saharan Africa: A review. Field Crops Research, 275, 108370. https://doi.org/10.1016/j.fcr.2021.108370

[2] Gram, G., Roobroeck, D., Pypers, P., Six, J., Merckx, R., & Vanlauwe, B. (2020). Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. PLOSONE, 15 (9), e0239552. https://doi.org/10.1371/journal.pone.0239552

[3] Mugwe, J., Felix, N., & Erick, O. O. (2019). "Integrated soil fertility management in sub-Saharan Africa: Evolving paradigms toward integration." Zero Hunger. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. https://doi.org/10.1007/978-3-319-69626-3_71-1

[4] Gowing, J. W., Golicha, D. D., & Sanderson, R. A. (2020). Integrated crop-livestock farming offers a solution to soil fertility mining in semi-arid Kenya: evidence from Marsabit County. International Journal of Agricultural Sustainability, 18 (6), 492-504. https://doi.org/10.1080/14735903.2020.1793646

[5] Soma, D. M., Kiba, D. I., Ewusi-Mensah, N., Gnankambary, Z., Lompo, F., Sedogo, M. P., & Abaidoo, R. C. (2018a). Changes in sorghum production, soil P forms and P use efficiency following long-term application of manure, compost and straw in a Ferric Lixisol. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 68 (5), 401-411. https://doi.org/10.1080/09064710.2017.1414871

[6] Soma, D. M., Kiba, D. I., Gnankambary, Z., Ewusi-Mensah, N., Sanou, M., Nacro, H. B., Lompo, F., Sedogo, M. P., & Abaidoo, R. C. (2018b). Effectiveness of combined application of Kodjari phosphate rock, water soluble phosphorus fertilizer and manure in a Ferric Lixisol in the centre west of Burkina Faso. Archives of Agronomy and Soil Science, 64 (3), 384-397. https://doi.org/10.1080/03650340.2017.1353216

[7] Sedogo, M. (1981). Contribution à la valorisation des résidus culturaux en sol ferrugineux et sous climat tropical semi-aride. Thèse de doctorat, Nancy, Institut national polytechnique de Lorraine (INPL).

[8] Berger, M., Belem, P. C., Dakouo, D., & Hien, V. (1987). Le maintien de la fertilité des sols dans l'Ouest du Burkina Faso et la nécessité de l'association agriculture-élevage. Coton et Fibres Tropicales, 42 (3), 201-210.

[9] Blanchard, M., Vall, É., Tingueri, L. B., & Meynard, J. (2017). Identification, caractérisation et évaluation des pratiques atypiques de gestion des fumures organiques au Burkina Faso: sources d'innovation ?. Autrepart, 81, 115-134. https://doi.org/10.3917/autr.081.0115

[10] Compaoré, E., Frossard, E., Sinaj, S., Fardeau, J. C., & Morel, J. L. (2003). Influence of land-use management on isotopically exchangeable phosphate in soils from Burkina Faso. Communications in soil science and plant analysis, 34 (1-2), 201-223. https://doi.org/10.1081/CSS-120017426

[11] Mando, A., Bonzi, M., Wopereis, M. C. S., Lompo, F., & Stroosnijder, L. (2005). Long-term effects of mineral and organic fertilization on soil organic matter fractions and sorghum yield under Sudano-Sahelian conditions. Soil Use and Management, 21 (4), 396-401. https://doi.org/10.1079/SUM2005339

[12] Ouandaogo, N., Pouya, B. M., Soma, D. M., Gnankambary, Z., Kiba, D. I., Ouattara, B., Lompo, F., Nacro, H. B., & Sedogo, P. M. (2021). Microbial Properties of a Ferric Lixisol as Affected by Long Term Crop Management and Fertilization Regimes in Burkina Faso, West Africa. Open Journal of Soil Science, 11, 256-270. https://doi.org/10.4236/ojss.2021.114014

[13] Ouandaogo, N., Soma, D. M., Pouya, M. B., Gnankambary, Z., Ouattara, B., Lompo, F., Nacro, H. B., Sedogo, M. P., & Kiba, D. I. (2022). Long-Term Organic Inputs Determine Soil Productivity Better in Sorghum-Cowpea Rotation Than in Sorghum Monoculture. Journal: Journal of Agricultural Science, 14 (12). https://doi.org/10.5539/jas.v14n12p166

[14] Hien, E. (2004). Dynamique du carbone dans un Acrisol ferrique du Centre Ouest Burkina: Influence des pratiques culturales sur le stock et la qualité de la matière organique. Thèse de doctorat, Ecole Nationale Supérieure Agronomique de Montpellier, 140p.

[15] FAO-UNESCO (1994). Soil map of the world. ISRIC Wageningen Netherlands.

[16] Anderson, J. M., & Ingam, J. S. I. (1993). Tropical soil biology and fertility. A handbook of methods. CAB International, Wallingford, Oxon, UK. 221p. https://doi.org/10.2307/2261129

[17] Van Veldhoven, P. P., & Mannaerts, G. P. (1987). Inorganic and organic phosphate measurements in the nanomolar range. Analytical Biochemistry, 161, 45-48. https://doi.org/10.1016/0003-2697(87)90649-x

[18] Bowman, R. A., & Moir, J. O., (1993). Basic EDTA as an extractant for soil organic phosphorus. Soil Science Society of America Journal, 57, 1516-1518. https://doi.org/10.2136/sssaj1993.03615995005700060020x

[19] Bray, R. H., & Kurtz, L. T. (1945). Determination of Total Organic and Available Forms of Phosphorus in Soils. Soil Science, 59, 39-45. http://dx.doi.org/10.1097/00010694-194501000-00006

[20] Kiba D. I. (2012). Diversité des modes de gestion de la fertilité des sols et leurs effets sur la qualité des sols et la production des cultures en zones urbaine, péri urbaine et rurale et Burkina Faso. Thèse de doctorat unique, Université Polytechnique de Bobo Dioulasso, 120 p.

[21] Lompo, F. (2009). Effets induits des modes de gestion de la fertilité sur les états du phosphore et la solubilisation des phosphates naturels dans deux sols acides du Burkina Faso. Thèse doctorat d'Etat, Université de Cocody, 254p.

[22] Basak, B. B., Sarkar, B., Saha, A., Sarkar, A., Mandal, S., Kumar, B. J., Wang, H., & Bolan, N. S. (2022). Revamping highly weathered soils in the tropics with biochar application: What we know and what is needed. Science of The Total Environment, 822, 153461. https://doi.org/10.1016/j.scitotenv.2022.153461

[23] Abdalla, K., Sun, Y., Zarebanadkouki, M., Gaiser, T., Seidel, S., & Pausch, J. (2022). Long-term continuous farmyard manure application increases soil carbon when combined with mineral fertilizers due to lower priming effects. Geoderma, 428, 116216. https://doi.org/10.1016/j.geoderma.2022.116216

[24] Molin, D., Junkes, S., Ernani, P. R., & Gerber, J. M. (2020) "Soil acidification and nitrogen release following application of nitrogen fertilizers. Communications in Soil Science and Plant Analysis, 51 (20) 2551-2558. https://doi.org/10.1080/00103624.2020.1845347

[25] Singh, S. R., Yadav, P., Singh, D., Shukla, S. K., Tripathi, M. K., Bahadur, L., Aradhana, M. & Kumar, S. (2021). Intercropping in sugarcane improves functional diversity, soil quality and crop productivity. Sugar Tech, 23 (4), 794-810. https://doi.org/10.1007/s12355-021-00955-x

[26] Shahid, M., Shukla, A. K., Bhattacharyya, P., Tripathi, R., Mohanty, S., Kumar, A., Lal, B., Gautam, P., Raja, R., Panda, B. B., Das, B. & Nayak, A. K. (2016). Micronutrients (Fe, Mn, Zn and Cu) balance under long-term application of fertilizer and manure in a tropical rice-rice system. Journal of soils and sediments, 16 (3), 737-747. https://doi.org/10.1007/s11368-015-1272-6