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Long-term Effects of Crops Residues Management on Soil Chemical Properties and Yields in Cotton - Maize - Sorghum Rotation System in Burkina Faso

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Authors' contributions

This work was carried out in collaboration between all authors. Authors BK and DD designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors OT and KO managed the analyses of the study. Author FL managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

In cotton and cereals production systems, one of the most important causes of soil fertility depletion is the inappropriate crop residues management.
Aims: To improve the productivity and soil fertility, crop residues management (CRM) and fertilization effects on soil chemical properties and crops yields were assessed in a cotton-cereals rotation.
Study Design: The experimental design was simple non-randomized blocks design having 3 treatments.
Place and Duration of Study: This long-term experiment was carried out on station from 1982 to 2012.

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Methodology: The treatments were three crops residues management practices, combined with rock phosphate (25% P_2 O_5 and 35% CaO) application and the use of inorganic fertilizers. Extensive CRM consisting in exportation of crop residues was compared to semi-intensive CRM (recycling the residues into compost) and intensive CRM (recycling crop residues into farmyard manure). Soil samples were collected at 0-20 cm depth and chemical characteristics analysed. Cotton, maize and sorghum yields were also evaluated.
Results: Continuous cropping during 30 years affected significantly (*P* =.05), the main chemical characteristics of soils under the different crop residues management practices. From 25th to 30th year, the decrease of soil carbon, Nitrogen, total P contents was very high as well as that of exchangeable bases, particularly Ca^{2+} and Mg^{2+} contents. The cation exchange capacity (CEC) decrease was 63%, 31% and 26%, respectively in extensive, semi-intensive and intensive CRM. Recycling crop residues into compost or farmyard manure did not prevent soil chemical degradation and crops yields decrease but reduced them significantly.
Conclusion: Moreover, integrated management of crop residues, reduction of soil tillage frequency and preventing soil erosion are suggested for a sustainable maintenance of soil chemical properties.

Keywords: Crop residues; soil properties; organic and inorganic fertilizers; yields; crop rotation; Burkina Faso.

1. INTRODUCTION

Maintaining and improving soil quality is crucial for agricultural productivity and environmental quality sustainability for future generations [1,2,3]. Most of soils in Africa exhibit low nutrient levels with a high propensity towards nutrients losses due to their fragile nature [4]. Problems of degradation of soil health are due to unbalanced inorganic fertilizer use, inadequate use or no use of organic manure and crop residues [5,6]. Determination of appropriate crop residues management practices could give a welcome agricultural technology as it will improve and sustain crops yields [7,8]. In addition to the main nutrients (N, P, and K), crop residues contain also substantial amounts of secondary nutrients and micronutrients; therefore, returning back these residues into the soil may be one of the best alternative practices for improving the physical, chemical, and biological properties of the poor soils [9,10,11]. With expanding strategies of direct sowing and conservation agriculture often associated to minimum tillage, the use of cover plants or crops residues as mulch, contributed also to protect and improve soil properties [12].

In the cotton growing zones of Burkina Faso, as well as many parts in the tropics, crop residues are, in general, burned or removed from the fields for various domestic uses [13,7,14] while their incorporation increases the soil organic matter content [15,8]. These inappropriate practices in continuous cropping are unfavorable to soil fertility maintenance as they led to low organic matter content affecting soil fertility, and also crop yields [14].

A lot of researches have highlighted the interest of recycling crops residues in organic manure or their incorporation into soil [16,17,18]. Using only inorganic fertilizers can compromise the intensification of cotton and cereals production system without calco-magnesian amendments through the application of rock phosphate or dolomite which improve the status of cropped soils. Long-term experiments were implemented and analyzed, in many places in the world, to look for sustainable options of cultivated soils management and improve productivity [19,20].

The objective of this study was to evaluate crops residues management (CRM) and fertilization effects on soil chemical properties and crop yields under cotton-maize-sorghum rotation systems, through 30 years experimentation. These effects are analyzed for better recommendation of integrated soil fertility management and sustainable crops production systems.

2. MATERIALS AND METHODS

2.1 Site Description

This study has been conducted since 1982 at the experimental and seed production farm of Boni (3°26 ' W Longitude, 11°32 ' N Latitude and 302 m above sea level) on a lixisol. Climate is of South-Sudanese type, with a rainy season occurring between May and October, and a dry season, from November to April. In general, the annual rainfall distribution was very irregular and ranged between 723 and 1353 mm with 40 to 75 rainy days.

2.2 Experimental Design/Layout and Treatment

A non-randomized blocks design was used in this experiment covering 6 hectares (ha), subdivided in 3 plots of 2 ha, each spaced by 4 m (Fig. 1). The experimental unit was 0.5 ha (100 m x 50 m) assigned to each treatment. Every year, each plot of 2 ha containing compared treatments, was affected to cotton, maize or sorghum and cropped according to a cotton-maize-sorghum rotation system. The treatments were three crops residues management practices, combined with rock phosphate (25% P_2O_5 and 35% CaO) application and the use of inorganic fertilizers, as defined below:

T1 - Extensive management of crop residues: the straws of maize and sorghum are removed from the field or grazed, while cotton straws were burned. Every three years, on the maize sub-plots, 300 kg ha^{-1} of rock phosphate are applied after ploughing and harrowing.

T2 - Semi-intensive management of crop residues: the maize straws are incorporated into the soil by ploughing at the end of the rainy season and the cotton straws were burned in the field. The total sorghum straws harvested (an average of 4 t ha^{-1}) were composted after 45 days of crushing by 20 cows in a traditional cowshed, located near the field. During composting process, 300 kg of rock phosphate were mixed with the sorghum straws. Every three years, the compost obtained by recycling sorghum straws, is applied on maize sub-plots at the rate of 6 t ha^{-1}. The mean composition of the compost produced was: 20.5, 2.2, 1.9, 1.8, 0.3, 0.64 and 0.15% of C, N, P, K, S, Ca and Mg.

T3 - Intensive management of crop residues: the maize straws are incorporated into the soil by ploughing at the end of the rainy season and the cotton straws were burned in the field. The total sorghum straws harvested (an average of 4 t ha^{-1} of sorghum straws) are recycled into farmyard manure, in a raining season park, under only rains watering after 60 days of crushing by 20 cows [16]. This farmyard manure composition was the following: 20.1, 2.2, 1.1, 1.7, 0.3, 2.14 and 0.19% of C, N, P, K, S, Ca and Mg. Every 3 years, 6 t ha^{-1} of farmyard manure combined with 300 kg ha^{-1} of rock phosphate, were applied on maize sub-plots.

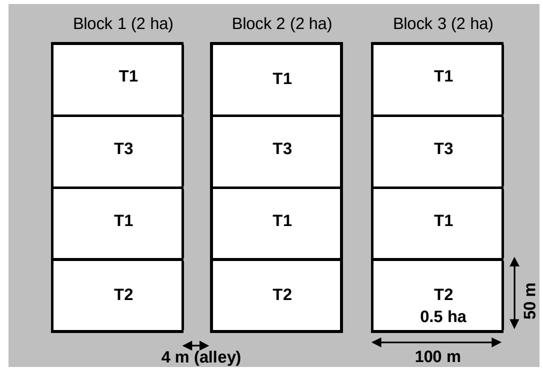

Fig. 1. Representation of experiment design at Boni

2.3 Fertilization, Material Description and Study Management

The annual fertilization (inorganic fertilizers and rock phosphate), applied per hectare was 46 kg N, 25 P, 48 K, 18 S and 1 kg B on cotton; 74 kg N, 25 P, 60 kg K on maize and 46 N, 25 kg P, on sorghum.

Plant materials used in this study were improved varieties of cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) with potentials yields of 3 to 4 t ha^{-1}, 4 to 5 t ha^{-1} and 2 to 3 t ha^{-1}, respectively.

Every year, before sowing the crops (between May 20 and July 10), each plot was ploughed using a tractor drawn plough at 20 to 25 cm soil depth, and then harrowed. Cotton was sown in rows spaced by 0.80 m and plant distance was 0.40 m. Fifteen days after emergence, cotton plot was thinned to two plants per hill, to obtain a theoretical stand of 62 500 plants per hectare. Maize and sorghum were sown using a tractor and thinned manually. The plots were kept weed free by manual weeding combined to herbicides application (999 g ha^{-1} métolachlor + 501 g ha^{-1} terbutryne on cotton, 1250 g ha^{-1} pendimethalin on maize and 750 g ha^{-1} terbutryne + g ha^{-1} terbutylazine on sorghum). Cotton pest control was ensured by usual insecticides applied according to recommended procedure.

A liming of all the plots was carried out in 1989 with the amount of 1 t ha^{-1} using lime containing 53% CaO and 35% MgO. In 1995, a subsoiling at 30-35 cm soil depth was carried out using chisel, before planting *Andropogon gayanus* grass strips, to prevent soil erosion.

2.4 Sampling and Measurements

Before crops sowing, three composite soil samples were randomly collected in each cotton sub-plots, in May, at 0-20 cm depth, for chemical analysis. All the soil samples for each treatment were air-dried, crushed and sieved on 2 mm mesh for laboratory analyses. Soil organic carbon was measured by the Walkley-Black procedure [21]. Total Nitrogen was determined by the Micro-Kjeldahl method [22]. Available P was determined using Bray I method as explained in Fixen and Grove [23]. Soil pH was determined using glass electrode pH meter, in a suspension of soil to water at the ratio of 1:25 [24]. Exchangeable cations were determined according to the procedure described by Landon [25].

Crop yields (seed cotton, grain yield of maize and sorghum) were measured at the end of each growing season on the sub-plot.

2.5 Statistical Data Analysis

Analysis of variance of soil data collected at 6 years frequency corresponding to two cycles of triennial rotation were done using GENSTAT 9.2 software. The test of Student-Newman-Keuls was used for means comparison when the analysis of variance reveals significant differences between treatments at 5% probability.

3. RESULTS AND DISCUSSION

3.1 Crops Residues Management Effects on Soil Carbon and Nitrogen Contents

The soil C and N contents decreased significantly (P = .05) with cropping duration in all the three crop residues management (CRM) practices (Table 1). After 30 years of continuous cultivation in extensive CRM (T1), semi-intensive CRM (T2) and intensive CRM (T3) practices, the soil organic carbon decline was 43%, 29% and 23%, respectively, for annual decrease of 1.4%; 0.9% and 0.8%. The decline of carbon might be related to the high mineralization rate of soil organic matter [26,5] accentuated by annual ploughing and water erosion effects [27,28]. The C/N ratio values ranging between 10 and 12 (Table 1) confirms this mineralization of soil organic matter [29] for all the compared CRM practices, leading to a decrease of soil nitrogen contents, which is important with residues exportation [30,31]. Maize straws incorporation into the soil and the use of organic and inorganic fertilizers in semi-intensive CRM and intensive CRM, reduced the degradation of soil fertility, particularly, the decline of C and N as these nutrients are important in farming under the tropic [32,13]. Using inorganic fertilization, without any organic restitution, depress soil chemical characteristics with the cropping duration, indicating the limits of the use of these fertilizers, because they lead generally to soil nutrients decline and soil acidification [33,34,35]. The soil production potential is then affected by reduction of the soil carbon stock [2,5] while it should be considered as a capital to maintain and improve soil quality, for sustainable management of cropping systems [11]. Autfray et al. [14] reported that increasing the biomass to be recycled combined to a better management of livestock and avoiding crop residues burning, gave a balance in terms of organic fertilization for the large majority of south-Mali exploitations.

3.2 Evolution of Soil P Contents according to Crop Residues Management

In 30 years of continuous cropping, total P (107 to 340 mg kg^{-1}) and available P (18.5 to 21 mg kg^{-1}) contents decreased significantly (P = .05) in control plots as well as those with compost and farmyard manure application (Table 2). Then, the P values are established under the critical level contents reported to be 200 and 30 mg kg^{-1} for total P and available P, respectively [16,36]. The decline of total P which was 25% in all treatments after 25 years [13], reached after 30 years 47%, 40% and 28%, respectively in extensive CRM (T1), semi-intensive CRM (T2) and intensive CRM (T3). Available P contents varied from 21 to 6.75 mg kg^{-1}, corresponding to a loss of 68% in 30 years of extensive CRM (Table 2). The available P and total P contents, lower than critical level, indicate that these soils presented phosphorus deficiency [30]. The rock phosphate application combined to the restitution of crop residues increased the phosphorus solubility and release by micro-organisms [37,8]. According to Fabre and Kockman [38], liming activates the biological processes and improves the assimilability of phosphorus. Crop residues contain inorganic and organic P forms, easily available for plants and microorganisms [6]. Tillage practices can also influence P release from crop residues [3]. Vanlauwe et al. [37]

showed that mixing crop residue with soil particles by moldboard ploughing resulted in acceleration of crop residues decomposition and subsequently, increased nutrient release.

Table 1. Variation of soil organic carbon and nitrogen contents on 0-20 cm depth at Boni

Treatments	Cropping duration	C	N	C/N
		g kg^{-1}		
T1= Extensive CRM*	1 year	9.25 ± 0.02	0.81 ± 0.006	11.50 ± 0.21
	6 years	5.85 ± 0.08	0.55 ± 0.003	10.50 ± 0.78
	12 years	5.55 ± 0.22	0.37 ± 0.003	14.81 ± 2.19
	18 years	5.50 ± 0.04	0.50 ± 0.012	11.21 ± 0.42
	25 years	6.23 ± 0.16	0.49 ± 0.010	12.74 ± 1.58
	30 years	5.25 ± 0.06	0.48 ± 0.006	11.02 ± 0.64
Cumuleted decrease over 30 years (%)		43	41	4
T2 = Semi-intensive CRM	1 year	7.90 ± 0.08	0.74 ± 0.008	10.75 ± 0.85
	6 years	7.25 ± 0.01	0.69 ± 0.001	10.37 ± 0.07
	12 years	7.10 ± 0.07	0.53 ± 0.003	13.45 ± 0.71
	18 years	6.88 ± 0.02	0.63 ± 0.002	11.01 ± 0.16
	25 years	6.56 ± 0.16	0.52 ± 0.010	12.53 ± 1.58
	30 years	5.64 ± 0.08	0.44 ± 0.001	12.76 ± 0.80
Cumuleted decrease over 30 years (%)		29	40	-
T3= Intensive CRM	1 year	7.45 ± 0.11	0.65 ± 0.005	11.52 ± 1.06
	6 years	5.60 ± 0.16	0.53 ± 0.012	10.49 ± 1.56
	12 years	6.30 ± 0.18	0.50 ± 0.002	12.65 ±1.84
	18 years	7.01 ± 0.01	0.56 ± 0.004	12.51 ±0.13
	25 years	7.14 ± 0.01	0.57 ± 0.002	12.46 ± 0.06
	30 years	5.77 ± 0.08	0.55 ± 0.016	10.81 ± 0.76
Cumuleted decrease over 30 years (%)		23	16	6
Probability (0.05)	Cropping duration	0.010	0.001	0.045
	Treatments	0.375	0.203	0.946
	Trait. x Cropping duration	0.002	0.003	0.441

**CRM= Crop residues management. Values after the sign ± represent standard deviation of means*

Table 2. Variation of soil contents of available P and total P according to crops residues management (0-20 cm depth) at Boni

Treatments	Cropping duration	Available P (Bray 1)	Total P
		mg kg^{-1}	
T1= Extensive CRM*	1 year	21.00 ±1.41	241.50 ± 12.12
	6 years	19.50 ±2.12	279.00 ± 37.98
	12 years	10.07 ± 3.82	232.80 ± 12.45
	18 years	9.00 ± 4.26	107.17 ± 20.03
	25 years	7.69 ± 2.28	190.97 ± 22.96
	30 years	6.75 ± 0.81	127.83 ± 20.55
T2 = Semi-intensive CRM	1 year	18.50 ± 0.71	279.50 ± 20.51
	6 years	18.00 ± 1.41	296.00 ± 2.83
	12 years	12.63 ± 4.70	330.20 ± 14.42
	18 years	15.28 ± 5.08	221.73 ± 39.21
	25 years	7.87 ± 2.28	199.01 ± 22.96
	30 years	8.16 ± 1.07	167.12 ± 68.77
T3= Intensive CRM	1 year	19.50 ± 0.71	221.00 ± 5.66
	6 years	18.50 ± 0.71	235.00 ± 14.14
	12 years	16.07 ± 5.71	239.75 ± 15.20
	18 years	10.79 ± 4.44	140.31 ± 66.91
	25 years	6.08 ± 0.11	164.63 ± 12.42
	30 years	7.81 ± 0.91	159.61 ± 46.43
Probability (0.05)	Cropping duration	0.001	<0.0001
	Treatments	0.850	0.001
	Treat. x Cropping duration	0.034	< 0.0001

**CRM= Crop residues management. Values after the sign ± represent standard deviation of means*

Table 3. Soils bases reserves and cation exchange capacity according to crops residues management (0-20 cm depth) at Boni

Treatments	Cropping duration	Ca++	Mg++	K+	Na+	SBE	CEC
		Cmol^{+}kg^{-1}					
T1 = Extensive CRM*	1 year	2.64	1.05	0.37	0.04	4.10	6.50
	6 years	1.91	0.60	0.15	0.04	2.70	3.32
	12 years	1.95	0.43	0.10	0.05	2.65	4.16
	18 years	1.77	0.36	0.19	0.05	2.36	3.68
	25 years	1.51	0.39	0.12	0.03	2.05	3.22
	30 years	1.39	0.29	0.11	0.05	1.84	3.05
T2 = Semi-intensive CRM	1 year	2.13	0.74	0.35	0.06	3.28	5.42
	6 years	1.95	0.66	0.23	0.05	2.89	3.68
	12 years	2.43	0.62	0.14	0.08	3.37	5.00
	18 years	2.19	0.47	0.19	0.05	2.90	4.46
	25 years	1.50	0.33	0.12	0.03	1.99	3.82
	30 years	1.54	0.45	0.12	0.02	2.12	3.75
T3 = Intensive CRM	1 year	2.21	0.86	0.34	0.03	3.43	4.81
	6 years	2.16	0.76	0.21	0.04	3.20	3.70
	12 years	2.71	0.77	0.49	0.05	3.72	6.63
	18 years	2.16	0.55	0.19	0.03	2.92	3.94
	25 years	2.07	0.54	0.14	0.03	2.77	3.82
	30 years	2.37	0.37	0.13	0.03	2.90	3.56
Probability (0.05)	Cropping duration	0.034	< 0.0001	0.069	0.816	0.001	0.031
	Treatments	0.039	0.008	0.348	0.758	0.016	0.775
	Treat. x Cropping duration	0.003	< 0.0001	0.244	0.997	0.002	0.035

**CRM= Crop residues management*

3.3 Evolution of Exchangeable Bases and CEC of Soil according to CRM Practices

The soils used in the study are characterized by low reserves in exchangeable bases which decreased significantly after 30 years of continuous cultivation (Table 3). Decline of Ca^{2+} contents from 2.64 to 1.39 cmol^{+} kg^{-1}, and those of Mg^{2+} from 1.05 to 0.29 cmol^{+} kg^{-1} represents cumulated decrease of 47% and 72%, respectively, in extensive CRM plots. This trend is also observed for soil K^{+} and Na^{+} contents (Table 3), which decline significantly in all the CRM practices and then, confirm the soil degradation [25,3]. During 30 years, gradually decline of exchangeable bases, resulted primarily from the nutrients uptake by the crops. These negative effects of continuous land cultivation, accentuated by crop residues removal without any organic restitution are frequently reported by numerous authors [20,30]. Important decrease of soil Ca^{2+} and Mg^{2+}, affect the total exchangeable bases as well as the CEC and damaged adsorbing complex, making it more sensitive to degradation, especially lead to soil acidification [11]. Cation exchange capacity, while declining from 4.81 to 3.56 cmol^{+} kg^{-1}, decreased by 26% after 30 years of intensive CRM (T3) versus 31% in semi-intensive CRM (T2) and 63% in extensive CRM (T1).

The low values of cation exchange capacity confers to these soils a poor capacity to maintain nutrients coming from soil mineralization or from inorganic manure applications [6,12]. It is known that CEC declining reveals chemical degradation of soil and the decline of both, CEC and soil organic matter, confirms the relations between these two parameters on lixisol [26,37]. Recycling crop residues into compost or farmyard manure reduced significantly, the losses of these two cations [26]. The effects of liming carried out in 1989, seem to be more beneficial on soil Ca^{2+} contents by its improvement. Beyond the direct effects on the solid phase of soil and the soil solution, liming is characterized especially by indirect effects on soil properties [38,37].

3.4 Crop Residues Management Effects on Soil pH

Results showed that the variations of soil pH water and pH KCl were statically significant after 30 years of continuous cropping for the three CRM treatments (Table 4).

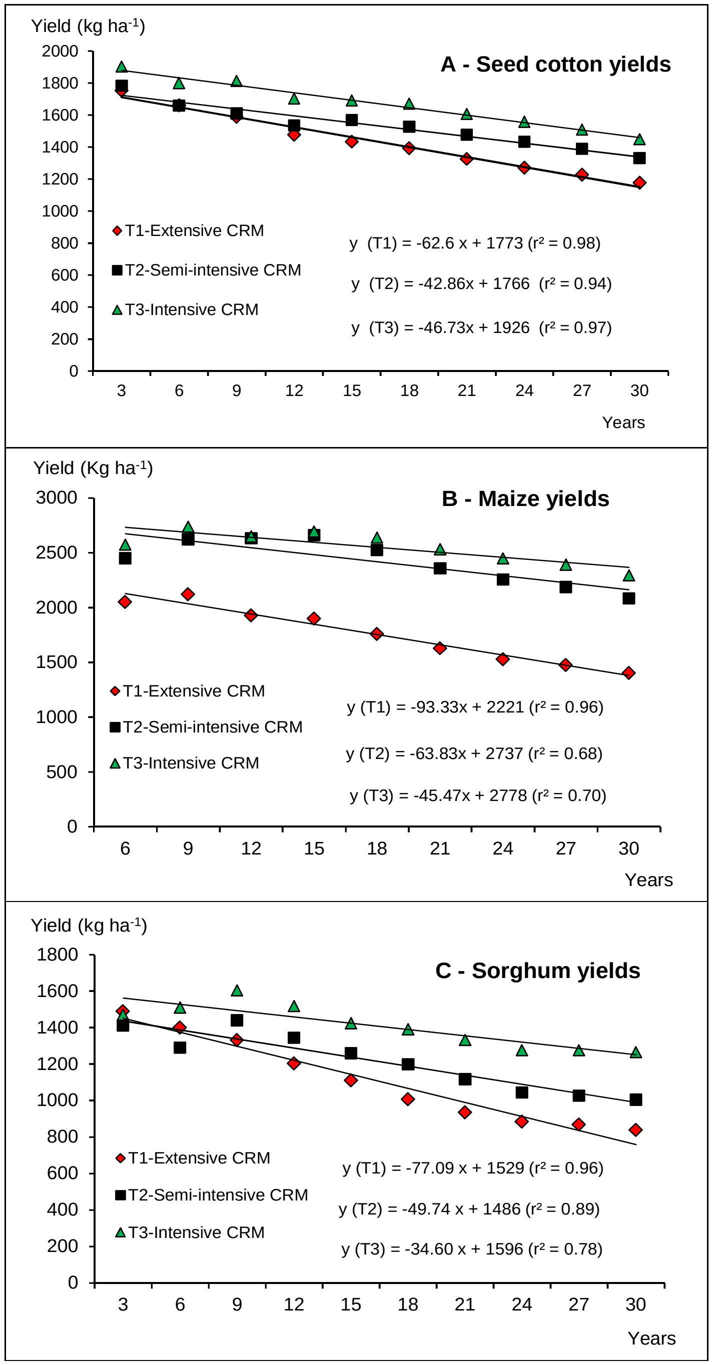

Fig. 2. Evolution of crops yields (A, B, C) during 30 years under crop residues management practices and fertilization at Boni

After six years, the pH water values highly decreased, requiring a liming in 1989 to solve this problem [39,40]. After this liming and subsoiling in 1995, the effect of CRM showed few influence on pH which, after 25 years of continuous cropping, presented comparable values with those observed at the beginning of the study. However, various authors reported an influence of CRM on soil pH [8]. In addition, it was observed △pH values of 1 in average, particularly in the first and 30th years of soil exploitation, which represented an acidification induced by exchangeable aluminum [41,37].

Table 4. Evolution of soils pH depending on cropping duration and CRM (0-20 cm depth) at Boni

Treatments	Cropping duration	pH Water	pH KCl	△pH
T1 = Extensive CRM*	1 year	6.43 ± 0.11	5.50 ± 0.14	0.92
	6 years	5.95 ± 0.21	4.70 ± 0.28	1.25
	12 years	5.88 ± 0.04	4.93 ± 0.39	0.95
	18 years	5.90 ± 0.42	5.27 ± 0.04	0.63
	25 years	6.33 ± 0.21	5.49 ± 0.01	0.84
	30 years	5.86 ± 0.53	4.69 ± 0.66	1.17
T2 = Semi-intensive CRM	1 year	6.10 ± 0.00	5.05 ± 0.07	1.05
	6 years	5.93 ± 0.25	5.00 ± 0.14	0.92
	12 years	5.94 ± 0.27	5.34 ± 0.56	0.60
	18 years	5.97 ± 0.48	5.39 ± 0.02	0.58
	25 years	6.27 ±0.21	5.43 ± 0.01	0.84
	30 years	5.56 ± 0.57	4.67 ± 0.93	0.89
T3 = Intensive CRM	1 year	6.35 ± 0.07	5.01 ± 0.21	1.35
	6 years	6.08 ± 0.32	5.38 ± 0.32	0.70
	12 years	6.17 ± 0.30	5.42 ± 0.10	0.74
	18 years	5.99 ± 0.35	5.25 ± 0.35	0.74
	25 years	6.37 ± 0.06	5.62 ± 0.02	0.75
	30 years	5.74 ± 0.09	4.52 ± 0.27	1.22
Probability (0.05)	Cropping duration	0.021	0.009	
	Treatments	0.460	0.781	
	Treat. x Cropping duration	0.309	0.108	

**CRM= Crop residues management. Values after the sign ± represent standard deviation of means*

3.5 Crop Residues Management and Fertilizers Effects on Crops Yields

The continuous cultivation of soil, induced a decreasing pattern of crops yields, higher in extensive CRM than the other treatments (Fig. 2).

The low yields level in extensive CRM plots (T1), using mainly inorganic fertilizers, might be related to soil fertility decline intensity as well as the low efficiency of applied fertilizers [4,15,8]. However, recycling of crop residues in compost (T2) and farmyard manure (T3) improved soil properties, particularly by inducing a better availability of water and nutrients [9,15,18] which reduced yields decrease due to both the soil fertility decline and rainfall irregularity [19,40,12].

4. CONCLUSION

Continuous cropping led to the decline of soil chemical properties involving its degradation increase when crop residues are removed. Crop residues recycling and the use of compost or farmyard manures, reduced yields decrease and the degradation of soil fertility, particularly, the decline of carbon content, exchangeable bases and CEC. The relative stability of pH during 30 years of continuous cultivation of soil is mainly related to the liming effects combined to regular application of rock phosphate, which revealed to be essential to prevent soil acidification.

In general, the crop residues incorporation influences soil biological activities and the availability of nutrients which need to be better specified. Because of early end of rainfall which often compromises incorporation of maize straws, a more suitable valorization should be considered for these residues as well as cotton straws whose burn is not acceptable any more. Moreover the crop residues management and valorization of rock phosphate, the decline of soil fertility observed in this experiment, suggested a reduction of the ploughing frequency, for a better sustainability of this production system.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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