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Long-term effect of forest and landscape restoration practices on soil organic carbon stock in semi-arid Burkina Faso

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ABSTRACT

In semi-arid areas, forest and landscape restoration (FLR) practices are being implemented to reverse the land degradation process. The objective of this study was to investigate the long-term effect of FLR practices on soil organic carbon stock (SOCs) under different land uses in the semi-arid region of Burkina Faso. The study was conducted on degraded land under rehabilitation practices for 45, 27, 18 and 11 years, which were compared to similar land without specific rehabilitation measures. The soil was collected in 2018 in 35 sampling plots of 30 m x 30 m. Soil analysis concerned bulk density, soil particle size, soil pH, soil organic carbon content, and respiratory activity of microorganisms. SOCs increased by 150%, 98% and 29% over 0-10 cm depth in 45-, 27- and 11-year of FLR practices, and decreased by 6% in 18-year of FLR practices compared to their respective

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control. SOCs were not linearly increased with the duration of the implementation of FLR practices because the variation of SOCs depends on several other parameters such as soil texture, and types of combination of FLR practices. The highest SOCs were recorded for 27 years (9.5 $t.ha^{-1}$) and 45 years (8.5 $t.ha^{-1}$) of FLR practices. This study revealed the importance of including Assisted Natural Regeneration (ANR) as one of the combined FLR practices, for improvement of SOCs.

Keywords: Land rehabilitation, agricultural lands, assisted natural regeneration, Burkina Faso.

INTRODUCTION

Soil organic carbon (SOC) is an essential component of ecosystems (Ouandaogo et al. 2016; Ouattara et al., 2017). It plays a key role in biomass production through its positive influence on nutrients availability, soil water retention, and biodiversity (Lal, 2004). SOC is also important for fighting against soil erosion because of its contribution to soil aggregates stabilization and reduction of soil erodibility (ADEME, 2014). Depending on its management, soil-plant systems can be a source or a sink of carbon. It has therefore a key role for mitigating greenhouse effect and global warming. Indeed, climate change appears to be one of the major challenges of current agriculture. Nevertheless, sub-Saharan Africa which is characterized by the combined effects of low soil fertility level, poor management of an already fragile ecosystem and erratic climatic conditions (Mando et al., 2001), is one of the most affected. In Burkina Faso, 69% of land are considered as requiring restoration and rehabilitation measures and 22% of land are assessed as highly degraded, and even stripped (MEEVCC, 2017). In its northern region, erosion leads to rainwater losses resulting from runoff of about 31% and losses of soils estimated at 28 $t.ha^{-1}.an^{-1}$ (INERA, 2000). Availability of arable land is then reduced and its worsening due to the increase in bare land beaches (locally called *zipéllé*) is a major problem (Zougmoré et al., 2004).

Various forest and landscape restoration (FLR) practices, such as *Zaï*, stone bunds and Assisted Natural Regeneration (ANR), have been initiated to reverse land degradation process. In most contexts, FLR practices may have positive effects on soil fertility and SOCs. Indeed, stone bunds lead to an improvement in fine soil particles and soil moisture (Zougmoré et al., 2003; Doamba et al., 2011). Compost applications also lead to a decrease in bulk density and an increase in SOCs, depending on the quality of compost (Bambara et al., 2015). FLR practices have also positive effects on soil biological parameters, particularly on microorganism activity and macrofauna (Doamba et al. 2011; Coulibaly et al., 2018).

According to Coulibaly et al. (2018), it is necessary to combine FLR practices to optimize their agroecological value. In the same way, Gnissien (2018) has shown that the combination of several practices including stone bunds had the best potential of SOCs improvement. But, the effects of combined FLR practices on soil fertility depend on several parameters such as the duration of the implementation and the type of combination of FLR practices which deserve to be more elucidated. Indeed, in eastern Burkina Faso, it has been shown that two years of stone bunds implementation were not sufficient to significantly improve soil chemical parameters (Doamba et al., 2011). Bambara et al. (2012) who investigated the effects of *zaï*, and stone bunds implemented for ten years, have concluded that duration alone does not permit to restore soil fertility. Besides, under a south-soudanian climate of western Burkina Faso, *Zaï* forest, *Zaï* forest + stone bunds and stone bunds treatments resulted in an increase of soil organic carbon stock by 166%, 77% and 21% in the 0-20 cm depth, respectively (Yameogo et al., 2019). It seems that the effect of the combination of FLR practices is not the same as the sum of the effects of each individual FLR practice. However, under what conditions are these interactions positive? What role do soil parameters play in the success of the combination of these practices? In addition, in the semi-arid area, most authors have investigated the effect on peasant fields rather than the whole landscape and they did not consider forest land in their analysis. However, in this fragile ecosystem, long-term effect of FLR practices on fertility of rehabilitated forests deserve to be investigated, as a leeway to adapt to climate change. Thus, in this study, we seek to evaluate long-term SOCs change under different combinations of FLR long-term practices on various semi-arid soils in Burkina Faso.

MATERIALS AND METHODS

Study area

The study was conducted in a semi-arid-climate, in northern and central-north regions of Burkina Faso. One site in Ouahigouya, Yatenga province, is located in the northern region where latitude ranges between 13°06’N and 14°26’N and longitude between 1°43’E and 2°55’E (Figure1). In the Sanmatenga province, two sites were identified in Kaya and Pissila. Those sites are in central-north region between 12˚30’N and 13˚56’N of latitude and 0˚40’E and 1˚37’E of longitude. A mean annual precipitation of 750 mm and 800 mm are recorded in Yatenga and Sanmatenga provinces respectively, with a dry season that extends from November to June, a wet season that extends from July to October and peak rainfall observed in August. Ferric Lixisols (WRB, 2015) are the dominant types of soil found in those areas. FLR practices for agricultural and forestry purposes have been implemented for decades in these areas.

Experimental design

FLR treatments were chosen based on the duration of implementation of FLR practices on an initial degraded land, as shown in Table 1. In all cases, FLR practices included at least *zai* and stone bunds. Varying additional practices were implemented on each site, including Assisted Natural Regeneration (ANR), cropping practices with temporary fallows and/or manure application.

Zaï consists in making hollows of 10-15 cm of depth and 20-40 cm of diameter on crusting lands to permit their recuperation for crops production (Kagambega et al., 2010). Organic matter is also added to prepare the seed bed. Stone bunds are mechanical barriers use to stop or slow down runoff water (Kagambega et al., 2010). They consist in making rows with stones following points of equal altitude, perpendicularly to the inclination. ANR consists in protecting young trees from grazing or weeding to boost their growth. This technique was developed and promoted to fight against deforestation and land degradation in semi-arid regions. Crop management (rotation + crop/fallow successions) consists in staggering the production of different crops and fallow on the same plot of land. This method aims to maximize the management of soil fertility from one year to the next and to diversify production to limit the risk of poor production.

In Ouahigouya, two FLR treatments were identified, Gourga Forest (GF) and Ouahigouya Agricultural Rehabilitated Land (OARL). GF is a forest restored from degraded land for 45 years. OARL is an agricultural land restored from degraded land for 27 years. Two FLR treatments were also identified in Sanmatenga province: Pissila Agricultural Rehabilitated Land (PARL) in Pissila and Kaya Agricultural Rehabilitated Land (KARL) in Kaya. Both were agricultural lands Rehabilitated from degraded land for 18 years and 11 years, respectively. Each FLR treatment was compared to control treatments, in which no FLR practices were applied, leading to highly degraded land. The controls were chosen in the condition that they were identified near each site to ensure that the current site with FLR practices had in the past (before the implementation of FLR practices) the same soil condition as the control. They have a similar type of soil (Ferric Lixisols). Control treatments were respectively named: Control of the Gourga Forest (CGF) for GF, Control of Ouahigouya Agricultural Rehabilitated Land (COARL) for OARL, Control of Pissila Agricultural Rehabilitated Land (CPARL) for PARL and, Control of Kaya Agricultural Rehabilitated Land (CKARL) for KARL.

The data were collected on 35 plots of 30 m x 30 m (Figure 1) distributed over the treatments as well as following 9 plots on GF and 6 plots on TGF; 3 plots on OARL and 2 plots on COARL; 4 plots on PARL and 4 plot on CPARL; 4 plots on KARL and 3 plots on CKARL. On each treatment, the number of repetitions were chosen to cover a uniform area and to be representative of density and type of vegetation cover in each site.

Soil sampling and analysis

Soil samples were randomly collected in 2018 at the depth of 0-10 cm, 10-20 cm, and 20-30 cm from five replicated sampling points following a zigzag pattern per plots of 30 m x 30 m. Undisturbed soil samples were collected from all treatment by cylinder method for analysis of bulk density, and composite soil samples were made from the five samples per plots to analyze other soil characteristics. The soil samples were air-dried. All plant materials were removed. Soil samples were sieved through 2 mm sieve and the coarse particles were weighed. Soil particle size, soil pH, soil organic carbon content (SOCc), and respiratory activity of microorganisms were also determined.

The undisturbed soil samples were oven dried at 105ºC for 24 h to determine bulk density (ρ). Bulk density was calculated as a mass of oven-dried soil divided by the volume of soil core [ρ (g.cm^{-3}) $= m\ (g)/v\ (cm)$]. Soil particle size distribution (< 2 mm) was determined using the densimetric method (Bouyoucous, 1962). It consists in breaking the chemical bonds of the soil aggregates in a solution containing sodium hexametaphosphate ($Na_6(PO_3)_6$) and sodium carbonate (Na_2CO_3), and by performing density measurements for the calculation of the contents of sand, clay and silt. pH water and pH KCl were measured with an electronic pH meter (SensION^{TM+}) using a 1:2.5 soil/water and soil/KCl solution suspension (AFNOR, 1999). Soil organic carbon content (SOCc) was measured following the dichromate oxidation method (Walkley and Black, 1934). The soil organic carbon stock (SOCs) (g C.cm^{-2}) was estimated as a product of SOCc (%) of fine soils (< 2 mm), bulk density (g.cm^{-3}) and by depth (cm) (Blanchart and Bernoux, 2005). Thereafter SOC stock was expressed in t.ha^{-1}:

$\boldsymbol{SOC}$s (t.ha^{-1}) = SOCc × $\boldsymbol{\rho}$ × $\mathbf{D}$ × ($\mathbf{1-frag}$) × 100.

SOCs: soil organic carbon stock; **SOCc:** soil organic carbon content (%); **ρ**: soil bulk density (g.cm^{-3}); **D:** depth at which the sample was collected (cm); **frag:** percentage of coarse (> 2 mm).

Respiratory activity of microorganisms was measured following Dommergues (1960). The method consists in incubating soil samples for 21 days and measuring the CO_2 released by microorganisms by trapping it in a solution of NaOH. Carbon mineralization coefficient was also calculated by Dommergues (1960) formula:

$$\frac{C - CO2\ (mg/100g\ sol))}{C\ (mg/100g\ sol)} * 100$$

C-CO_2 represents the carbon mineralized in form of CO_2 in mg per 100 g of soil and C, the SOC content in mg per 100 g of soil.

Statistical analysis

The student and Wilcoxon tests were used to assess differences between FLR and control treatments on each site, depending on the normality of data, which was verified by the Shapiro-Wilk test. Differences between treatments were significant at $p < 0.05$. To identify and test the relationships between SOCs and soil properties, a Principal Component Analysis (PCA) was carried out by not taking into account the depth. Statistical analysis was performed using R (v. 3.5.2). The package FactoMiner (Sebastien et al., 2008) of R was used to perform the PCA.

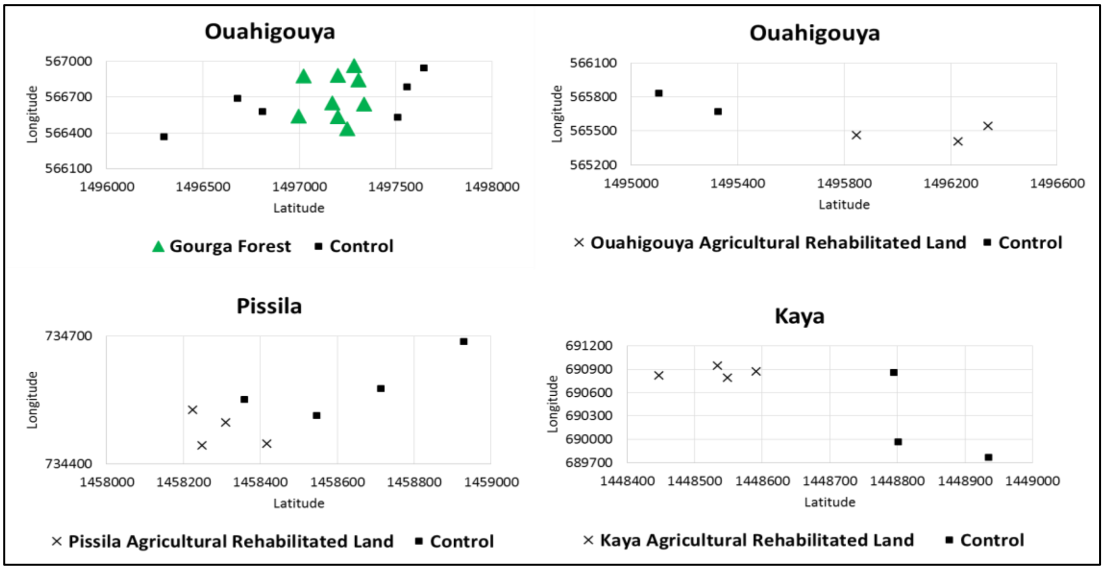

Figure 1: Repartition of the 30 m x 30 m sampling plots on four sites of the semi-arid region of Burkina Faso.

Table 1: Presentation of type of FLR practices, duration of FLR implementation, Woody plant density, Soil texture (0-10 cm) for each treatment in Yatenga and Sanmatenga provinces.

Province	Treatments	Types of FLR practices	Duration of FLR implementation (years)	Soil texture (0-10 cm)	Woody plant density (trees.ha^{-1})	Number of sampling plots
Yatenga	**GF**	Zaï + ANR + stone bunds + organic manure	45	Sandy-loam	594	9
	CGF	None	None	Sandy-loam	-	6
	OARL	Zaï + ANR + stone bunds + crop management (rotation + crop/fallow sucessions)	27	Sandy-clay-loam	93	3
	COARL	None	None	Sandy-loam	-	2
Sanmatenga	**PARL**	Zaï + ANR + stone bunds + organic manure	18	Sandy-loam	19	4
	CPARL	None	None	Sandy-clay-loam	-	4
	KARL	Zaï + stone bunds + organic manure	11	Sandy-clay-loam	11	4
	CKARL	None	None	Sandy-clay-loam	-	3

GF: Gourga Forest; CGF: Control of Gourga Forest; OARL: Ouahigouya Agricultural Rehabilitated Land; COARL: Control of Ouahigouya Agricultural Rehabilitated Land; PARL: Pissila Agricultural Rehabilitated Land; CPARL: Control of Pissila Agricultural Rehabilitated Land; KARL: Kaya Agricultural Rehabilitated Land; CKARL: Control of Kaya Agricultural Rehabilitated Land.

RESULTS

Soil physical characteristics on FLR practices and controls

Soil particle size distribution, bulk density, and coarse percentage of FLR practices and control treatments are presented in Table 2. The comparison between 45-year-old FLR treatment of the forest and its control treatment in Ouahigouya has shown that their soils were statistically similar on the three depths, for all the measured physical characteristics. For the comparison between croplands under FLR treatment and their respective control treatment, some differences were recorded on the three sites. In Ouahigouya, the 27-year-old FLR treatment of the cropland and its control treatment have shown significant differences only for the sand content and the coarse particles for the studied depths. The control treatment exhibited a higher sand content in comparison to the FLR treatment. The coarse particles were significantly higher on the FLR treatment than its control treatment. In Pissila, the 18-year-old FLR treatment of the cropland and its respective control have shown some significant differences regarding clay and sand contents. On the three depths, the clay content was significantly higher on the control treatment, with an increase of 158%, 122% and 72% on the 0-10 cm, 10-20 cm and 20-30 cm depth. The 10-20 cm and 20-30 cm depths presented a significant high sand content in the soil of the FLR treatment, compared to the control treatment. In Kaya, the soil of the cropland with 11-year-old FLR practices and its respective control treatment were statistically similar for all the parameters except on the 20-30 cm depth, on which the sand content was significantly higher on the FLR practice.

Soil chemical and biological characteristics on FLR treatments and control treatments

Soil pH water, pH KCl, respiratory activity of microorganisms and carbon mineralization coefficient (K_2) of FLR treatments and their control treatments are shown in Table 3. The 45-year-old FLR treatment of the forest of Ouahigouya has significantly increased the pH water from 5.3 to 5.7 on the 0-10 cm depth, and the cumulative CO_2 released by microorganisms (respiratory activity of microorganisms) from 43.8 to 69.8 mg CO_2/100 g of soil at the 10-20 cm depth, compared to its control treatment. The other measured characteristics were statistically similar for the two treatments. It was also observed that in Kaya, the coefficient of carbon mineralization increased with depth both on FLR and control treatment.

For the comparison between farmlands under FLR treatments and their respective control treatments, all the sites presented significant differences for some of the measured characteristics, except in Pissila where no significant difference was observed. On the 0-10 cm depth of the site 2 of Ouahigouya corresponding to cropland under the 27-year-old FLR treatment, the carbon mineralization coefficient (K_2) was the only characteristic which was not significantly higher on the FLR treatment, compared to its control treatment. On the 10-20 cm depth, in addition to K_2, the pH water was not significantly increased on the FLR treatment. On the 20-30 cm depth, the FLR treatment and the control treatment were statistically the same for all the measured characteristics. In Kaya, the pH water was the only measured characteristic which was significantly higher on the FLR treatment of the three studied depth (5.7, 6.1 and 6.1 respectively on the 0-10 cm, 10-20 cm, and 20-30 cm depths), in comparison to its control treatment (5.0, 4.9 and 4.8 at the three respective depths).

Soil organic carbon stock for different durations of FLR implementation

Table 4 represents the soil organic carbon stocks (SOCs) for different durations of

FLR implementation. Whatever the considered depth, there were no significant differences in SOCs between FLR treatment and its controls treatment for sites under FLR practices for less than 20 years, except in Pissila were SOCs under FLR practices at 10-20 cm depth was significantly lower than under control treatment. The cropland under 27 years of FLR practices implementation led to the highest SOCs at its 0-10 cm depth (9.5 $t.ha^{-1}$). Whatever the considered depth, the rate of SOCs increase was better in the forest with 45-year-old FLR practice, in comparison to its control treatment. Indeed, significant increases of 150% and 110% were respectively recorded at 0-10 cm and 10-20 cm depths in the forest, compared to 98% and 66% as SOCs increase rate at the respective depths of the 27 years old FLR practices. When degraded soil was converted into forest with a combined 45-year-old FLR practices, whatever the depth considered, SOCs was significantly higher, compared to its control treatment. It has also been observed that whatever the considered treatment, there is a decrease in SOCs at the deeper layers.

Relation between soil organic carbon stock and physico-chemical and biological characteristics of soils

The Principal Component Analysis (PCA) was performed to investigate the relations between the SOCs and other soil physico-chemical and biological characteristics (Figure 2). The first two dimensions explained 58% (CGF) to 85% (CKARL) of the variability depending on the site and the soil characteristics loaded differently on these dimensions. Less than 50% of the variation in SOCs was explained by individual variables, except for bulk density (r = 0.65) and pH KCl (r = 0.51) on GF, bulk density (r = 0.9) and coarse particles (r = - 0.8) on its control treatment CGF. On OARL, SOCs had a positive and strong coordinate with sand (r = 0.8), respiratory activity of microorganisms (r = 0.8) and carbon mineralization coefficient (K_2; r = 0.6). SOCs had also a negative and strong coordinate with clay (r = - 0.8), silt (r = - 0.7) and coarse particles (r = - 0.6). On COARL, less than 50% of the variation in SOCs was explained by individual variables, except for respiratory activity of microorganisms (r = 0.6), coarse (r = - 0.6) and pH water (r = - 0.7). Less than 50% of the variation in SOCs was explained by individual variables, except for bulk density (r = 0.8), coarse particles (r = - 0.8) and pH water (r = - 0.6) on PARL, bulk density (r = 0.5), coarse particles (r = - 0.8) and silt (r = 0.5) on its control treatment CPARL. On KARL, individual variables explained more than 50% of the variation in SOCs only for coarse particles (r = - 0.7), sand (r = 0.7), clay (r = - 0.5) and pH KCl (r = - 0.6). On CKARL, SOCs had a positive coordinate with pH KCl (r = 0.9), pH water (r = 0.9), coarse particles (r = 0.9), bulk density (r =0.7) and sand (r = 0.5). SOCs had also a negative coordinate with K_2 (r = - 0.8) and silt (r = -0.8).

Table 2: Soil physical characteristics on 0-10 cm, 10-20 cm and 20-30 cm depths of FLR practices and their controls.

		0-10 cm					**10-20 cm**					**20-30 cm**				
Site	Treatments	**Clay**	**Silt**	**Sand**	**Coarse**	**ρ**	**Clay**	**Silt**	**Sand**	**Coarse**	**ρ**	**Clay**	**Silt**	**Sand**	**Coarse**	**ρ**
		--------------%--------------				$g.cm^{-3}$	--------------%--------------				$g.cm^{-3}$	--------------%--------------				$g.cm^{-3}$
Ouahigouya (site 1)	**GF**	19^{a}	19^{a}	62^{a}	37^{a}	$1,4^{a}$	25^{a}	17^{a}	58^{a}	49^{a}	$1,4^{a}$	30^{a}	15^{a}	55^{a}	49^{a}	$1,1^{a}$
	CGF	22^{a}	18^{a}	60^{a}	55^{a}	$1,2^{a}$	29^{a}	18^{a}	53^{a}	57^{a}	$1,1^{a}$	23^{a}	17^{a}	60^{a}	57^{a}	1^{a}
Ouahigouya (site 2)	**OARL**	24^{a}	19^{a}	58^{a}	36^{b}	$1,3^{a}$	26^{a}	26^{a}	48^{a}	52^{b}	$1,2^{a}$	-	-	-	-	$0,4^{a}$
	COARL	16^{a}	7^{a}	77^{b}	1^{a}	$1,3^{a}$	18^{a}	5^{b}	76^{b}	10^{a}	$1,1^{a}$	15	5	80	6	$1,2^{a}$
Pissila (site 3)	**PARL**	12^{a}	12^{a}	76^{a}	29^{a}	$1,3^{a}$	18^{a}	11^{a}	71^{b}	35^{a}	$1,4^{a}$	25^{a}	11^{a}	64^{b}	49^{a}	$1,3^{a}$
	CPARL	31^{b}	12^{a}	57^{a}	19^{a}	$1,2^{a}$	40^{b}	11^{a}	49^{a}	20^{a}	$1,3^{a}$	43^{b}	12^{a}	45^{a}	26^{a}	1^{a}
Kaya (site 4)	**KARL**	23^{a}	17^{a}	61^{a}	13^{a}	$1,3^{a}$	30^{a}	10^{a}	60^{a}	15^{a}	$1,2^{a}$	35^{a}	11^{a}	54^{b}	13^{a}	$1,1^{a}$
	CKARL	31^{a}	17^{a}	52^{a}	8^{a}	$1,1^{a}$	35^{a}	15^{a}	50^{a}	9^{a}	$1,2^{a}$	37^{a}	15^{a}	48^{a}	8^{a}	$1,3^{a}$

-: no data. Coarse: coarse particles. For each measured characteristics, the different letter superscripts indicate a significant difference between FLR treatment and its control treatment on each site at $p < 0.05$. GF: Gourga Forest; CGF: Control of Gourga Forest; OARL: Ouahigouya Agricultural Rehabilitated Land; COARL: Control of Ouahigouya Agricultural Rehabilitated Land; PARL: Pissila Agricultural Rehabilitated Land; CPARL: Control of Pissila Agricultural Rehabilitated Land; KARL: Kaya Agricultural Rehabilitated Land; CKARL: Control of Kaya Agricultural Rehabilitated Land.

Table 3: Soil chemical and biological characteristics on three depths of FLR practices and controls.

		0-10 cm				10-20 cm				20-30 cm			
Site	Treatments	**pH water**	**pH KCl**	**Respira-tory** (mg CO2/100 g)	**k2** (%)	**pH water**	**pH KCl**	**Respira-tory** (mg CO2/100 g)	**k2** (%)	**pH water**	**pH KCl**	**Respira-tory** (mg CO2/100 g)	**k2** (%)
Ouahigouya (site 1)	**GF**	5.7±0.1^{b}	4.6±0.1^{a}	83.3±11.6^{a}	2.1±0.2^{a}	5.5±0.1^{a}	4.2±0.1^{a}	69.8±4.3^{b}	2.1±0.1^{a}	5.4±0.1^{a}	4.2±0.1^{a}	55.0±9.2^{a}	1.7±0.2^{a}
	CGF	5.3±0.1^{a}	4.3±0.1^{a}	56.9±11.1^{a}	2.3±0.1^{a}	5.2±0.1^{a}	4.4±0.1^{a}	43.8±5.1^{a}	1.6±0.2^{a}	5.2±0.2^{a}	4.4±0.1^{a}	49.2±4.7^{a}	1.8±0.2^{a}
Ouahigouya (site 2)	**OARL**	5.6±0.1^{b}	4.6±0.0^{b}	66.5±5.1^{b}	1.5±0.1^{a}	5.6±0.1^{a}	4.4±0.0^{b}	45.2±8.0^{b}	1.1±0.2^{a}	5.4±0.1^{a}	4.4±0.1^{a}	42.8±9.6^{a}	1.2±0.3^{a}
	COARL	5.0±0.1^{a}	4.1±0.1^{a}	27.4±10.4^{a}	2.1±0.9^{a}	5.2±0.2^{a}	4.1±0.1^{a}	24.3±4.3^{a}	1.9±0.4^{a}	5.3±0.2^{a}	4.2±0.1^{a}	27.5±7.9^{a}	2.0±0.7^{a}
Pissila (site 3)	**PARL**	5.5±0.1^{a}	4.4±0.1^{a}	44.7±12.9^{a}	2.3±0.6^{a}	5.4±0.1^{a}	4.3±0.1^{a}	41.8±4.7^{a}	2.2±0.3^{a}	5.4±0.1^{a}	4.4±0.1^{a}	26.1±6.7^{a}	1.3±0.3^{a}
	CPARL	5.2±0.1^{a}	4.4±0.2^{a}	37.1±11.5^{a}	1.8±0.6^{a}	5.2±0.2^{a}	4.5±0.2^{a}	35.5±3.9^{a}	1.7±0.2^{a}	5.0±0.2^{a}	4.4±0.2^{a}	16.9±3.0^{a}	0.8±0.1^{a}
Kaya (site 4)	**KARL**	5.7±0.1^{b}	4.6±0.1^{a}	30.4±4.1^{a}	1.2±0.2^{a}	6.1±0.1^{b}	4.6±0.1^{a}	34.5±3.3^{a}	1.4±0.2^{a}	6.1±0.1^{b}	4.7±0.1^{a}	29.6±2.8^{a}	4.9±3.6^{a}
	CKARL	5.0±0.2^{a}	4.2±0.2^{a}	28.7±3.4^{a}	1.7±0.3^{a}	4.9±0.2^{a}	4.3±0.2^{a}	42.4±1.0^{a}	2.3±0.6^{a}	4.8±0.2^{a}	4.4±0.2^{a}	50.1±16.7^{a}	3.1±1.2^{a}

Means ± standard errors; For each measured characteristics, the different letter superscripts indicate a significant difference between FLR treatment and its control treatment on each site at $p < 0.05$. Respiratory: cumulative CO_2 released by microorganisms; K2: Carbon mineralization coefficient; GF: Gourga Forest; CGF: Control of Gourga Forest; OARL: Ouahigouya Agricultural Rehabilitated Land; COARL: Control of Ouahigouya Agricultural Rehabilitated Land; PARL: Pissila Agricultural Rehabilitated Land; CPARL: Control of Pissila Agricultural Rehabilitated Land; KARL: Kaya Agricultural Rehabilitated Land; CKARL: Control of Kaya Agricultural Rehabilitated Land.

Table 4: Soil organic carbon stock at three depths of FLR practices and controls for different duration of implementation.

Site	**Treatments**	**Duration of FLR practice**	**0-10 cm**	10-20 cm	20-30 cm
			-------------------- **($t.ha^{-1}$)** --------------------		
Ouahigouya (site 1)	GF	45 years	8.5±0.5[b]	6.1±0.4[b]	4.6±0.3[b]
	CGF		3.4±0.4[a]	2.9±0.3[a]	3.3±0.4[a]
Ouahigouya (site 2)	OARL	27 years	9.5±1.1[b]	5.8±0.5[b]	6.7±1.4[a]
	COARL		4.8±0.5[a]	3.5±0.2[a]	4.4±0.5[a]
Pissila (site 3)	PARL	18 years	5.3±0,5[a]	4.6±0,4[a]	3.7±0.4[a]
	CPARL		5.6±0,3[a]	5.8±0,2[b]	4.6±0.6[a]
Kaya (site 4)	KARL	11 years	6.7±0.4[a]	6.7±0.6[a]	6.1±0.4[a]
	CKARL		5.2±1.1[a]	6.2±1.0[a]	5.8±0.6[a]

Means ± standard errors; The different letter superscripts indicate a significant difference between FLR treatment and its control treatment on each site at $p < 0.05$.
GF: Gourga Forest; CGF: Control of Gourga Forest; OARL: Ouahigouya Agricultural Rehabilitated Land; COARL: Control of Ouahigouya Agricultural Rehabilitated Land; PARL: Pissila Agricultural Rehabilitated Land; CPARL: Control of Pissila Agricultural Rehabilitated Land; KARL: Kaya Agricultural Rehabilitated Land; CKARL: Control of Kaya Agricultural Rehabilitated Land.

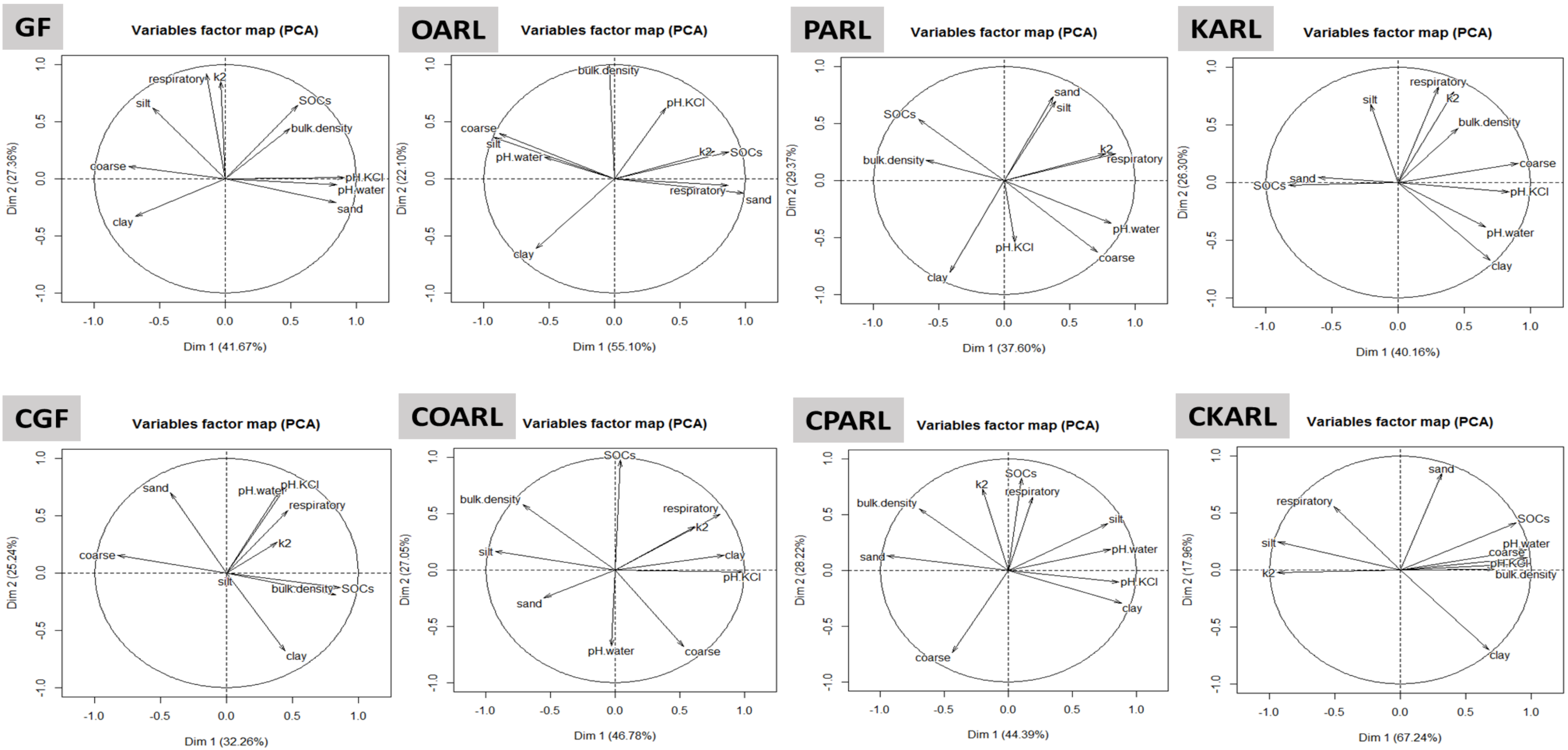

Figure 2: Relations between soil organic carbon stock and physico-chemical and biological characteristics of soils on the study sites.

Respiratory: respiratory activity of microorganisms. GF: Gourga Forest; CGF: Control of Gourga Forest; OARL: Ouahigouya Agricultural Rehabilitated Land; COARL: Control of Ouahigouya Agricultural Rehabilitated Land; PARL: Pissila Agricultural Rehabilitated Land; CPARL: Control of Pissila Agricultural Rehabilitated Land; KARL: Kaya Agricultural Rehabilitated Land; CKARL: Control of Kaya Agricultural Rehabilitated Land.

DISCUSSION

Effect of FLR practices on soil physico-chemical and biological characteristics

The difference between FLR treatments (example of the site 2 of Ouahigouya) and their respective control may be partially linked to the FLR practices which probably allowed a sedimentation of soil fine particles (clay and silt) as showed by some authors (Zougmoré et al., 2004; Doamba et al., 2011; Bambara et al., 2012). However, the comparison of their soil physical characteristics (site 2 of Ouahigouya and the one of Pissila) proves that some of them do not have the same soil characteristics. This does not permit a better appreciation of the FLR practices effects on soil physical characteristics.

The reduction of soil acidity that has been observed on the superficial depths of Ouahigouya and Kaya's FLR treatments, could be linked to their higher SOCs (Bambara et al. 2012; Xu et al., 2012). This may be the reason why on deeper layers where SOCs are low, an increase in soil acidity has been observed. This is all of more possible that on OARL that presented the most important SOCs on 0-10 cm, its pH KCl was also significantly higher compared to its control COARL. Indeed, SOC largely governs soil properties, namely pH that it can increase or decrease, depending on the organic matter quality (Xu et al., 2012). In western Burkina Faso, after ten years of implementation of combined FLR practices including *zaï*, Yaméogo et al. (2019) did not observe a decrease in soil acidity.

The highest level of respiratory activity of microorganisms was recorded in GF. GF and OARL were the only treatments that significantly increased the respiratory activity of microorganisms compared to their respective control. At the same time, the highest plant densities (594 and 93 trees per ha) were respectively recorded on FG and OARL (Table 1). The role of the trees in maintaining the biological activity of the soil through their roots, the deposition of litter due to the fall of the leaves and the maintenance of the macrofauna of the soil, being well known (Chapuy-Lardy et al., 2019), this vegetation has thus allowed an enrichment in organic compounds as shown by the highest SOCs recorded on these treatments (Table 4). These organic compounds would then have served as a source of energy and food for soil microbial communities (Coulibaly et al., 2018), as their high respiratory activity reflects. Likewise, the increase of the coefficient of carbon mineralization with depth in Kaya can be due to the highest SOCs recorded on these depths (10-20 cm and 20-30 cm) compared to the other sites (Table 4), in view of the importance of organic compounds stimulating their mineralizing activity (Coulibaly et al., 2018). This hypothesis is supported by the strong relationship between the coefficient of carbon mineralization and the SOCs on both FLR and control treatments in Kaya (Figure 2).

Effect of FLR practices and long-term implementation on soil organic carbon stock in a semi-arid area

The FLR treatments which lasted less than 20 years did not increase significantly the SOCs. This result proves that implementation duration plays a key role in the success of FLR practices. It is widely recognized that some FLR practices have a higher long-term positive effect on SOC than others. For example, the effect of stone bunds on SOC is more reduced in the short-term (Doamba et al., 2011), but z*aï* has a positive short-term effect on SOC and cereal crops (Zougmoré et al., 2003). Furthermore, the type of combined practices is a determining factor in the increase of SOCs. GF and OARL differs from KARL by the presence of an additional practice namely the ANR which permitted the establishment of a woody species (Doamba, 2007) which densities are 594 and 93 trees per ha on GF and OARL respectively. On KARL which does not present ANR in its combination of FLR practices, only 11 trees per ha were recorded.

On GF and OARL, the implementation of NRA for at least 27 years which permitted the establishment and the growth of woody plants was determinant in carbon storage. Woody species contribute significantly to the increase of soil carbon (Sauer et al. 2007). The plants permitted organic compounds input into the soil, including leaf litter, root exudates, plant roots, macrofauna corpses. However, the duration of implementation and the presence of ANR as one of the combined FLR practices are not the only factors which can explain the increase in the SOCs (Bambara et al., 2012). The interactions between the different combined FLR practices determine the direction and the magnitude of SOCs evolution (Gnissien, 2018). Indeed, combined FLR practices have a higher synergistic effect than the sum of effects of each FLR practice taken individually. GF and OARL combine more FLR practices compared to the less than 20-year-old FLR treatments. All the FLR treatments include *zaï* and stone bunds. They differ mainly by ANR, which was absent from KARL, crop rotation including fallow successions which was specific to OARL and marginal organic manure input in PARL. Besides, GF was the only FLR treatment which significantly increased SOCs on all the three depths, compared to its control treatment. The fact that the ecosystem of this forest is protected from anthropic activity would have permitted an important revegetation which allowed a better deeper accumulation of organic compounds in the soil. It is not the case with croplands–which are submitted to soil building exposing them to an important organic carbon depletion (Haddaway et al., 2017). Furthermore, the higher SOCs at the 0-10 and 10-20 cm depth is in accordance with the results of Atchada et al. (2018) who noticed a SOCs decrease from surface to depth. This result could be in link with the fact that this layer is mostly under the influence of external contributions of organic matters.

In Pissila, the most important SOCs recorded on the control (CPARL), compared to the FLR practice (PARL) could be due to repeated soil building (tillage) and the absence of substantial organic manure input on the sandy soil of PARL (76% of sand on the 0-10 cm depth). This could have caused a continuous SOCs depletion, compared to its control treatment. In addition, according to Atchada et al. (2018), the continuous turning of the soil over a certain depth (30 cm) brings to the surface the deep layers. However, our results showed that these deeper layers (10-20 cm and 20-30 cm) are less rich in organic carbon in Pissisa. On cultivated soils, the supply of organic matter in quantity and quality remains the key to successful FLR practices (Bambara et al., 2012).

Relation between soil organic carbon stock and physico-chemical and biological characteristics of soils on studied sites

On all the treatments, soil physical characteristics were controlling SOCs at least at 50%. Among these physical characteristics, coarse particles and bulk density were the most important factors. The contribution of bulk density to SOC storage was always positive. Bambara et al. (2015) showed in their study that compost applications lead to a decrease in bulk density and an increase in the SOCs. Then, the bulk density values (the maximum of which was 1.4 g. cm^{-3}) could have created a favorable porosity in the soil which allowed organic carbon storage. In most cases, SOCs had a negative coordinate with coarse particles except on CKARL which recorded less than 10% of coarse particles. Atchada et al. (2018) have observed a negative relationship between the size of soil particles and the organic matter content. Our result confirms it by indicating the negative influence of particles larger than 2 mm on soil capacity to store organic carbon.

Conclusion

The implementation of FLR practices for more than 27 years has increased SOCs in degraded soils of the semi-arid area, and the trend of increase seemed to be modulated by soil physical characteristics. Besides, synergistic effect between the combined FLR practices appears as decisive in the SOCs improvement. The highest improvement was recorded when the FLR practices associate ANR with as consequence, higher plant densities. These results reflect the key ecosystemic role of vegetation in soil carbon storage. However, as land needs are urgent, investigations must be continued to find faster land restoration techniques. As a perspective, it would be interesting to assess the relative contribution of each independent FLR practice on SOC increase in the short and long-terms, and to investigate whether a combined set of FLR practices has a higher impact on SOC than the addition of each independent practice.

COMPETING INTERESTS

The authors declared that they have no competing interests.

AUTHORS' CONTRIBUTIONS

ACC, SAK, SBMY and HBN carried out the field exercise. ACC made the soil analysis, the statistical analysis, and produced the first draft. SBMY, SAK, DH, OMI, MK, IBM and HBN corrected it. HBN was the supervisor in the realization of all the different steps.

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