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Evaluation of Combined Landscape Restoration Practices on Soil Organic Carbon Stocks in Semiarid Regions of Burkina Faso

Stéphanie Batchakoué Maïga-Yaleu[1*], Abdul-Charif Cissé[2], Sibiry Albert Kaboré[3], Damien Hauswirth[4], Oumarou Malam Issa[5], Maguette Kaire[6], Ibrahim Bouzou Moussa[7], Hassan Bismarck Nacro[2,6]

[1]Laboratory of Molecular Chemistry and Materials (LCMM), Joseph KI-ZERBO University (UJKZ), Ouagadougou, Burkina Faso
[2]Laboratory of Study and Research on Soil Fertility (LERF), Rural Development Institute (IDR), Nazi BONI University (UNB), Bobo Dioulasso, Burkina Faso
[3]University Center of Tenkodogo, Thomas SANKARA University (UTS), Ouagadougou, Burkina Faso
[4]ECO Consult GmbH & Co. KG (Niger), Oberaula, Germany
[5]IRD, UMR Institute of Ecology and Environmental Sciences of Paris (IEES-Paris), SU/IRD/CNRS/INRAE/UPEC, Centre IRD de France Nord, Bondy Cedex, France
[6]AGRHYMET Regional Center, Permanent Interstates Committee for Drought Control in the Sahel (CILSS), Niamey, Niger
[7]Abdou Moumouni University, Department of geography, Niamey, Niger
Email: *yalsteph01@yahoo.fr

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Abstract

Forest and landscape restoration (FLR) practices have been reported to improve soil organic carbon stocks (SOCs) and contributing to climate change mitigation. This study aims to evaluate the impact of combined FLR practices, mainly developed in semiarid regions, on SOCs. The SOCs, soil texture, bulk density (ρ), pH, CO_2 emissions, and herbaceous biomass were determined at a 0 - 30 cm depth. The experimental design comprised degraded land without FLR practices and three sets of combined FLR practices. These practices included "*zai*" + stone bunds + organic manure + assisted natural regeneration (ANR) used to convert degraded land into forest (GF) and cropland (PARL); "*zai*" + stone bunds + crop rotation + crop/fallow successions + ANR used to convert degraded land into cropland (OARL) and "*zai*" + stone bunds + organic manure used to convert degraded land into cropland (KARL). SOCs were highest (20.02 t C ha^{-1}) under OARL compared with the other combinations of FLR practices. SOCs increased by 99% (+0.2 t C ha^{-1}·yr^{-1}), 58% (+0.3 t C ha^{-1}·yr^{-1}) and 13% (+0.2 t C ha^{-1}·yr^{-1}) under GF, OARL and KARL, respectively, and decreased by 15% (−0.1 t C ha^{-1}·yr^{-1}) under PARL. This study provides additional information explaining SOC variation in restored degraded land through the implementation of a combination of FLR practices. This is useful for recommending the combination "*zai*" + stone bunds + crop rotation + crop/fallow successions + ANR to improve SOCs in the semiarid agroecosystem.

Keywords

Soil Organic Carbon, Improved Management, Soil Restoration, Management Practices, Semiarid Area

1. Introduction

Soil organic carbon (SOC) is a vital component of terrestrial ecosystems and the largest component of the global carbon stock [1] [2]. The amounts of SOC in the entire land area of the world are approximately 684 to 724 Pg of C in the upper 30 cm and 2376 to 2456 Pg of C in the upper 200 cm [3]. Thus, all activities that affect the superficial soil layers can impact the SOC stock [2] [4]. Farming intensification in sub-Saharan Africa is known as the main cause of severe soil degradation [5], leading to nutrient and organic matter depletion or loss through water and wind soil erosion [6]. Conversely, restoring degraded soils across landscapes by implementing cover crop or erosion control practices increase the potential of SOC annual sequestration [7] [8]. Therefore, investigating the potential of practices developed to reverse land degradation with the ability to increase carbon inputs and/or reduce losses is a paramount issue for climate change adaptation and mitigation [9].

Forest and landscape restoration (FLR) are among those processes that apply to reversing the degradation of soils, forests and agricultural areas, thereby regaining their ecological functionality and controlling carbon sequestration in soils [10] [11]. The FLR process is still widely studied, not only for its potential to restore degraded soils and improve agricultural productivity but also for its capacity to improve soil organic carbon stocks [1] [8] [12] [13] [14]. FLR practices commonly promoted in semiarid regions of sub-Saharan Africa include practices such as "*zai*", stone bunds, half-moons, assisted natural regeneration (ANR), and crop/fallow rotations. These practices were developed for one or several specific objectives to allow the development of sustainable land uses from degraded land [14]. For example, stone bunds slow soil erosion, keep the soil in place, improve the structural stability of the soil and improve soil fertility [15] [16]. Generally, practiced on bare soils, soil, and water conservation practices such as "*zai*" and half-moons improve soil moisture and the biological activity of soil and increase crop yield [17]. To protect and take care of regrowth in their agricultural fields, the farmers use assisted natural regeneration, which is an extended practice in Sub-Saharan Africa [14]. Most of these FLR practices can enhance biomass production and promote organic matter supply in the soil. These practices may consequently reduce surface runoff and carbon losses by soil erosion or mineralization [18]. However, none of the techniques used individually provides a miracle solution when targeting several objectives at the same time [14].

Designing land restoration interventions for climate change mitigation should also consider the implementation of diversified and combined practices in the same area to benefit from their synergy [12] [13]. While forest and landscape restoration (FLR) practices on degraded land can improve soil organic carbon (SOC) stocks [19] [20], little is known about the potential accumulation of SOC under the combination of several FLR practices, especially in semiarid regions. Furthermore, the management practices that most increase soil organic carbon still need to be identified [20]. The potential of SOC sequestration in a given restoration practice is measured through its ability to increase carbon input and/or its ability to reduce its loss [13] [14] [21]. Therefore, knowledge of the potential of carbon input or loss reduction is necessary for the choice of relevant combinations of FLR practices to increase SOC sequestration in restored sites [22] [23]. In addition, the long-term implementation should also be considered to quantify the contribution of FLR practices to SOC sequestration [24].

Within this context, the main objective of this study was to evaluate the impact of combinations of several FLR practices on SOC stocks during the conversion of degraded soil into forest and cropland. We hypothesize that the implementation of FLR practices in forest and cropland may result in soil carbon stock improvement. To test this hypothesis, we developed a comparative approach using soil physicochemical properties and SOC stocks before and after the introduction of a combination of FLR practices to convert 27 ha of degraded land to forest and 31 ha, 4 ha, and 2.7 ha of degraded land into cropland.

2. Materials and Methods

2.1. Characteristics of the Study Area

The study was conducted in semiarid region in three municipalities of Burkina Faso, specifically in Ouahigouya, Kaya, and Pissila (**Figure 1**). Ouahigouya is located in Yatenga Province in the northern region (Lat. 13˚06' and 14˚26'N; Long. 1˚43' and 2˚55'E). Kaya and Pissila are located in Sanmatenga Province in the central northern region (Lat. 12˚30' and 13˚56'N; Long. 0˚40' and 1˚37'E). The mean annual precipitation is 750 mm and 800 mm in Yatenga and Sanmatenga provinces, respectively. For the two regions, the dry season extends from November to June, and the rainy season, which corresponds to the peak period of agricultural activities, extends from July to October. The main soil found in these two regions is Ferric Lixisols [25]. This soil is prone to physical and chemical alteration due to depletion of organic matter, low aggregate stability, extensive land uses, and aridity. The preservation of the surface soil with its organic matter is of the utmost importance [25]. Forest and landscape restoration (FLR) are practices commonly implemented with the purpose of recovering or maintaining soil functions for agriculture and forestry in these regions.

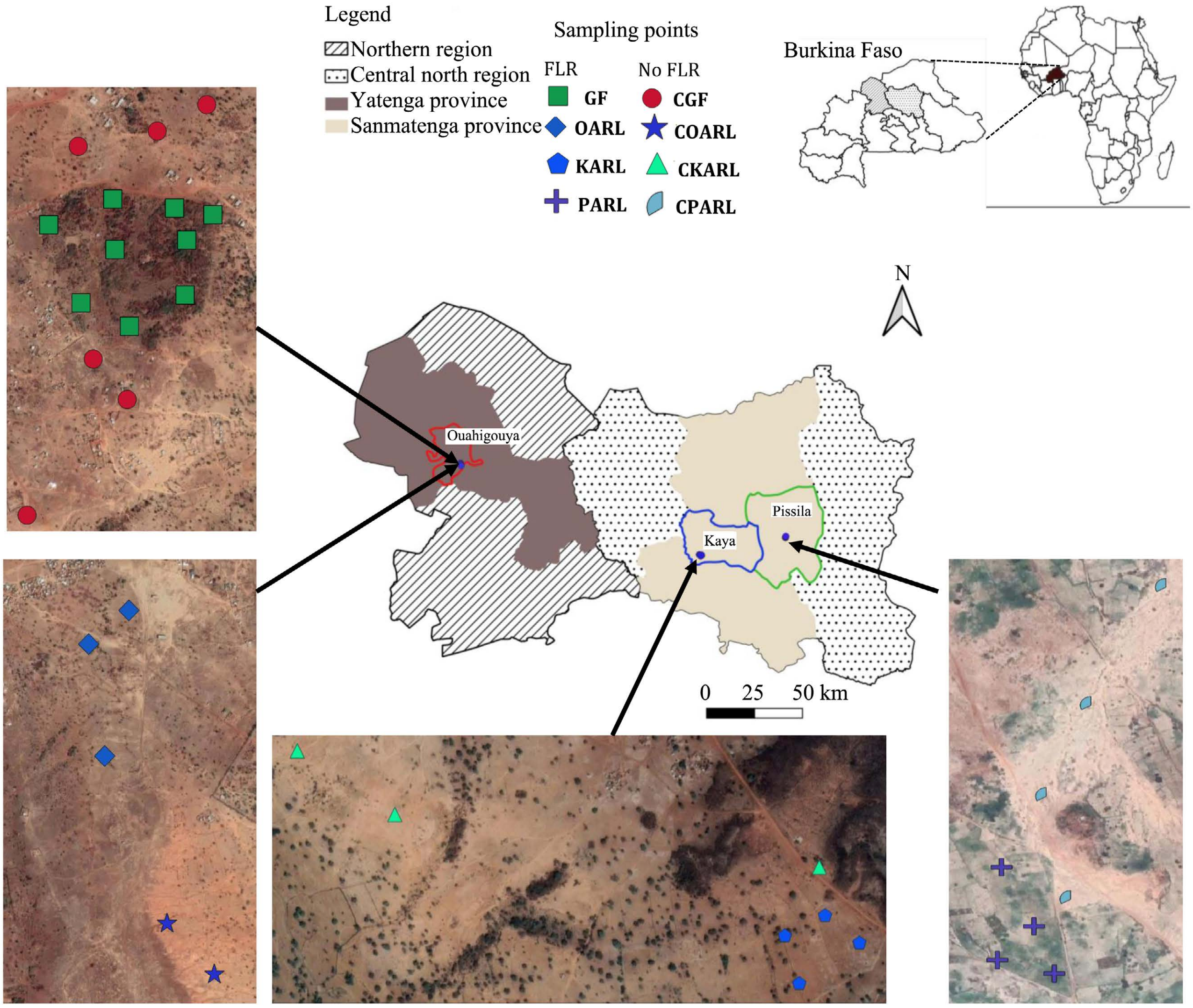


Figure 1. Location of the study sites with 30 m × 30 m experimental plots of the sites.

2.2. Experimental Design

Four study sites were chosen according to their differences in the types of combinations of FLR practices, the type of land use changes (LUC), and the duration of implementation of the FLR practices on degraded land (**Figure 1**). The sites were selected based on visual analysis of google map images and field observations. A survey was also conducted in 2017 among the over 40-year-old population at the selected sites to ensure real Land Use Change over the long term. The two LUC types identified for this study were degraded land to forest and degraded land to cropland.

The minimum time since conversion was 11 years. Each combination of FLR practices included at least "*zaï*" and stone bunds. Varying additional practices were operated at each site, including assisted natural regeneration (ANR), cropping practices with temporary fallows and/or manure application. The characteristics of each site are as described in **Table 1**.

Table 1. General soil characteristics in the 0 - 30 cm layer for different combinations of forest and landscape restoration (FLR) practices. Sand: 50 - 2000 µm; silt: 2 - 50 µm; clay: 0 - 2 µm; ρ: soil bulk density; pH: soil pH; SOCc: soil organic carbon content; and coef min C: carbon mineralization coefficient.

	Area (ha), age (years); Type of FLR	*Woody density*	*Herbaceous biomass density*	*Sand*	*Silt*	*Clay*	*Texture*	ρ	*pH*	Coef min C
		feet ha^{-1}	kg·ha^{-1}		%			g·cm^{-3}		%
GF	27 ha, 45 years; "*zai*" + stone bunds + organic manure + ANR	594	152.21	58	17	25	*Sandy clay loam*	1.30	5.5	1.9
CGF	No FLR		66.11	57	18	25	*Sandy clay loam*	1.10	5.2	1.9
OARL	31 ha, 27 years; "*zai*" + stone bunds + crop management (crop rotation + crop/fallow successions) + ANR	93	79.09	53	22	25	*Sandy clay loam*	1.17	5.5	1.3
COARL	No FLR		55.50	78	6	16	*Sandy loam*	1.19	5.2	2
PARL	2.7 ha, 18 *years*, "*zai*" + stone bunds + organic manure + ANR	19	88.26	71	11	18	*Sandy loam*	1.33	5.4	1.9
CPARL	No FLR		12.97	51	11	38	*Sandy clay*	1.17	5.1	1.4
KARL	4 ha, *11* years, "*zai*"+ stone bunds + organic manure	11	22.17	58	13	29	*Sandy clay loam*	1.18	5.9	1.4
CKARL	No FLR		12.26	50	16	34	*Sandy clay loam*	1.20	4.9	2.4

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

We used a synchronous approach [14] [26] to compare SOCs within a combination of FLR practices of a given duration with SOCs in degraded land, which is considered to represent the type of initial land use before the introduction of FLR practices (time t_0). This synchronous approach consisted, at a given time t_n (time at which the study was conducted), of comparing the carbon stock under the plot with the sequestering practice tested during x years to that of a control plot (without sequestering practice) assumed to represent the reference point (time t_0) [14] [26]. The objective of this approach is to quantify the SOC stock between time t_0 an t_n.

Areas of degraded land, as controls, were chosen near the current site with FLR practice (**Figure 1**). For GF, the corresponding degraded land used as a control was named CGF. For OARL, PARL and KARL, the corresponding degraded land used as controls were named COARL, CPARL and CKARL, respectively.

Replicated plots of 30 m × 30 m were installed on each site. The plots were arranged to cover a uniform area and to be representative of the density and vegetation cover type at each site. The four study sites had different areas (2.7 ha, 4 ha, 27 ha and 31 ha, respectively), and the number of replicated plots among the study sites was different. A total of thirty-five observation plots were installed as follows: 9 plots in GF, 3 plots in OARL, 4 plots in PARL, 4 plots in KARL, 6 plots in CGF, 2 plots in COARL, 4 plots in CPARL and 3 plots in CKARL (**Figure 1**).

2.3. Soil Sampling and Physicochemical Analyses

The soil samples were collected in 2018, before (June) and after (October) the rainy period for all sites. Soil samples were randomly collected at five replicate points following a zigzag pattern per plot of 30 m × 30 m. The samples were collected at depths of 0 - 10 cm, 10 - 20 cm, and 20 - 30 cm. The five samples were combined into a composite sample of approximately 2 kg (weight after drying). A total of 210 composite soil samples were used to determine the soil organic carbon content (SOCc), soil particle size, soil pH and carbon mineralization coefficient (coef min C). In addition, undisturbed soils were sampled before the rainy season (June) for bulk density (ρ) determination. The samples were collected at each point with a 118.8 cm^3 cylinder (5.5 cm diameter and 5 cm height). This sample was oven-dried at 105˚C for 24 hours to determine the dry weight. The soil particle size distribution was determined using the hydrometer (densimetric) method. The soil samples (<2 mm) were chemically dispersed with 5% sodium hexametaphosphate and sodium carbonate. The soil textural classes are based on USDA particle size.

An electronic pH meter (SensION$^{\text{TM+}}$) was used to measure the soil pH using a 1:2.5 soil-water ratio method, which consisted of a mixture of soil samples and distilled water.

The CO_2 emissions from the soil due to biological activity were measured by the method described by Dommergues (1960). A sample of 100 g of soil was incubated for 21 days in a closed chamber, and the released CO_2 was trapped in a solution of NaOH (0.1 N). The carbon mineralization coefficient (Coef min C), in %, was calculated as follows Equation (1):

$$\text{Coef min C} = \left(\text{C} - \text{CO}_2/\text{C}\right) \times 100 \quad [27] \tag{1}$$

where C-CO_2 is the amount of carbon losses as CO_2 due to biological activity in mg per 100 g of soil (mg C 100 g^{-1}) and C is the SOC content in mg per 100 g of soil (mg C 100 g^{-1}).

2.4. Soil Organic Carbon Stocks

The samples were air-dried after all plant materials were removed and sieved through a 2 mm mesh before determining the soil organic carbon content (SOCc). The SOCc, expressed as a percentage (%), was analyzed using the Walkley and Black method. The dried soils (<2 mm) were further crushed and sieved again at 0.1 mm. The procedure of Walkley and Black method used in this study was previously described [28]. The soil organic carbon stock (SOCs) was calculated at 0 - 30 cm, *i.e.* the depth of the plowed layer affected by management techniques [19] and the development of plant roots.

The soil organic carbon stock at 0 - 30 cm depth (SOCs), expressed in tons per hectare (t C ha^{-1}), was estimated as a product of SOCc (%), bulk density (g·cm^{-3}) and thickness of the considered soil layer as follows (Equation (2)):

$$\mathrm{SOC_S} = \mathrm{SOC_C} \times \rho \times X_1\left(1-\left(X_2/100\right)\right)\times b \quad (2)$$

where X_1 is the depth of the soil horizon (cm); X_2 is the proportion of fragments > 2 mm in percent; and b is a constant equal to 100.

The SOCs sequestration rate was calculated as the difference between SOCs for a combination of FLR practices (treatment) and that for the degraded land (control) as follows Equation (3):

$$\mathrm{SOC_S}\ \text{sequestration rate} = \left(\mathrm{SOCs_t} - \mathrm{SOCs_{t0}}\right)/n_y \quad (3)$$

where $\mathrm{SOCs_t}$ is the SOCs for the combination of FLR practices (t C ha^{-1}), $\mathrm{SOC_{t0}}$ is the SOCs for the degraded land (t C ha^{-1}), and n_y is the number of intervening years between the initial year and year of comparison (years).

2.5. Statistical Analyses

Descriptive analyses and statistical analyses were performed using International Business Machines Corporation (IBM) Statistical Package for the Social Sciences (SPSS) Statistics V18.0 software. The effects of the combination of FLR practices and soil types were tested using one-way analysis of variance (ANOVA) combined with the Tukey post hoc test for multiple comparisons of simultaneous pairwise differences. This test was conducted under the hypothesis that there were no differences between the groups. The differences were significant at p values < 0.05. A correlation matrix was performed using the Pearson test to determine the absence or presence of a significant linear relationship between the variables. Following the significant linear relationship between variables, we performed a principal component analysis (PCA) to identify the explicative variables on the total variance of SOCs and SOCc. The following variables were considered: sand, silt, and clay content (soil texture); bulk density; herbaceous biomass; soil acidity (pH); carbon mineralization coefficient (coef min C); and CO_2 emissions.

3. Results

3.1. Soil Physicochemical Characteristics

The physicochemical and environmental characteristics of the soil in the 0 - 30 cm layer are presented in **Table 1**. The sand content was significantly higher for a combination of FLR practices under PARL, followed by GF and KARL, with the lowest value for a combination of FLR practices under OARL (**Table 2**). However, the clay and silt contents were lower for PARL (**Table 1**). The soils were classified as sandy clay loam for a combination of FLR practices under GF, OARL and KARL, while for PARL, the soil was classified as sandy loam (**Table 1**). Sand content was highest for a combination of FLR practices under KARL

Table 2. Analysis of variance (ANOVA) combined with Turkey post hoc test for sand, clay, silt, SOCc: soil organic carbon content, SOCs: soil organic carbon stock, CO$_2$: microbial activities and Coef min C: Carbon mineralization coefficient.

Site	Site	Sand		Clay		Silt		SOCc		SOCs		CO$_2$		Coef min C	
(I)	(J)	M.D	S.E	M.D	S.E	M.D	S.E	M.D	S.E	M.D	S.E	M.D	S.E	MD	S.E
		(I-J)		(I-J)		(I-J)		(I-J)		(I-J)		(I-J)		(I-J)	
GF	CGF	0.7	1.6	0.2	1.4	−0.9	1.0	2.1*	0.4	9.6*	0.7	19.2*	5.9	0.1	0.2
	OARL	5.0	2.2	0.1	1.9	−5.1*	1.3	−2.0*	0.6	−0.9	0.9	16.8	7.8	0.7	0.3
	KARL	0.3	1.9	−4.2	1.6	4.0*	1.1	3.0*	0.5	−0.3	0.7	37.9*	6.7	0.6	0.3
	PARL	−11.7*	1.9	6.3*	1.6	5.4*	1.1	4.2*	0.5	5.6*	0.7	31.9*	6.7	0.0	0.3
OARL	COARL	−24.3*	2.9	8.5*	2.6	15.9*	1.7	7.89*	0.8	7.3*	1.2	26.3	10.5	−0.7	0.4
	KARL	−4.7	2.5	−4.3	2.2	9.0*	1.4	5.1*	0.7	0.6	1.0	21.1	8.8	−0.1	0.3
	PARL	−16.7*	2.5	6.3	2.2	10.4*	1.4	6.2*	0.7	6.5*	1.0	15.1	8.8	−0.6	0.3
KARL	CKARL	8.5*	2.4	−5.3	2.1	−3.2	1.4	1.2	0.6	2.3	1.0	−8.8	8.5	−1.0	0.3
	PARL	−12.0*	2.2	10.6*	1.9	1.4	1.3	1.1	0.6	5. 9*	0.9	−6.0	7.9	−0.6	0.3
PARL	CPARL	19.7*	2.2	−19.8*	1.9	0.1	1.3	−0.5	0.6	−2.4	0.9	7.7	7.9	0.5	0.3

For each variable, compare site (I) with site (J). M. D (I-J): mean difference between I and J; S.E: standard error; Sig.: significant * at $p < 0.05$ level. GF: Gourga Forest; CGF: Control of GF; OARL: Ouahigouya Agricultural Rehabilitated Land; COARL: Control of OARL; PARL: Pissila Agricultural Rehabilitated Land; CPARL: Control of PARL; KARL: Kaya Agricultural Rehabilitated Land; CKARL: Control of KARL.

and PARL compared with their controls, while clay and silt contents were higher for the controls. On the other hand, a significant depletion in sand and a significant enrichment in clay and silt content are observed for a combination of FLR practices under OARL compared with its control (Table 1). There was no difference in sand, clay, and silt between a combination of FLR practices under GF and its control. The soil bulk density (ρ) was not significantly different among the separate combinations of FLR practices; it varied from 1.17 g·cm^{-3} for OARL to 1.33 g·cm^{-3} for PARL. The soil bulk density was 1.18 g·cm^{-3} and 1.30 g·cm^{-3} in KARL and GF, respectively. The soil was slightly acidic ($4.9 \le \text{pH} \le 5.9$), and the pH values among combinations of FLR practices were not significantly different. The carbon mineralization coefficient (coef min C) (Table 1) varied between 1.3 and 1.9 under separate combinations of FLR practices and between 1.4 and 2.4 under control plots. The difference was not significant among combinations of FLR practices and their controls. The carbon mineralization coefficient was lower before the rainy season and higher after the rainy season, whether under a combination of FLR practices or for control plots.

The soil organic carbon content (SOCc) was significantly higher under a combination of FLR practices under OARL (11.62 g C kg^{-1}) than under PARL (5.43 g C kg^{-1}), whereas the SOCc under a combination of FLR practices under GF and KARL was 9.59 g C kg^{-1} and 6.55 g C kg^{-1}, respectively (Figure 2). The mean SOCc was higher for a combination of FLR practices under GF, OARL and

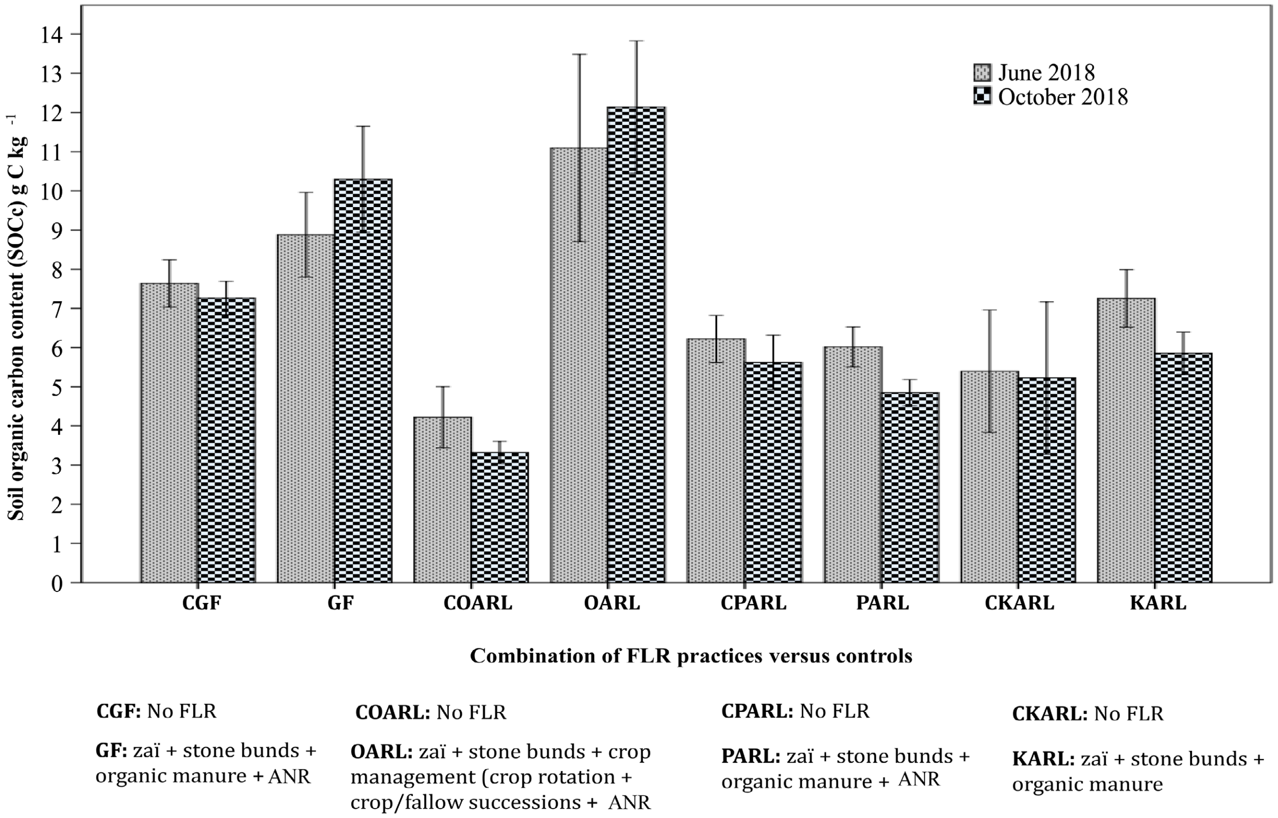
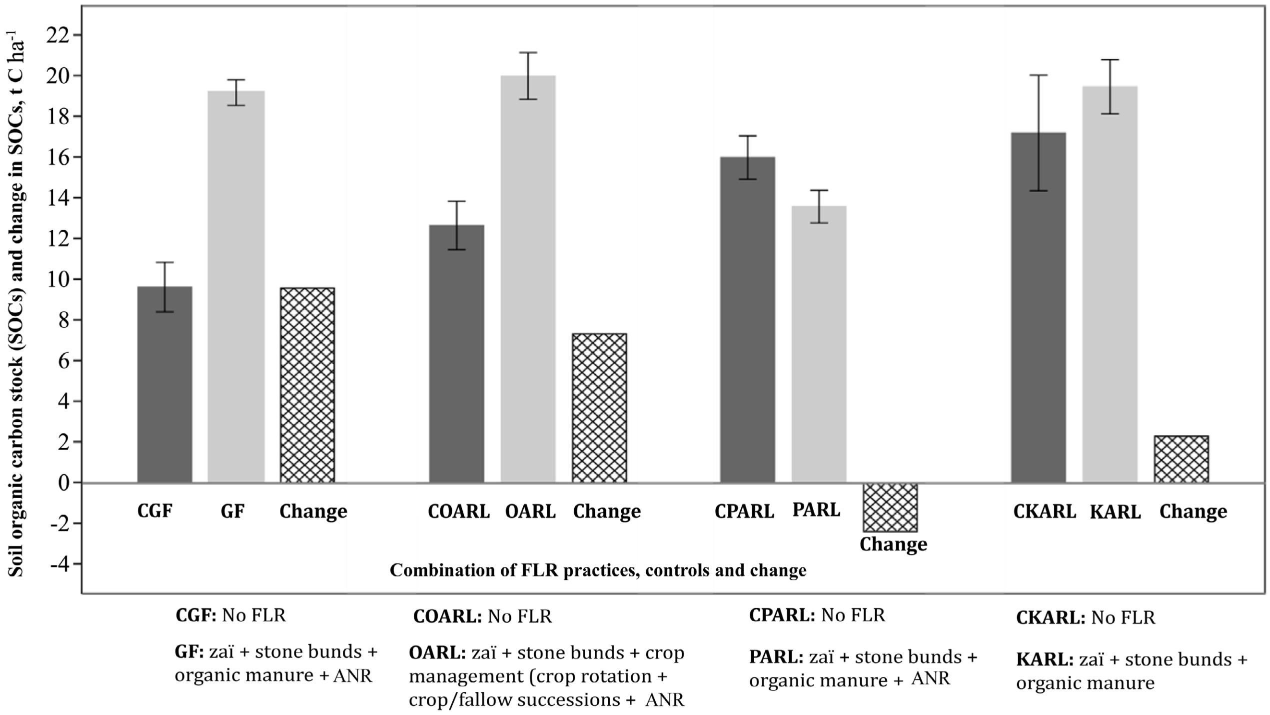


Figure 2. Soil organic carbon content (SOCc) before (light pattern) and after (dark pattern) the rainy season on 0 - 30 cm depth, under different combinations of FLR practices and their controls. Error bars: 95%.

KARL compared with their control plots: CGF, COARL and CKARL. The SOCc was higher for the control plot CPARL and lower for the combination FLR practice of PARL. We found changes in SOCc when comparing samples before the rainy season (June) and after the rainy season (October). There was an increase in SOCc for a combination of FLR practices under GF (8.88 g C kg^{-1} in June to 10.30 g C kg^{-1} in October) and OARL (11.10 g C kg^{-1} in June to 12.14 g C kg^{-1} in October) (Figure 2). We found a significant decrease in SOCc for a combination of FLR under PARL (6.02 g C kg^{-1} in June to 4.85 g C kg^{-1} in October) and KARL (7.25 g C kg^{-1} in June to 5.86 g C kg^{-1} in October) (Figure 2). For all control plots, the SOCc was higher before the rainy season and lower after the rainy season.

3.2. Soil Organic Carbon Stock under Combinations of Forest and Landscape Restoration Practices

The soil organic carbon stock (SOCs) at a 0 - 30 cm depth was significantly lower for a combination of Forest and landscape restoration (FLR) practices under PARL (13.56 t C ha^{-1}) compared to than for other types of combinations of FLR practices (Figure 3). The highest value of SOCs was found for a combination of FLR practices under OARL (20.02 t C ha^{-1}), followed by a combination of FLR practices under KARL (19.46 t C ha^{-1}) and GF (19.17 t C ha^{-1}) (Table 2). SOCs



CGF: No FLR

GF: zaï + stone bunds + organic manure + ANR

COARL: No FLR

OARL: zaï + stone bunds + crop management (crop rotation + crop/fallow successions + ANR

CPARL: No FLR

PARL: zaï + stone bunds + organic manure + ANR

CKARL: No FLR

KARL: zaï + stone bunds + organic manure

Figure 3. Soil organic carbon stock (SOCs) (t C ha^{-1}) (uniform colour) and the change (colour with pattern) on 0 - 30 cm during the conversion of degraded land into forest (GF) and cropland (OARL, PARL and KARL) by different combinations of FLR practices.

ranged from 17.40 t C ha^{-1} to 22. 68 t C ha^{-1} for a combination of FLR practices under OARL and from 11.17 t C ha^{-1} to 16.79 t C ha^{-1} for a combination of FLR practices under PARL. The variation in SOCs was quite similar for combinations of FLR practices under KARL and GF (from 16.00 t C ha^{-1} and 25.49 t C ha^{-1}, respectively). Lower values of SOCs for a combination of FLR practices under GF and OARL were found before the rainy season, and higher values were found after the rainy season. Lower values of SOCs were found after the rainy season, and higher values were found before the rainy season for a combination of FLR practices under KARL and PARL. For all control plots, the difference in SOCs between and after the rainy season was not significant, although SOCs was highest before the rainy season.

3.3. Changes in Soil Organic Carbon Stock

The change in soil organic carbon stock (SOCs) along the conversion of degraded land to forest and cropland, according to different combinations of FLR practices, is presented in Figure 3.

SOCs under a combination of FLR practices increased by 99% (+9.56 t C ha^{-1}) in GF compared with its associated degraded land (CGF). An increase in SOCs by 58% (+7.35 t C ha^{-1}) and 13% (+2.28 t C ha^{-1}) was also observed when converting degraded land into croplands OARL and KARL, respectively. In contrast, SOCs declined by 15% (−2.42 t C ha^{-1}) under cropland PARL after the conversion of degraded land into cropland (Figure 3).

The annual rate of increase of SOCs at a 0 - 30 cm depth was estimated at 0.2 t C ha^{-1}·yr^{-1} after the conversion of degraded land into forest (GF) and cropland (KARL), which was lower than the annual accumulation rate of SOCs (0.3 t C ha^{-1}·yr^{-1}) after the conversion of degraded land into cropland OARL. In contrast, a loss of SOCs of approximately 0.1 t C ha^{-1}·yr^{-1} was observed when converting degraded land into cropland PARL.

3.4. Relationships of Soil Physicochemical Properties and Carbon Content and Stock

Principal component analysis (PCA) was performed between soil physicochemical properties (sand, clay, silt, ρ, and pH), CO_2, herbaceous biomass (biom), carbon mineralization coefficient (coef min C), SOCc and SOCs (**Figure 4**). The first two axes explained nearly the same level of the total variance of the variable (27% and 22%, respectively). The carbon mineralization coefficient, herbaceous biomass, silt, and CO_2 had positive coordinates with the first axis. This axis can be considered to explain the combined action of herbaceous biomass, carbon mineralization coefficient and CO_2 on the variation in SOCs because of the significant positive correlation ($p < 0.01$, **Table 3**) between these variables. The correlation matrix analysis showed an increase in SOCc and SOCs with herbaceous biomass. With PCA, only sand and clay content explained 22% of the total variation in SOCs on Axis 2. Sand had a positive coordinate ($r = 0.959$), and clay had a negative coordinate ($r = -0.855$) (**Figure 4**). The sand and clay contents

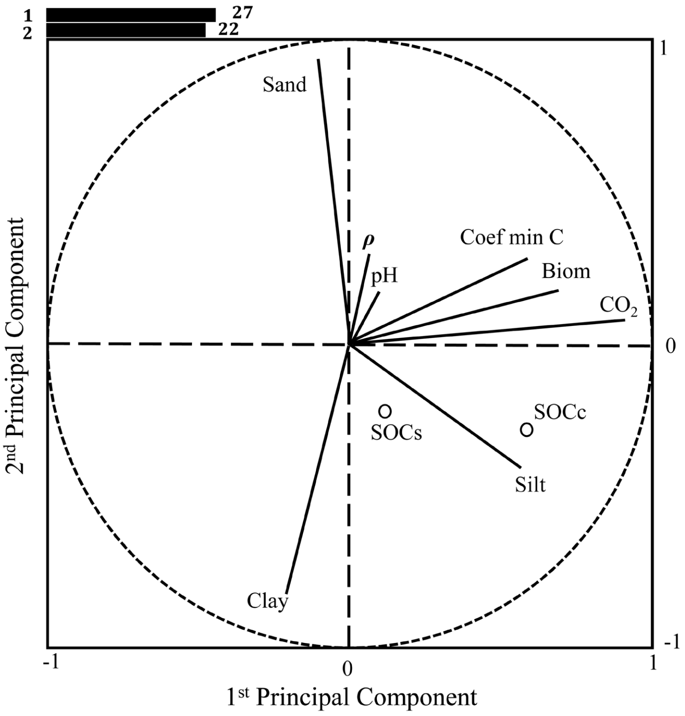


Figure 4. Diagram of principal component analysis (PCA) for sand, clay, silt, bulk density (ρ), pH, CO_2, herbaceous biomass (biom), carbon mineralization coefficient (coef min C), soil organic carbon content (SOCc) and soil organic carbon stock (SOCs).

Table 3. Correlation matrix between SOCc: soil organic carbon content, SOCs: soil organic carbon stock, physicochemical properties of soil (pH, sand, clay, and silt), ρ: soil bulk density, Biom: herbaceous biomass, CO_2: microbial activities and Coef min C: Carbon mineralization coefficient.

	ρ	pH	Biom	sand	clay	silt	SOCc	SOCs	CO_2	Coef min C
ρ	1									
pH	0.131	1								
Biom	0.209*	0.179*	1							
sand	0.169*	0.121	0.094	1						
clay	−0.170*	−0.083	−0.306*	−0.834*	1					
silt	−0.042	−0.09	0.303*	−0.518*	−0.04	1				
SOCc	0.049	0.203*	0.539*	−0.251*	−0.001	0.455*	1			
SOCs	0.334*	0.339*	0.174*	−0.164*	0.181*	0.016	0.422*	1		
CO_2	0.121	0.122	0.543*	−0.068	−0.168*	0.383*	0.524*	0.098	1	
Coef min C	0.059	−0.057	0.148*	0.106	−0.188*	0.099	−0.123	−0.202*	0.712*	1

* Significant at $p < 0.05$ level.

highlighted a strong negative relationship (r = −0.834, p < 0.01) (**Table 3**), indicating that the mean sand content decreased as the clay content increased and vice versa. The silt content had a low negative coordinate (r = −0.424) with Axis 2 compared with a high positive coordinate (r = 0.641) with Axis 1. The silt content decreases as the sand content increases, as highlighted by a significant negative relationship between silt and sand (r = −0.518, p < 0.01) (**Table 3**). In the correlation matrix, clay content was significantly and negatively correlated with herbaceous biomass, carbon mineralization coefficient and CO_2, while no correlation was found between sand and these variables. Clay was significantly and positively correlated with SOCs, while sand was significantly and negatively correlated with SOCc and SOCs (**Table 3**).

4. Discussion

This study displayed contrasting trends in soil SOC dynamics following the conversion of degraded land through the implementation of a combination of forest and landscape restoration (FLR) practices in semiarid regions. While the conversion of degraded land into forest (GF) and cropland (OARL and KARL) led to an increase in SOCs, we also observed a decrease in SOCs when converting degraded land into cropland (PARL). An increase in SOCs after the restoration of degraded lands was also observed by [29]. In contrast, [30] found higher SOCs at a 0 - 40 cm depth in degraded land compared with parkland agroforestry in semiarid regions. These contradictory results on SOC dynamics following the restoration of degraded lands can be explained by two main factors. Both the effects of different combinations of FLR practices on SOC, and on the other hand, soil particles changed with restoration practice. The variation in SOCs is most likely due to some environmental and physical factors of soil rather than the simple consideration of the conversion of degraded land.

4.1. Effects of Different Combinations of FLR Practices on SOC Stock

Our results show that the annual accumulation rate of SOCs varied widely according to the different combinations of FLR practices when converting degraded land into forest or cropland. Since all combinations of FLR practices used in this study included at least "*zaï*" and stone bunds (erosion control measures), the increase in SOCs was then partly attributed to these practices, and the difference observed between the combination of FLR practices could be related to other additional FLR practices, such as organic manure, crop rotation, crop/fallow succession, ANR, and the types of land use change. In the study of [31], 59% of the total potential of soil/crop management practices for SOC sequestration is due to the adoption of erosion control measures. Thus, the introduction of measures to control soil erosion was an important source of SOC sequestration [8].

[21] showed in a meta-analysis that the accumulation rate of soil C is generally lower for land restoration into cropland than for land restoration into forest. We would expect higher SOCs in GF than in OARL since GF is a forest and OARL is a cropland. In contrast, we observed higher SOCs in OARL than in GF. This difference in SOC levels may be related to soil management practices applied to each type of land use [32]. The association of "crop rotation + crop/fallow succession" practices with "*zaï*" + stone bunds + ANR practices (case of OARL) exhibited higher SOCs than the association of organic manure with "*zaï*" + stone bunds + ANR practices (case of GF). The higher SOCs in the first type of combination can be attributed to the role played by crop rotations, which favor the return of root biomass and aboveground biomass in the soil as SOCs [13]. The association of bare fallow increased SOCs by reducing herbaceous biomass input (fresh organic matter), a source of energy for microbial activity [16] [33] [34]. The impact of bare fallow on SOCs was measured through a decrease in microbial activities and a lower rate of organic carbon mineralization. The lower SOCs in the second type of combination might be explained by the higher rate of organic carbon mineralization being more active when direct carbon input through organic manure is used as energy for soil microorganisms, which further decomposes organic matter and thus causes destocking of carbon stores in the soil [35].

Several studies have investigated the impact of organic manure practices on soil organic carbon stock and have concluded an increase in SOCs after organic manure was applied [16] [34] [36]. This was explained by a direct carbon input by organic manure that serves as a source of nutrients leading to an increase in biomass residue inputs and root biomass, which in turn both enhance SOC stock

[37] [38] [39]. However, these effects differ widely according to many factors, including soil texture (mainly soil clay content) and climate [36]. In dry regions, the rate of decomposition of organic matter is generally higher [40] [41], and direct carbon input generally stimulates microbial activities that accelerate the decomposition of SOC [34].

These details explain how in our study, all types of combinations of FLR practices, including organic manure (GF, PARL, and KARL), presented higher carbon mineralization coefficients, lower SOC annual accumulation rates and lower SOCs than the FLR combination without organic manure application (OARL). This might be the result of the "priming effect", which consists of an increase in older SOC mineralization by the addition of fresh organic carbon [33] [39]. Indeed, the fresh carbon input through organic manure is used as energy for microbial activities that accelerate SOC mineralization, and therefore the loss of older SOCs. The priming effect might clearly explain the decrease in the SOC stock after the change in land use and the application of a combination of FLR practices to convert degraded land to cropland in the case of PARL.

The benefit of crop rotation on SOCs has been reported by several authors [11] [31] [42] [43] [44]. [42] in a meta-analysis describing the temporal dynamics of soil organic carbon after land management changes, identified "crop rotation" as a land management practice that can increase soil organic carbon. The study of [43] indicates that crop rotation can increase the carbon input from crop residues and by consequence, carbon sequestration, particularly in soybean cropping rotations. [44] found higher SOC in millet/cowpea rotation than in a continuous millet plot. The potential of SOC sequestration was estimated to 0.036 million metric ton of carbon per year for adopting crop rotation [31]. [42] reported that implementing crop rotation, reducing the fallow period, and reducing erosion were among the best land management practices to increase SOC. In our study, these practices correspond to crop rotation, crop/fallow succession and "*zai*" + stone bunds, respectively. The combination of these FLR practices in our study significantly increased soil organic carbon storage. However, the resulting effect of combinations of FLR practices was linked to several factors, including the physical properties of the soil and microbial activity.

Assisted natural regeneration (ANR) involves protecting young trees from grazing or weeding to stimulate their growth. The establishment and growth of woody vegetation appear to have been facilitated across all FLR practices, including the implementation of ANR, particularly under GF and OARL. These practices were also associated with the highest SOC increase in the soil found in this study. These findings are consistent with the results of a previous study that revealed a substantial contribution of organic compounds in the soil related to ANR practice [43] [44]. The SOC increase in the soil led by ANR in Sahelian sandy areas varied from 25% to 46% [45]. This potential of carbon sequestration in soil results from biomass accumulation in the root system, including exudates [43] [46] and leaf litter [47] but also limited outputs of organic matter through respiration due to the tree shade effect on the local microclimate.

4.2. Impact of Physicochemical Properties on SOC Stock

We found a decrease in clay content versus an increase in sand content in PARL after implementing a combination of FLR practices for PARL. In OARL, we observed a decrease in sand content versus an increase in clay content. There were no significant changes in clay content after the introduction of a combination of FLR practices in GF and KARL. The variation in SOCs among combinations of FLR practices and the control was likely due to the variation in the particle-size amount, which impacts the physical protection of soil organic carbon (**Figure 4**). Indeed, the study by [48] on the stability of aggregates showed that soil containing large amounts of organic carbon generates relatively stable aggregates with a clay texture. In this study, the correlation matrix and PCA (**Figure 4** and **Table 2**) showed a significant increase in SOCs with clay content and a significant decrease in SOCs with sand content. This observation is consistent with many other studies suggested that SOCs are significantly and positively correlated with clay content [48] [49] [50]. An explanation for this is that the fine fractions of the soil form a highly stable soil structure with organic carbon compared with the coarse fractions of sand [48] [50] [51] [52]. Under these conditions, the fact that the clay content decreased, and the sand content increased in the case of PARL could only have caused a loss of soil organic carbon, while for OARL, the increase in clay content against sand content led to an increase in soil organic carbon. PARL and OARL are both the agricultural land and are different by the type of combination of Forest and Landscape restoration practices (FLR).

The variation in SOCs might also be explained by the combined action of herbaceous biomass, coef min C and CO_2, as similar to the PCA, they explained at the same level that soil particles changed the variation in SOCs (**Figure 4**). The carbon mineralization coefficient (coef min C) is the parameter that measures the fraction of SOC that is mineralized in the form of CO_2 [27] and therefore the fraction of SOC lost as CO_2. Our results showed that the higher the coef min C was, the lower the SOCs. A negative correlation of clay content with coef min C and a negative correlation of clay with sand support the fact that the lower clay content (sand enrichment) involves the exposure of organic carbon, which is then mineralized and lost as CO_2. This is in agreement with the studies by [53] [54], who showed that organic carbon was easily decomposable in soils containing high amounts of sand. In this context, the increase in SOCs in OARL and KARL might result in a decrease in the carbon mineralization coefficient compared with their adjacent degraded land. In the same trend, a decrease in SOCs in PARL was the result of an increase in the carbon mineralization coefficient. The decrease in the coef min C under OARL and the increase in the coef min C under PARL were then related to the clay and sand contents, as previously explained. The fact that the SOCs were significantly higher in GF than in CGF, although the coef min C, clay and sand contents were not significantly different among these plots, indicates that the increase in SOCs, in this case, could have been due to other factors. There was a significant increase in SOCs with increasing herbaceous biomass, and this trend was influenced by clay content and CO_2 (**Table 3**). The increase in clay content with a decrease in herbaceous biomass development involved a reduction in SOC losses by SOC mineralization and consequently, an increase in SOCs.

5. Conclusion

This study aims to evaluate the impact of combined FLR practices mainly developed in semiarid regions on SOC stocks (SOCs) during the conversion of degraded soil into forest and cropland. Several combinations of FLR practices applied to convert degraded land into forest and cropland induced an increase between 0.2 and 0.3 t C $ha^{-1}\cdot yr^{-1}$ of SOCs, together with an improvement of clay content in the soil, better development of herbaceous biomass and a reduction of biological activities. In contrast, one combination of FLR practices applied to convert degraded land into cropland, induced a loss of approximately 0.1 t C $ha^{-1}\cdot yr^{-1}$. When deciding the kind of FLR practices to be implemented, their potential to sequester SOC by increasing carbon inputs and reducing carbon losses should be considered along with their specific objectives. All combinations of FLR practices are not necessarily transferable from one soil to another because they have shown an amelioration of SOCs on a specific type of soil. This study finally provides additional information on the mechanisms explaining SOC variation to predict the potential storage of SOC when degraded land is converted into forest and croplands. The dynamics of soil organic carbon storage in lands restored through a combination of forest and landscape restoration practices are related to microbial activities, carbon mineralization rate and soil particle size. This study needs to be performed at other study sites with various climates, types of soil and environmental conditions to identify and promote the best combination of FLR practices that improve SOCs. This study shows that the choice of best management practices is important to ensure the increase of carbon stocks in soils.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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