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Original article

Organic carbon stocks and dynamics in Ferrallitic Red leached soils with grasslands in western Cuba

Reservas y dinámica de carbono orgánico en suelos Ferralíticos Rojos Lixiviados con pastizales en el occidente de Cuba

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ABSTRACT: Agriculture faces the challenge of being both productive and sustainable, requiring practices that improve soil quality and contribute to climate change mitigation. The accumulation of organic carbon in soil is a key factor in this process, as it enhances ecosystem stability and reduces greenhouse gas emissions. This study determined the organic carbon (SOC) stocks and their temporal dynamics (2004-2017) in Ferrallitic Red Leached soils under different land-use systems (monoculture grasslands and silvopastoral systems with fruit trees) in three provinces of western Cuba (Mayabeque, Artemisa, and Pinar del Río). Nine soil profiles were analyzed in areas covered by *Dichanthium caricosum* grass, revealing stocks of up to 58 Mg ha^{-1} in the 0-20 cm layer and up to 80 Mg ha^{-1} in the 0-50 cm layer, while values in the 50-100 cm layer were lower (17-36 Mg ha^{-1}). Temporal evaluation in five profiles showed significant accumulation, with rates of up to 2.62 Mg ha^{-1} year^{-1} at a depth of 0-30 cm. Silvopastoral systems (associated with mango, citrus, and guava) showed higher SOC stocks than monoculture grasslands. These findings provide valuable insights for developing agricultural strategies aimed at carbon capture and sequestration, promoting soil conservation and environmental sustainability in tropical soils.

Key words: Climate change, Cuba, soil science, organic carbon, sustainability.

RESUMEN: La agricultura enfrenta el desafío de ser productiva y, al mismo tiempo, sostenible, lo que requiere prácticas que mejoren la calidad del suelo y contribuyan a la mitigación del cambio climático. La acumulación de carbono orgánico en el suelo es un factor clave en este proceso, ya que favorece la estabilidad de los ecosistemas y reduce las emisiones de gases de efecto invernadero. En este estudio se determinaron las reservas de carbono orgánico (RCO) y su dinámica temporal (2004-2017) en suelos Ferralíticos Rojos Lixiviados bajo diferentes sistemas de uso (pastizales en monocultivo y sistemas silvopastoriles con frutales) en tres provincias del occidente de Cuba (Mayabeque, Artemisa y Pinar del Río). Se analizaron nueve perfiles de suelo en áreas cubiertas por el pasto jiribilla (*Dichanthium caricosum*), encontrando reservas de hasta 58 Mg ha^{-1} en la capa de 0-20 cm y hasta 80 Mg ha^{-1} en la capa de 0-50 cm, mientras que en la capa de 50-100 cm los valores fueron menores (17-36 Mg ha^{-1}). La evaluación temporal en cinco perfiles mostró una acumulación significativa, con tasas de hasta 2,62 Mg ha^{-1} año^{-1} en la profundidad de 0-30 cm. Los sistemas silvopastoriles (asociados a mango, cítricos y guayaba) presentaron mayores RCO que los pastizales en monocultivo. Estos resultados proporcionan información relevante para el desarrollo de estrategias agrícolas orientadas a la captura y secuestro de carbono, promoviendo la conservación del suelo y la sostenibilidad ambiental en suelos tropicales.

Palabras Clave: Cambio climático, Cuba, edafología, carbono orgánico, sostenibilidad.

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INTRODUCTION

In recent decades, the issue of soil carbon has gained global relevance due to its impact on food security and climate change. The loss of soil organic carbon (SOC) in agricultural ecosystems, together with climate change, represents a critical threat to agricultural production. Studies indicate that agricultural soils worldwide have lost between 30 and 75 % of their original SOC stocks, equivalent to 30-40 Mg C·ha^{-1} (1). This decline has significantly contributed to the increase in greenhouse gases (GHG), exacerbating global warming and its consequences, such as extreme weather events (droughts, floods) and declines in agricultural productivity (2).

Organic carbon is a key indicator of soil health, as it directly influences physical and chemical soil properties such as bulk density, structure, porosity, and water retention capacity (3,4). Conversely, its degradation leads to the deterioration of these properties, compromising the sustainability of agroecosystems (3,5). Research conducted in various regions, including Mexico (6,7), the Peruvian, Brazilian, and Colombian Amazon (8-11), Ecuador (12-15), and Russia (16-18), demonstrates the universality of this challenge and the need to address it.

In this context, in tropical soils, although studies exist on Nitisols in Brazil (19-21) and on silvopastoral systems in Latin America (22,23), Cuban Ferrallitic soils classified as Rhodic Nitisols (24) have been little investigated, especially under silvopastoral management. This knowledge gap limits the design of local sustainable management and carbon sequestration strategies. Therefore, the aim of the present study was to determine the content and temporal dynamics (2004-2017) of organic carbon in Leached Red Ferrallitic soils (25) under different land-use systems (monoculture grasslands and silvopastoral systems with fruit trees) in western Cuba, in order to provide baseline data on the evolution of carbon stocks under different management systems over time, for the design of sustainable management strategies and climate change mitigation in the region.

MATERIALS AND METHODS

Study area and profile characterization

The study was conducted on Leached Red Ferrallitic soils (25), predominant in the western region of Cuba, under a subhumid tropical climate. Nine soil profiles were evaluated under grassland systems (associated or not with fruit trees), distributed across three provinces and over two initial sampling periods (2004 and 2010) and a final sampling in 2017 for temporal assessment. The profiles were located in the following localities (UTM coordinates):

Mayabeque province

- Profiles 1, 8, and 36: National Institute of Agricultural Sciences (INCA), San José de las Lajas.
    - Profile 1: N 353250, E 383225
    - Profile 8: N 353125, E 383100
    - Profile 36: N 353300, E 383300
- Profile 6: "Las Papas" Farm, San José de las Lajas (N 351800, E 383250).
- Profile 38: Jamaica locality, San José de las Lajas (N 350600, E 380100).

Artemisa province

- Profiles 11, 12, and 13: San Antonio de los Baños Municipality.
    - Profile 11: Héctor's Farm (N 341000, E 344700)
    - Profile 12: Bernardo's Farm (N 341900, E 345800)
    - Profile 13: State livestock farm (N 339650, E 342550)

Pinar del Río province

- Profile 28: "Niña Bonita" Enterprise, Pinar del Río (N 358600, E 346000).

The land-use systems remained constant throughout the study period (2004-2017):

- Profiles 1 and 36: Jiribilla grass (*Dichanthium caricosum*) under mango tree grove (*Mangifera indica*) for over 40 years.
- Profile 6: Jiribilla grass under citrus grove (*Citrus spp*.) for 30 years.
- Profile 8: Jiribilla grass under guava grove (*Psidium guajava*) for 20 years.
- Profile 28: Jiribilla grass in monoculture for 30 years.
- Profiles 11, 12, 13, and 38: Jiribilla grass in monoculture for 15-20 years.

Soil Sampling

Spatial distribution: The profiles were located in representative plots of the Red Ferrallitic soil ecosystem formed from hard limestone under a subhumid tropical climate.

Sampling depth

- Complete profiles (2004 and 2010): Profiles were described down to 1 m depth, divided by horizons (A, B, C), taking into account the Cuban manual for profile description (26).
- SOC monitoring (2017): Additional samples were taken at 0-10 cm, 10-20 cm, and 20-30 cm, in triplicate (in a triangle around the original profile point, with 1 m separation between points) to assess spatial variability.

Sampling method

- Extraction using an auger and volumetric cylinder (100 cm³) for bulk density.
- Sampling was carried out under natural soil moisture conditions during the study period.
- Samples were dried at 105 °C to constant weight to determine gravimetric moisture content.

Laboratory analysis

Soil samples were analyzed at the Chemical Analysis Laboratory of the National Institute of Agricultural Sciences, using standardized methods according to the manual of analytical methods for tropical soils (27), as detailed in Table 1.

Calculation of soil organic carbon (SOC) stocks

SOC stocks were calculated per horizon using the standard formula (28):

$$COS\left(Mg \cdot ha^{-1}\right) = \left(Mg \cdot m^{-3}\right) \times OC\left(\%\right) \times Thickness\left(cm\right) \times \left(1 - I\right)$$

Where:

ρ: Bulk density (determined *in situ* with a 100 cm^3 cylinder, dried at 105 °C to constant weight).

OC: Organic carbon, calculated as OM/1.724 (conversion factor for tropical soils).

I: Fraction of inclusions (ferruginous nodules, gravels). In this study, I = 0 for surface horizons.

Temporal assessment of SOC

In 2017, the dynamics of SOC stocks were assessed by comparing historical data (2004-2010) versus recent samples (0-30 cm), with emphasis on changes due to management (silvopastoral vs. pure grassland). To this end, resampling was carried out at the same original coordinates, controlling spatial variability through triplicates. The annual gain rate was calculated as:

$$Rate\left(Mg\ ha^{-1}\ year^{-1}\right) = [SOC\_final - Soc\_inicial] \ / \ [Years\ elapsed]$$

Statistical analysis

Data were processed using STATGRAPHICS Centurion software. Means and standard deviations were calculated for each parameter. Differences between land-use systems were assessed using analysis of variance (ANOVA) and Tukey's test ($p < 0.05$).

RESULTS AND DISCUSSION

Physical and chemical characterization of the soils

The descriptions of the analyzed profiles confirm that the studied soils possess a Ferrallitic composition, characterized by their red color, depth, and clayey texture. These soils present an A-Bt-BC-C profile, with granular and nutty-granular structure in the A horizon, while polyhedral structures with cutans predominate in the Bt horizon.

Table 2 presents the mean values (± standard deviation) of mechanical particles according to depth for the nine soil profiles, along with the textural classification. The soils are observed to be predominantly clayey, with a progressive decrease in clay and silt with depth, while clay enrichment is evident in the middle part of the profile due to the presence of the argillic horizon, resulting from the leaching process.

Based on these characteristics, the analyzed soils are classified as Leached Red Ferrallitic soils (25). However, according to the World Reference Base classification, they are considered Ferralic Lixic Rhodic Nitisols (24).

The increase in sand and silt content in the upper horizon of these soils is due to the relative enrichment caused by the translocation of clay toward the lower Bt horizon, as a result of the leaching process. Furthermore, these soils present a pH in the cumulative humic horizon ranging between 6.7 and 7.2, with a mean of 6.96 ± 0.15. This condition influences the distribution of exchangeable bases, especially calcium and magnesium, whose mean values for the nine analyzed profiles are presented in Table 3.

Table 1. Analytical methods used for soil characterization

Parameter	Method	Number of replicates
pH	Potentiometric (soil:water ratio 2:1)	3
Ca^{2+}, Mg^{2+}	Extraction with ammonium acetate ($NH_4CH_3CO_2$ 1 mol L^{-1}, pH 7), complexometry	3
K^+	Extraction with ammonium acetate ($NH_4CH_3CO_2$ 1 mol L^{-1}, pH 7), flame photometry	3
Available P	Extraction with H_2SO_4 0.1 mol L^{-1} (soil:solution ratio 1:25)	3
Organic matter	Walkley-Black	3
Texture	Pipette method	2

Table 2. Average mechanical composition and texture (± SD) of the 9 studied profiles

Depth (cm)	% of particles			Texture
	Sand	Silt	Clay	
0-20	19.2 ± 2.1	16.4 ± 1.8	65.3 ± 3.2	Clayey
20-50	16.1 ± 1.9	9.3 ± 1.2	74.9 ± 2.8	Clayey
50-90	12.4 ± 1.5	9.1 ± 1.1	78.8 ± 2.5	Clayey

The results show that surface pH is higher than expected, with some profiles exceeding 7.0, which is unusual for Ferrallitic soils. However, comparisons with studies conducted on similar soils 30-40 years ago reveal an increase in pH in the surface layer. Several hypotheses have been proposed to explain this phenomenon, including the impact of climate change in Cuba, which has generated temperature increases (29), as well as the effect of irrigation with hard water from the underlying Miocene limestone aquifer, which supplies calcium and magnesium (5,30).

The increase in surface pH is accompanied by a higher concentration of exchangeable bases, mainly calcium and magnesium. Furthermore, the contribution of grassland roots, particularly from grasses, to the increase in soil calcium cannot be ruled out. In contrast, sodium content is negligible, since during the Ferrallitization process it is practically eliminated by leaching, while potassium remains at medium to low levels due to the same process.

Soil organic carbon stocks in the studied profiles

Regarding the content and stocks of organic carbon in Leached Red Ferrallitic soils under grasslands or fruit trees with grasslands, a significant accumulation is observed in the 0-20 cm layer, reaching up to 56 Mg ha^{-1}. In the 0-50 cm layer, values can exceed 80 Mg ha^{-1} in some cases, as shown in Table 4.

The results on the accumulation of soil organic carbon (SOC) stocks in grassland soils coincide with those reported by (31-34). According to these studies, in the 0-100 cm layer, soils can accumulate between 80 and 149 Mg·ha^{-1} of SOC, values consistent with the findings of the present study.

However, at the soil depth of 50-100 cm, accumulation is considerably lower, with values ranging between 17 and 36 Mg·ha^{-1}. This is due to the root development of grasslands, whose fine roots do not reach great depths, unlike crops such as sugarcane or maize, which present deeper and more extensive root systems.

Temporal dynamics of soil organic carbon stocks

In six of the analyzed Leached Red Ferrallitic soil profiles, the annual SOC gain has been determined, with results presented in Table 5, over a period of 7 to 13 years. For the 0-30 cm layer, total SOC capture ranges between 12 and 34 Mg·ha^{-1}·yr^{-1} over the evaluated period, demonstrating the potential of these soils for carbon storage in the medium and long term.

A relevant finding of this study is the difference in SOC stocks between land-use systems. Profiles associated with fruit trees (mango, citrus, guava) showed higher SOC stocks compared to monoculture grasslands (Tables 4 and 5). This difference can be attributed to several factors:

1. Additional biomass input: Silvopastoral systems receive contributions of leaf litter and roots from trees, which add to those from the grass, increasing carbon input into the soil.
2. Favorable microclimate: Partial shade provided by trees reduces soil temperature and the rate of organic matter decomposition.
3. More diverse root system: The combination of grass roots (shallow) and tree roots (deeper) explores a greater soil volume, incorporating carbon at different depths.

These results coincide with previous studies in tropical silvopastoral systems (35,36), which report higher carbon stocks in diversified systems compared to monocultures.

Table 6 presents the annual gain of soil organic carbon stocks (SOC), which can reach up to 2.62 Mg·ha^{-1}·yr^{-1} for jiribilla grass (*Dichanthium caricosum*) in the 0-30 cm layer, over a 13-year period. These results coincide with previous studies, such as those conducted by (37), who reported similar results in soils under grasslands, reinforcing the relevance of these plant species in carbon accumulation and sequestration.

These results are highly relevant for sustainable soil management and should be considered in the planning of long-term grassland rotations, especially in soils that tend to degrade due to continuous cultivation (5). The implementation of conservation management practices can significantly contribute to restoring soil fertility and optimizing organic carbon accumulation.

Furthermore, these results provide a scientific basis for the future development of a carbon capture and sequestration policy in the province's grassland soils. Adopting strategies aimed at improving carbon retention would not only benefit agricultural productivity but also represent a significant advance in climate change mitigation efforts, thereby strengthening the resilience of local ecosystems in the face of changing environmental conditions.

Table 3. Selected average chemical characteristics (± SD) of the 9 studied profiles

Depth (cm)	pH (H_2O)	Cation Exchange Capacity (CEC) cmol kg^{-1})				Available P (mg kg^{-1})	
		Ca	Mg	Na	K	Suma	
0-20	6.96 ± 0.15	17.0 ± 2.3	5.0 ± 0.8	0.1 ± 0.02	0.42 ± 0.07	22.52 ± 3.1	25.0 ± 3.5
20-50	6.92 ± 0.18	12.0 ± 1.9	4.0 ± 0.6	0.1 ± 0.02	0.12 ± 0.03	16.22 ± 2.4	18.0 ± 2.8
50-90	6.71 ± 0.21	9.0 ± 1.5	4.0 ± 0.7	0.1 ± 0.02	0.17 ± 0.04	13.27 ± 2.1	16.0 ± 2.4

Table 4. Soil Organic Carbon stocks in Mg·ha⁻¹ for the 9 studied profiles of Leached Red Ferralitic soils (FRL)

Profile No.	Horizon	Depth (cm)	OM (%)	OC (%)	Moisture (%)	ρ (Mg m⁻³)	SOC (Mg ha⁻¹)	SOC by layers (cm) 0-20 0-50 0-100 50-100
1	A_{11}	0-8	3.55	2.06	35.7	0.98	6.99	38 62 90 28
	A_{12}	8-22	3.12	1.81	34.2	1.00	6.05	
	$B_{11}t$	22-41	1.38	0.80	32.7	1.09	5.12	
	$B_{12}t$	41-64	0.70	0.40	33.6	1.04	5.26	
	B_2	64-100	0.50	0.60	33.8	1.03	5.34	
8	A_1	0-12	3.58	2.08	34.1	1.08	6.50	41 63 80 17
	B_1t	12-28	2.70	1.57	33.4	1.13	6.40	
	B_2t	28-50	0.55	0.32	34.8	1.10	6.50	
	B_3	50-70	0.45	0.26	35.1	1.08	6.60	
	BC	70-100	0.60	0.34	34.2	1.10	-	
11	Agr	0-24	4.20	2.44	36.1	1.05	61.5	51 89 115 26
	B11	24-50	1.64	0.95	35.1	1.10	27.2	
	B12p	50-67	1.29	0.75	34.2	1.12	14.3	
	B2	67-85	0.55	0.32	34.7	1.15	12.1	
12	A	0-18	3.82	2.22	37.4	1.07	42.8	46 81 116 35
	B_{1t}	18-38	2.31	1.34	39.5	1.10	29.5	
	B_2t	38-100	1.08	0.63	33.2	1.13	44.1	
6	A_{11}	0-3	4.07	2.36	Nd	Nd	6.7	41 84 110 26
	A_{12}	3-16	4.00	2.32	35.9	0.95	28.7	
	B_1t	16-52	2.23	1.29	34.6	1.10	51.1	
	$B_{21}t$	52-78	0.95	0.55	34.2	1.11	15.9	
	$B_{22}t$	78-105	0.55	0.32	33.9	1.12	9.7	
13	A	0-18	4.23	2.45	34.9	1.04	45.9	49 78 113 35
	AB	18-30	2.23	1.29	34.1	1.09	16.9	
	B_1t	30-52	1.21	0.70	33.7	1.12	17.2	
	B_2t	52-100	1.06	0.61	33.8	1.14	33.4	
28	A	0- 20	4.59	2.66	34.9	1.09	58.0	58 87 115 28
	AB	20-32	2.12	1.23	32.5	1.12	16.5	
	B_1t	32-47	1.03	0.60	32.8	1.13	10.2	
	B_2t	47-84	0.89	0.52	30.2	1.20	23.1	
	B_3	84-130	0.60	0.35	28.8	1.22	19.6	
36	A	0-19	3.59	2.08	33.8	1.04	41.1	43 81 112 31
	AB	19-29	3.23	1.87	32.6	1.07	20.0	
	B_1t	29-59	1.34	0.78	31.5	1.17	29.0	
	B_2t	59-92	0.86	0.50	30.2	1.19	19.6	
	B_3	92-120	0.45	0.26	29.8	1.20	8.7	
38	A	0-15	4.74	2.75	35.1	1.09	44.96	56 109 149 40
	AB	15-40	3.39	1.97	33.6	1.14	56.14	
	B_1t	40-100	1.14	0.66	28.5	1.22	48.31	
	B_2t	100-200	0.70	0.41	29.4	1.19	48.79	

OM (%): Organic Matter, OC (%): Organic Carbon, ρ (Mg·m⁻³): Bulk density (international symbol rho), SOC_horiz (Mg·ha⁻¹): Soil Organic Carbon stock per individual horizon, SOC_layer (Mg·ha⁻¹): Soil Organic Carbon stock accumulated by depth layer (0-20, 0-50, 0-100, 50-100 cm), Nd: Not determined, -: Not calculated or not applicable

Table 5. SOC stock gain in Leached Red Ferrallitic soils under grasslands in San José de las Lajas Municipality (2004-2017)

Sampling moments	Date	SOC stock (Mg ha^{-1})		
		0-10 cm	0-20 cm	0-30 cm
Profile 1: Jiribilla grassland under mango tree grove				
Initial sampling	22-04-2010	54	86	107
Final sampling	07-03-2017	65	102	140
Difference	(7 years)	+11	+16	+33
Profile 36: Jiribilla grassland under mango tree grove				
Initial sampling	22-07-2010	22	43	62
Final sampling	06-03-2017	28	49	74
Difference	(7 years)	+6	+6	+12
Profile 8: Jiribilla grassland under guava tree grove				
Initial sampling	2004	20	41	56
Final sampling	2017	37	62	71
Difference	(13 years)	+17	+21	+15
Profile 6: Jiribilla grassland under citrus tree grove				
Initial sampling	2004	21	41	55
Final sampling	2017	29	55	89
Difference	(13 years)	+8	+14	+34
Profile 38: Jiribilla grassland in pasture at the entrance of Jamaica				
Initial sampling	2010	28	56	80
Final sampling	2017	38	61	92
Difference	(7 years)	+10	+5	+12

Table 6. Annual SOC stock gaining in FRL soils in western Cuba

Sampling period (years)	SOC Stock Gain Rate (Mg·ha^{-1}·yr^{-1})		
	0-10 cm	0-20 cm	0-30 cm
Profile 1: Jiribilla grassland under mango tree grove			
7	+1.07	+0.86	+1.07
Profile 36: Jiribilla grassland under mango tree grove			
7	+0.86	+0.86	+1.71
Profile 8: Jiribilla grassland under guava tree grove			
12	+1.42	+1.75	+1.25
Profile 6: Jiribilla grassland under citrus tree grove			
13	+0.61	+1.08	+2.62
Profile 38: Jiribilla grassland in pasture at the entrance of Jamaica			
9	+1.11	+0.96	+1.33

CONCLUSIONS

The study conducted on Leached Red Ferrallitic soils (Rhodic Nitisols) under grasslands in western Cuba demonstrates the potential of these systems for organic carbon (SOC) accumulation and their contribution to agricultural sustainability and climate change mitigation. Based on the results obtained, the following conclusions are highlighted:

- These results underscore the capacity of grasslands, especially Jiribilla grass (*Dichanthium caricosum*), to store carbon in surface horizons over the medium term.
- Profiles associated with fruit trees (mango, citrus, and guava) showed higher SOC stocks compared to monoculture grasslands, suggesting that diversified systems favor carbon stability.

RECOMMENDATIONS

Based on the results of this study, the following recommendations are formulated for the sustainable management of Leached Red Ferrallitic soils in Cuba and similar tropical regions:

1. Promote agroforestry and silvopastoral systems: The integration of fruit trees (especially mango and citrus) into grasslands is recommended, as these systems demonstrated a greater capacity for soil organic carbon storage.
2. Implement long-term rotations: In annual cropping areas, the introduction of rotations that include prolonged periods (minimum 5-7 years) with jiribilla grass (*Dichanthium caricosum*) is suggested to allow the recovery of soil carbon stocks.

3. Establish a monitoring program: The creation of a network of permanent observation plots is recommended to track carbon dynamics under different land-use systems, which would allow for the adjustment of management practices and the validation of mitigation strategies.
4. Consider carbon sequestration in agricultural policies: The results provide a quantitative basis for including grassland and silvopastoral system management in local and national strategies for payments for ecosystem services related to climate change mitigation.

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