

Green manure: Alternative to carbon sequestration in a Typic Ustipsamment under semiarid conditions

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Abono verde: una alternativa al secuestro de carbono en un Typic Ustipsamment bajo condiciones semiáridas

Adubação verde: uma alternativa ao sequestro de carbono num Typic Ustipsamment em condições semiáridas

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ABSTRACT

Vegetative soil cover mitigates climatic variability and enhances the balance between mineralization and humification processes. Under aerobic conditions, most of the carbon that enters the soil is labile, but a small fraction (1%) is humified and stable, contributing to the soil carbon reserve; therefore, it is important to assess the carbon content captured after green manure cultivation and decomposition. During two consecutive semesters, July to December 2016 and January to June 2017, green manure plots (*Zea mays* L., *Andropogon sorghum* subsp. *sudanensis* and *Crotalaria longirostrata*) were cultivated individually, in a consortium or amended with palm oil agro-industrial biosolids in a randomized complete block design with 12 treatments. Once decomposed, the different carbon fractions (organic, oxidizable, non-oxidizable, removable and total) were determined. The results showed high total and organic carbon contents under the sorghum treatment, at 30 and 28 Mg ha⁻¹, respectively, followed by those under the fallow + biosolid treatment, at 29.8 Mg ha⁻¹ and 27.5 Mg ha⁻¹, respectively. Despite the short experiment duration and the possible contributions of previous management on recalcitrant carbon soil stocks, these findings suggest the importance of maintaining plant cover and utilizing green manure in the Colombian Caribbean region. Long-term experiments may be conducted to confirm the full potential of cover crops on carbon sequestration under tropical semiarid conditions.

RESUMEN

*La cobertura vegetal mitiga la variación climática y favorece el balance entre los procesos de mineralización y humificación del suelo. En condiciones aeróbicas, parte del carbono que entra en el suelo es lábil, pero una pequeña fracción (1%) es humificada, estable y constituye la reserva de carbono del suelo; por ello, es importante conocer la cantidad de carbono capturada después del cultivo y descomposición de abonos verdes. Durante dos semestres consecutivos, julio a diciembre de 2016 y enero a junio de 2017, parcelas fueron cultivadas con abonos verdes (*Zea mayz* L., *Andropogon sorghum* subsp. *sudanensis* y *Crotalaria longirostrata*) individuales, consociadas o con aplicación de biosólidos de la agroindustria de palma de aceite, totalizando 12 tratamientos en un diseño en bloques*

al azar. Una vez descompuestos se determinaron las diferentes fracciones de carbono (orgánico, oxidable, no oxidable, removible y total). Los resultados indicaron altas concentraciones de carbono total y orgánico en el tratamiento con sorgo con 30 y 28 Mg ha⁻¹, respectivamente, seguido por barbecho + biosólido con 29.8 Mg ha⁻¹ de carbono total y 27.5 Mg ha⁻¹ de carbono orgánico. Pese a la corta duración del experimento y la posible contribución de cultivos previos en el almacenamiento de carbono recalcitrante en el suelo, los resultados sugieren la importancia de mantener la cobertura vegetal y la utilización de abonos verdes en la región del Caribe Colombiano. Más estudios de larga duración deben ser conducidos para la determinación del potencial máximo de los abonos verdes en el secuestro de carbono bajo condiciones tropicales semiáridas.

RESUMO

A cobertura vegetal atua na mitigação das alterações climáticas e favorece o balanço entre os processos de mineralização e humificação da matéria orgânica no solo. Em condições aeróbicas, a maior parte do carbono que entra no solo é lábil, porém uma pequena fração (1%) é húmica, estável e contribui para a reserva de carbono no solo, assim sendo, é importante conhecer a quantidade de carbono sequestrada após o cultivo e decomposição dos adubos verdes. Durante dois semestres consecutivos, Julho a Dezembro de 2016 e Janeiro a Junho de 2017, foram cultivadas parcelas com adubos verdes (Zea mayz L., Andropogon sorghum subsp. sudanensis and Crotalaria longirostrata) individuais, consociadas ou com aplicação de biosólidos da agroindústria do óleo de palma, totalizando 12 tratamentos delineados em blocos totalmente casualizados. Após a decomposição, foram determinadas as diferentes frações de carbono (orgânica, oxidável, não oxidável, lábil e total). Os resultados indicaram altas concentrações de carbono total e orgânico no tratamento com sorgo, 30 e 28 Mg ha⁻¹, respectivamente, seguido por pousio + biosólido com 29,8 de carbono total e 27,5 Mg ha⁻¹ de carbono orgânico. Apesar da curta duração dos ensaios e da possível contribuição de culturas prévias no armazenamento de carbono recalcitrante no solo, os resultados obtidos sugerem a importância da manutenção da cobertura vegetal e utilização da adubação verde na região do Caribe Colombiano. Ensaios de longa duração deverão ser conduzidos para a determinação do potencial máximo dos adubos verdes no sequestro de carbono em condições tropicais semiáridas.

1. Introduction

Agricultural practices can be a source of carbon dioxide (CO₂) to the atmosphere (Lal 2007, 2014), contributing to climate variability when it surpasses plant carbon fixation by photosynthesis. Reicosky (2002) estimated that soil tillage promotes carbon losses between 30% and 50% and results in moisture and biodiversity losses in edaphic systems. However, biomass incorporation into soil has the potential to capture CO₂ through the humification of organic matter (OM) fractions after the mineralization process (Escalante 2015) and increase the soil carbon (SC) content.

The adoption of more sustainable agricultural practices, such as cover crops, can increase SC and the retention of soil moisture (Carvajal et al. 2014). In humid tropical climates, biomass added to soil is readily mineralized to CO₂ and quickly released into the atmosphere due to the higher turnover rates (Davidson and Janssens 2006). However, under semiarid conditions, soils are more resistant to carbon losses (Donohue et al. 2013; Romanyá et al. 2000) and can be considered an important sink for atmospheric CO₂ (Evans et al. 2014). It was also demonstrated that the type of cover crop directly affects the soil organic carbon (SOC) mineralization rates under semiarid conditions (Ghimire et al. 2017). Exposing semiarid soils to elevated concentrations of CO₂ resulted in increases in net ecosystem productivity and carbon storage primarily as a result of direct effects on photosynthesis

KEY WORDS

Andropogon sorghum, Crotalaria longirostrata, carbon fractions, CO₂ capture technologies.

PALABRAS

CLAVE

Andropogon sorghum, Crotalaria longirostrata, fracciones de carbono, tecnologías de captura de CO₂.

PALAVRAS-

CHAVE

Andropogon sorghum, Crotalaria longirostrata, frações de carbono, tecnologias de captura de CO₂.

(Dijkstra et al. 2010; Evans et al. 2014). The indirect effect of SOC on soil physical properties and water retention, together with total N and K, was also identified as a key ecosystem function driving plant biodiversity and contributing to the rehabilitation of deserted areas (Qiu et al. 2018).

Another alternative to semiarid SC stocks is amendment with agro-industrial wastes. During oil palm production, a large quantity of solid and liquid wastes in the form of empty fruit bunches, pericarp fibers, and palm biosolids is generated. It is estimated that 0.3-0.6 t of biosolids are produced for every t of oil palm fresh fruit bunches processed (Rashid et al. 2009). The biosolid produced is a colloidal suspension with a sufficient amount of nutrients for N, P and K as well as cellulose, which could be favorable for microbial growth and soil chemical and physical characteristics. Many attempts have been reported in the bioconversion of these oil palm wastes (Alam et al. 2008), but the high production of these wastes forces the search for alternative uses.

Present and future greenhouse gas (GHG) emissions from agriculture are highly uncertain in Latin America due to the real adoption or absence of climate mitigation policies (Calvin et al. 2016). FAO (2014) estimates that GHGs derived from agricultural activities in Latin America account for 17% of agricultural emissions and have doubled in the last 50 years. Alternatives are necessary to mitigate GHG emissions and reduce the impacts of agricultural practices on global warming. Because semiarid and arid ecosystems cover 47% of the terrestrial surface (Evans et al. 2014), it is very important to accurately determine carbon capture under these environmental conditions and their potential as atmospheric carbon sinks under the current atmospheric CO₂ concentration.

Here, we evaluated the carbon fixation rates of a *Typic Ustipsamment* planted with green manures (*Zea mays* L., *Andropogon sorghum* subsp. *sudanensis*, and *Crotalaria longirostrata*) to which biosolids were added (residue from palm oil processing), in a short-term experiment in Santa Marta, Colombia, in a semiarid ecosystem with tropical dry forests converted to intensive agricultural fields after deforestation.

2. Materials and Methods

2.1. Site description and experimental design

The study site is characterized by a tropical dry climate, with an average annual precipitation of 674 mm and bimodal rainfall. The seasons are divided into rainy (March to May and September to November) and dry (December to February and June to August) periods. The mean temperature and relative humidity are 29.5 °C and 70%, respectively. The natural plant community is composed of a dry tropical forest with xerophytic vegetation (IDEAM et al. 2015). Soils in the area are derived from strata of sedimentary parent rock from the Tertiary period of the Cenozoic Era with successive strata of sandstones and schistose clays, colored yellow, brown, greenish-gray and bluish, from the Oligocene and Miocene eras. There are also calcareous limestones, calcareous sandstones, gravel, coal layers and marly limestone from the Pliocene. This formation has considerable thickness and is characterized by its Miocene fauna, plant remains, and strongly bituminous lignite layers. The soil mineralogy is dominated by kaolinite (50%), quartz (5-15%), feldspar (5-15%), interstratified trace minerals, micas (5-30%), montmorillonite (30-50%) and vermiculite (5-30%) (IGAC 2009; Aguirre et al. 2015).

Field experiments were carried out in 2016 at the Center for Agricultural and Forestry Development of the Universidad del Magdalena, Santa Marta, Colombia (11°13'24" N; 74°10'56" W) (**Figure 1**), with mean monthly temperatures that varied within the annual cycle from 27.9-29.9 °C and with an average annual rainfall of 565.5 mm. Approximately 60% of the annual rainfall occurred during the rainy season.

Soils were classified as *Typic Ustipsamments* of alluvial origin. According to Idárraga et al. (2011), these are recent unconsolidated alluviums composed of sands, gravels, and pebbles that are poorly selected and have fragments of plagioclase, mica biotite, quartz and rocks from the Batolito de Santa Marta rocks. They are located in the western part of the study area and come from the mountainous part of the

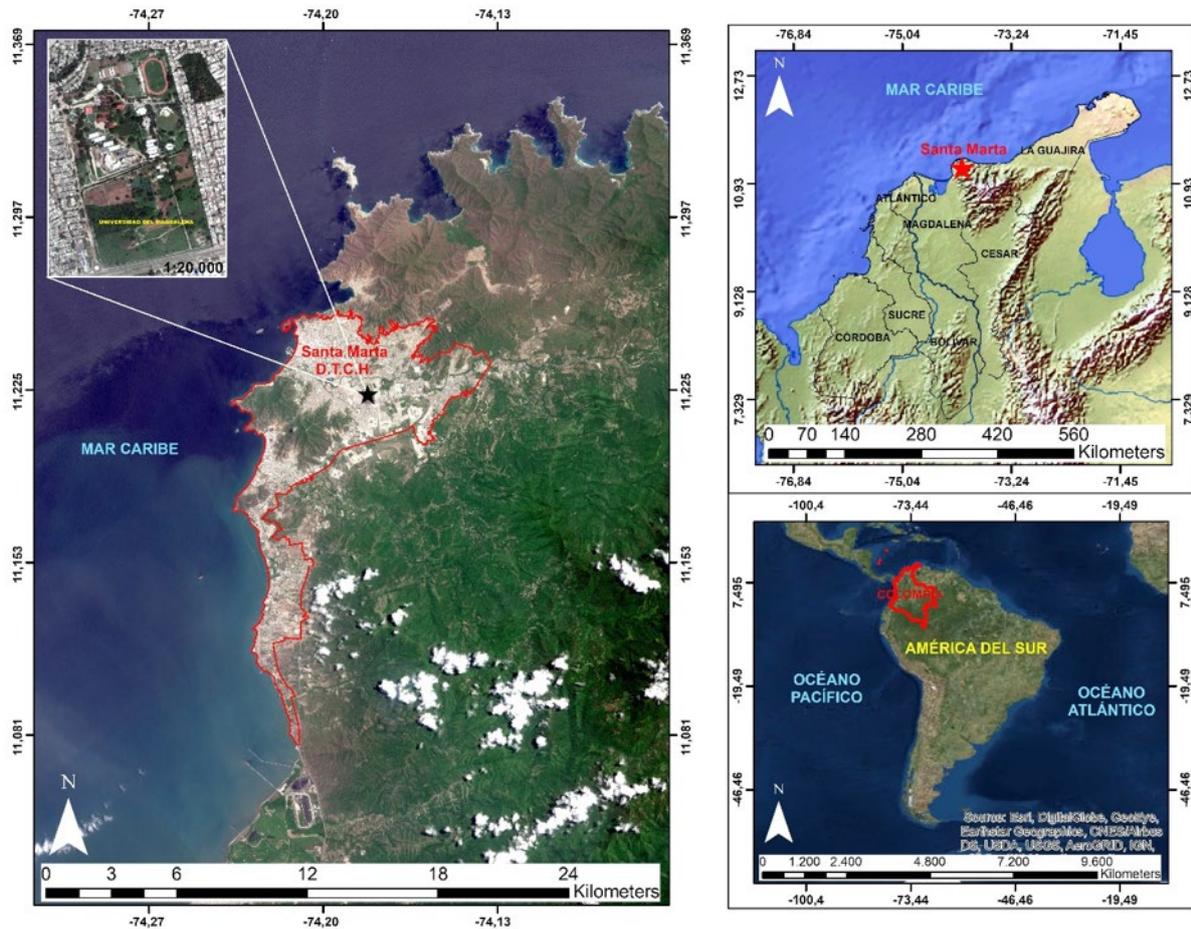


Figure 1. Map showing the location of the Universidad del Magdalena, Santa Marta - Department of Magdalena, Colombia, where the carbon capture rates of a *Typic Ustipsamment* planted with green manures were determined.

Sierra Nevada de Santa Marta - SNSM, forming small fans and fluvial terraces and showing a pH (determined in a 1:1 soil and distilled de-ionized water mixture) of 8.06, bulk density (ρ_b) of 1.35 g cm^{-3} , organic carbon (OC) of 1.17% (15.8 Mg ha^{-1}), and electric conductivity ($EC_{1:1}$ -laboratory measured electrical conductivity of a 1:1 soil to water extract) of 0.80 dS m^{-1} at $25 \text{ }^\circ\text{C}$. Seeds of maize (*Zea mays*), sorghum (*Andropogon sorghum* subsp. *sudanensis*) and crotalaria (*Crotalaria longirostrata*) were sown as green manure in $5 \times 5 \text{ m}$ plots in addition to a control plot in which weeds grew freely. The experimental design was a randomized complete block with twelve treatments and three replications (Table 1), totaling 36 experimental units distributed across 900 m^2 .

Fertilizer rates were calculated according to the species' nutrient requirements; fertilizer applications consisted of 0.5 kg of 17-6-18-2 (N-P-K-Mg) fertilizer and 5 kg plot^{-1} of biosolids (4.3% N, 1.2% P, 1.5% K, 1.7% Ca, and 1.2% Mg, with 23.4% ash and a pH of 6.8) from the palm agro-industry in T6, T7, T8, T9, T10, and T12. SC fractions were determined during two harvesting cycles. Treatments were randomly distributed, and plants were cut and laid out on the ground after they reached 75% flowering. Four soil samples were collected from a 0-10 cm depth in three stages: before planting, 45 days after planting, and 30 days after cutting or being laid out for organic material on the ground, for a total of 24 samples per plot. Fifty grams of each undisturbed soil sample was taken for bulk density (ρ_b) measurement and stored carbon

Table 1. Treatment descriptions and crop density during two cycles of green manures

Treatments		Crop Density (kg of seeds ha ⁻¹)	Fertilizer (N-P-K-Mg)
T1	Maize	30	17-6-18-2
T2	Sorghum	25	17-6-18-2
T3	Crotalaria	15	17-6-18-2
T4	Maize + Crotalaria	21-4.5	17-6-18-2
T5	Sorghum + Crotalaria	17.5- 4.5	17-6-18-2
T6	Maize + Biosolids	30- 2	17-6-18-2+biosolids
T7	Sorghum + Biosolids	25-2	17-6-18-2+biosolids
T8	Crotalaria + Biosolids	15-2	17-6-18-2+biosolids
T9	Maize + Crotalaria + Biosolids	21- 4.5- 2	17-6-18-2+biosolids
T10	Sorghum + Crotalaria + Biosolids	17.5- 4.5-2	17-6-18-2+biosolids
*T11	Control plot	Fallow	Without
*T12	Control plot + Biosolids	Fallow	Biosolids

*The control plots were established by the spontaneous vegetation (fallow) of natural weed species.

content (Mg ha⁻¹) estimation. Fresh and dry plant weights were calculated from an area of 0.25 m² from each treatment and replication.

2.2. Biomass and dry mass production by green fertilizers

Plant samples were taken from each plot and replicated when the plants showed 75% flowering after cutting all the plants at their maximum flowering stage (75 days after planting). Random samples using an iron square of 0.25 m² were taken, with three replications per plot. All plants present in the area were cut at the root's neck and weighed for biomass determination. Then, 500 g of plant material was dried at 65 °C for 72 hours and weighed to determine the dry matter.

2.3. Determination of SC fractions

Total SC (TSC) and SC fractions of different labilities were determined based on the methodology developed by Macías et al. (2004)

at the Soil Laboratories of the University of Magdalena and the University of Santiago de Compostela, Spain. The soil samples from the three sampling stages were mixed to create a composite sample before SC fraction analysis. A brief description of each method is provided in **Table 2**.

SOM was estimated from the SOC multiplied by empirical factors such as van Benmelen's (Pribyl 2010), with a value of 1.724 in surface horizons.

SOC differs from labile carbon (LC) or available carbon as an energy source in that it maintains the chemical characteristics of the source material (carbohydrates, lignin, proteins, tannins, and fatty acids) and a stable humic fraction, constituted by fulvic acids, humic acids and humins (Martínez et al. 2008). Removable carbon with pyrophosphate (C_p) is related to the humic fractions of OM (Islas et al. 2014) and represents the "humified C" or "active C," which forms different C compounds bound to metallic elements and even to soil mineral components. Additionally, oxidizable carbon with dichromate

(C_{od}), but not C_p , refers to the fractions that escaped biological activity and oxidative processes (hot oxidation with dichromate in sulfuric medium) (Macías et al. 2005). Likewise, oxidizable carbon (C_{ox}), resulting from the difference between C_{od} and C_p , is the readily

available carbon. Finally, the residue between TSC and C_{ox} represents nonoxidizable carbon (C_{nox}), which is recalcitrant C and is not oxidized under extreme or forced conditions (Macías et al. 2005, quoted by Islas et al. 2014).

Table 2. Methods used in the determination of carbon soil fractions

Carbon fraction	Principles	Reference
Total Soil Carbon (TSC)	High-temperature combustion of the soil sample with an elemental analyzer (Leco Truspec cn.)	Macías et al. 2005
Labile Soil Carbon (LC)	TSC* 0.02	Macías et al. 2005
Stored Carbon	TSC x MCA MCA = Soil volume*pa	Guo and Gifford 2002
Soil Organic Carbon (SOC)	Oxidation of organic matter by dichromate in sulfuric medium	Macías et al. 2004
Oxidizable Carbon in Dichromate (C_{od})	Oxidizable organic carbon with potassium dichromate in acid medium, cold and hot	Walkley and Black 1934, modified by Macías et al. 2004
Removable Carbon (C_p)	Removable carbon with sodium pyrophosphate C. Humified – Active	Bascomb 1968
Oxidizable Soil Carbon (C_{ox})	$C_{ox} = (C_{od} - C_p)$	Macías et al. 2005 in Islas et al. 2014
Nonoxidizable Carbon (C_{nox})	TSC - C_{ox} Fractions that have escaped biological activity and even oxidative processes; among them is removable C	Macías et al. 2004
Bulk Density	Measured by the core method	Blake and Hartge 1986

2.4. Data analysis

The data were subjected to ANOVA ($P < 0.05$) and Tukey's test ($P < 0.01$) for means comparison. Subsequently, the degree of association of the variables was verified by Pearson's correlation test to establish the correlation between the different forms of carbon. Statistical analyses were performed using R software v. 3.02 (R Development Core Team 2015, available at www.r-project.org).

3. Results and Discussion

Once the green manures were degraded, low average values of $EC_{1:1}$ (0.73 dS m^{-1} at 25°C) and pH (7.8) were observed in the soil, probably due to the production of organic acids resulting from the OM cycling. SOC concentration decreases with depth and is linked to organic residues (carbohydrates, lignins, proteins, and humus), promoting the aggregation and distribution of the porous space and the chemical characteristics of soil. Under natural conditions, SOC results from the balance between the incorporation of fresh organic material and the C output as CO_2 into the atmosphere (Duval et al. 2014).

Vegetative development depends in large part on the morphology of the species, but climate limits the capacity for CO₂ fixation by the plant (Azcón-Bieto et al. 2008). In the present study (Table 3), T2, T3, and T4 showed significant differences in the accumulation of dry weight (DW) when compared to the mixed treatments (green manure + biosolids). However, sorghum was more efficient than corn and crotalaria in

the environmental conditions of the studied area when comparing with the controls treatments (T11 and T12).

All the isolated green manure cultures, as well as combined treatments (T4, T5 and T6), showed significantly ($P < 0.05$) higher fresh biomass production compared to that of the control plots (T11 and T12) (Table 3).

Table 3. Means of plant biomass, fresh and dry weights in each treatment. Means calculated from three replicates per treatment

TREATMENT		FW Mg ha ⁻¹	SD	DW Mg ha ⁻¹	SD	FW/DW (%)
T1	Maize	55.09 ^{AB}	± 14.44	11.02 ^{AB}	± 4.99	20
T2	Sorghum	67.29 ^A	± 4.40	13.46 ^A	± 6.10	20
T3	Crotalaria	51.90 ^{AB}	± 20.26	10.38 ^{AB}	± 4.70	20
T4	Maize + Crotalaria	51.56 ^{AB}	± 21,28	10.31 ^{AB}	± 4.67	20
T5	Sorghum + Crotalaria	42.85 ^B	± 17.49	8.57 ^B	± 3.88	20
T6	Maize + Biosolids	41.12 ^B	± 14.82	8.23 ^C	± 3.73	20
T7	Sorghum + Biosolids	33.91 ^{BC}	± 10.95	6.78 ^D	± 3.07	20
T8	Crotalaria + Biosolids	33.75 ^{BC}	± 10.32	6.75 ^D	± 3.06	20
T9	Maize + Crotalaria + Biosolids	32.43 ^{BC}	± 12.25	6.49 ^D	± 2.94	20
T10	Sorghum + Crotalaria + Biosolids	31.65 ^{BC}	± 10.29	6.33 ^D	± 2.87	20
T11	Control plot (fallow)	23.49 ^C	± 6.51	9.96 ^B	± 4.51	42.4
T12	Control plot + Biosolids	20.49 ^C	± 11.85	9.58 ^B	± 4.34	46.76

FW: Fresh weight. DW: Dry weight. Means in the columns followed by the same letter were not significantly different ($P > 0.01$) according to Tukey's test. SD: Standard deviation.

The treatment T2 (sorghum) exhibited the highest TSC content, with 30.036 Mg ha⁻¹ (Table 4), followed by T12 (fallow + biosolids) with 29.876 Mg ha⁻¹. In contrast, T7 (sorghum + biosolids) showed the lowest values of TSC, at 22.571 Mg ha⁻¹. No significant differences were found ($P > 0.05$) in the carbon content between cycles and sampling periods.

These results agree with those reported by Prager et al. (2012), who evaluated *Sorghum bicolor*, *Crotalaria juncea* and *Canavalia ensiformis* as green manure in the tropics and found that the soils treated with *Sorghum bicolor* associated with mycorrhizae showed the

highest TSC content after being degraded in the soil, with a value of 5.94 Mg ha⁻¹. However, these values were lower than those found in the present study.

Salazar et al. (2004) evaluated the effect of cut and distribution of *Zea mays*, *S. bicolor*, *Phaseolus vulgaris* and *Panicum miliaceum* species on the TSC content of an *inceptisol* during a growing season and reported that sorghum provided 19.78 Mg ha⁻¹, surpassing the others, supporting the findings of the present research, where T2 (sorghum) surpassed the other treatments.

Table 4. Carbon content fractions (Mg ha⁻¹) in *Typic Ustipsamments* cultivated with green manures

TREATMENT		TSC	LC	C _{od}	C _p	C _{ox}	C _{nox}	SOC
T1	Maize	24.76 ^{AB}	0.49 ^A	4.69 ^A	2.33 ^A	2.35 ^A	22.40 ^A	22.90 ^B
T2	Sorghum	30.04 ^A	0.60 ^A	4.64 ^A	2.95 ^A	1.69 ^A	28.34 ^A	28.94 ^A
T3	Crotalaria	25.95 ^{AB}	0.52 ^A	5.32 ^A	2.31 ^A	3.01 ^A	22.94 ^A	23.46 ^B
T4	Maize + Crotalaria	23.21 ^{AB}	0.46 ^A	4.63 ^A	2.18 ^A	2.45 ^A	20.76 ^A	21.22 ^B
T5	Sorghum + Crotalaria	24.29 ^{AB}	0.48 ^A	4.33 ^A	2.41 ^A	1.92 ^A	22.37 ^A	22.86 ^B
T6	Maize + Biosolids	27.37 ^{AB}	0.55 ^A	6.15 ^A	2.00 ^A	4.15 ^A	23.22 ^A	23.77 ^B
T7	Sorghum + Biosolids	22.57 ^B	0.45 ^A	4.15 ^A	2.44 ^A	1.71 ^A	20.86 ^A	21.31 ^B
T8	Crotalaria + Biosolids	25.11 ^{AB}	0.50 ^A	5.74 ^A	2.64 ^A	3.10 ^A	22.01 ^A	22.51 ^B
T9	Maize + Crotalaria + Biosolids	24.55 ^{AB}	0.49 ^A	5.94 ^A	2.60 ^A	3.34 ^A	21.21 ^A	21.70 ^B
T10	Sorghum + Crotalaria + Biosolids	26.04 ^{AB}	0.520 ^A	5.04 ^A	1.97 ^A	3.06 ^A	22.97 ^A	23.49 ^B
T11	Control plot (fallow)	24.43 ^{AB}	0.48 ^A	4.48 ^A	1.81 ^A	2.66 ^A	21.77 ^A	22.26 ^B
T12	Control plot + Biosolids	29.88 ^A	0.597 ^A	6.180 ^A	3.19 ^A	2.97 ^A	26.90 ^A	27.50 ^A

Means in the columns followed by the same letter were not significantly different ($P > 0.05$) according to Tukey's test. TSC: Total Soil Carbon; LC: Labile Soil Carbon; C_{od}: Oxidizable Carbon in Dichromate; C_p: Removable Carbon; C_{ox}: Oxidizable Soil Carbon; C_{nox}: Nonoxidizable Carbon; SOC: Soil Organic Carbon.

The FAO (2002) studied grasslands, savannas and fallow fields with spontaneous vegetation and showed that these species had a high capacity for CO₂ storage. Likewise, González et al. (2014) proposed improved grasslands, fallow covers, and resting areas as zones with high potential for SC fixation. This hypothesis agreed with the results obtained here, which showed that T12 (fallow + biosolids) exhibited a high TSC fixation capacity.

Porlles (2011) argued the importance of C fixation in arid lands for contributing to the global C balance and reducing the rate of desertification with native species in each zone. According to the FAO (2002), a great proportion of arid lands are in the tropics, which represent 37.2% of the terrestrial surface (4900 million hectares) and could, through appropriate management, provide benefits of carbon sequestration in addition to their contribution to ecosystem restoration. T12, a fallow field composed of spontaneous vegetation of *Lolium perenne*, *Hordeum jubatum* L, *Cynodon dactylon*, *Panicum maximum*, *Cucumis melo*, *Boerhavia erecta*, *Amaranthus retroflexus*, *A.*

spinus and *Momordica balsamina*, showed acceptable biomass production and ability to fix TSC, probably due to the adaptation and aggressiveness of the species in the area.

In **Table 4**, the SOC content is reported in its C_{nox} and LC fractions. T2 and T12 were the treatments that fixed the greatest amounts of stable carbon, which is an important trait in the selection of species (*Sorghum*) for TSC sequestration in dry tropics. Ghimire et al. (2017) evaluated the amount and quality of cover crop biomass on carbon mineralization in semiarid soils, suggesting that large pools of canola and pea biomass can stimulate turnover rates. Likewise, the aggressiveness and adaptation of spontaneous species (T12) are remarkable for the revegetation of the area, suggesting the potential value of protecting fallow land in the area.

C_{nox} is the fraction of C that has already escaped biological activity and oxidative processes and represents a dynamic balance between the absorption of dead plant material and loss by decomposition (Macías et al. 2004). Treatment

T2 showed the highest C_{nox} content, followed by T12 and T6, with possible stable forms characteristic of SC stabilization mechanisms (Vásquez et al. 2011); however, no differences at the statistical significance level ($P > 0.05$) applied were observed. It is possible that soil C_{nox} pool was affected by previous crop managements in the studied area. The added organic matter may not be completely stabilized in the soil due to the short-time experiment and long-term studies would be needed for a proper evaluation.

Under aerobic soil conditions, microorganisms readily attack C. According to García (2013), only a small fraction enters and accumulates in the stable humic fraction; however, under semi-arid conditions, lower respiration rates result in less OM oxidation favoring the humification process and OM stabilization in the form of complex compounds (Sierra et al. 2016). The ability of microorganisms to use C_{nox} as a substrate and as a source of carbon assimilation in their metabolic processes is related to the amount of carbon flux, as CO_2 can disperse into the atmosphere. In this respect, soils treated with Poaceae, Fabaceae and herbaceous species (T11 and T12) increase the stable forms of SC. This condition coincides with Phillips et al. (2011), who state that rest systems (fallow fields) store large amounts of atmospheric carbon in the soil, possibly because of the ecological dynamics of the system and the higher diversity of species.

Analyses showed that C_{ox} contents did not differ among treatments ($P < 0.05$). The highest contents were reported in T6, followed by T9, coinciding with Robledo et al. (2011), who indicated that maize plant residues contain cellulose (45%), hemicellulose (35%), and lignin (15%), which are broken down by microorganisms at a low or medium rate of decomposition. The results are consistent with findings on the combination of maize-biosolids and maize-crotalaria-biosolids, which showed the highest content for the oxidized form. Redin et al. (2014) have shown that the contribution of roots to soil organic C is 2.4 to 13 times higher than the contribution of shoots. On the other hand, the roots of the Fabaceae (legumes) are characterized by their higher cellulose and lignin fractions compared to those of Poaceae roots (Redin et al. 2014). Conversely, the proportion

of root hemicellulose of the Poaceae family is higher than that of Fabaceae species, which are characterized by higher total N than that of Poaceae species. This may explain the behavior of Poaceae in terms of higher stable C than that of the Fabaceae or mixture treatments; thus, the decomposition is slower, and there is greater probability of humification.

Macías et al. (2005) claim that the OM derived from cellulose is more labile or has a lower cycle of resilience than the existing lignified OM present in many agroforestry systems. However, C appears in soil in recalcitrant fractions (C_{nox}), with possible stable forms inherent to the stabilization mechanisms of soil C (Vásquez et al. 2011). Those C portions are considered highly stable fractions that do not participate in the biotic processes of the soil, and for this reason, they can maintain stability over long periods of time, representing values that were observed in the field.

For removable carbon (C_p ; humified or active carbon, which results in the most recalcitrant forms of carbon present in the soil), there were no differences among treatments; however, the treatments with the best performance were T12, followed by T2, T8 and T9. These results suggest that the presence of Poaceae enhanced the humification of the material.

Plant cover enhances SC sequestration, which is one way to reduce the GHG effect (GEI) in the atmosphere. In this research, green manures were deposited on the soil, allowing the biological incorporation of the organic material, and the biomass produced by the root system was not quantified. According to Carrera et al. (2008), roots typically contain more lignified cells than do aerial plant parts and, in this form, may contribute differently to soil C inputs.

SOC showed significant differences, and the highest SOC was in T2, followed by T12, showing the potential for Poaceae to contribute to TSC. As shown in **Table 4**, approximately 90% of TSC corresponds to organic fraction forms with different degrees of oxidization.

The FAO (2002) argues that rangelands and rest areas, through extension and diversity, have a significant impact on carbon sequestration,

and fallow areas can be an economic tool to be included in agricultural practices with the purpose of making production more sustainable and mitigating soil degradation. In this work, soil treated with fallow + biosolids (T12) reported high SOC and TSC contents, contributing to the formation of biomass (from weeds) and thus the accumulation of carbon in the soil.

Jiménez et al. (2012) concluded that the carbon content of a soil under pasture and fallow land is higher than that in conventional production systems; this conclusion agrees with the results obtained by Bayer et al. (2006), who found that plowed and cultivated soils present a 36% reduction in carbon fraction contents. According to the FAO (2002), the values for different reservoirs of organic carbon fluctuate from 8-10 Mg ha⁻¹ in cultivated lands, 20 Mg ha⁻¹ in fallow lands and vineyards, 50 Mg ha⁻¹ in pastures and 60 Mg ha⁻¹ in forests without intervention. These values greatly exceed those of green manures incorporated into the production system and thus provide an easy and economical way to increase the SOC.

Diekow et al. (2005) showed that Fabaceae species with high biomass production, such as *Canavalia*, *Mucuna* and *Crotalaria*, provide an easy way to increase carbon and nitrogen reserves in the soil due to the high contribution of residues and to the biological nitrogen-fixing capacity of these species. In the present study, treatments T3, T4, T5, T9, and T10 in which *Crotalaria* was included showed high SOC, with additions higher than 20 Mg ha⁻¹ (Table 4). Increasing OC in terrestrial ecosystems is a means of removing considerable amounts of CO₂ from the atmosphere and decreasing the effects of global warming (Jiménez et al. 2012), and the increase in SOC depends on the quantity and quality of the residuals as well as on the climatic conditions.

In tropical regions, the rate of carbon mineralization is higher than that in temperate regions; therefore, the conservation of carbon must be more efficient. According to Méndez (2016), soils with the highest humified carbon content are associated with high total carbon content. This relationship is confirmed by the fact that in the present study, treatment T2 provided the highest total carbon content (TSC = 30.04 Mg ha⁻¹)

and also had the highest stabilized carbon content (C_{nox} = 28.3 Mg ha⁻¹). The same author reports that one-quarter of the total carbon that is found in the surface horizons exhibits recalcitrance due to the processes of OM humification from the necromass contributed by vegetative residues.

The main characteristic of arid lands is the scarcity of water, which, together with high pH, severely limits the productivity of plants and, therefore, the accumulation of carbon in soils. However, certain aspects of dryland soils favor carbon sequestration because they are less likely to lose carbon than are wet soils. Robert (2002) argued that the lack of water limits the mineralization of the soil; therefore, the flow of carbon into the atmosphere is lower, which promotes carbon fixation in these environments.

The SOC associated with soil colloids (OM and clay) increases the cation exchange capacity and has a direct effect on the physical properties. Over a long time period, the SOC could modify the structure and distribution of the porous space, which is directly related to the water flow and the water storage capacity.

From an environmental point of view, SOC is related to system sustainability and is linked to the availability of soil nutrients by providing nutrients, such as N, which is normally deficient in arid ecosystems; thus, SOC regulates the dynamics of plant biomass production and biodiversity. Inadequate management practices in vulnerable ecosystems, including the Colombian Caribbean coast, could lead to SOC degradation and increase the CO₂ content in the atmosphere. Therefore, the results obtained here should be considered for sustainable environmental policies in the area and to improve agricultural processes.

The SOM contents in arid and semiarid zones are very low, the biomass in these zones is limited, and the N by mineralization processes is transformed into inorganic compounds. The nitrogenase enzyme used by the bacteria to fix N decreases its activity according to the ecosystem temperature and humidity (Celaya-Michel and Castellanos-Villegas 2011; Moreno et al. 2014). In the present research, we found a low association ($r \leq 0.5$) between the

accumulation of TSC and biomass and dry mass yield, a situation that may be related to the fact that the fraction represented by the plant root system was not measured, which should be the object of a future study.

Due to the climate zone, the mineralization of SOC is intense, and the C fixation in stable forms is reduced. If combined with inadequate edaphic management of the system, this situation could cause rapid degradation and desertification. Therefore, we recommend prioritizing plant cover with the species that showed better results, a simple and rapid technique that promotes an increase in TSC and mitigates the effects of climate change.

4. Conclusions

The results of this study lead to the following conclusions regarding the use of green manures as an alternative to SC sequestration under semiarid conditions: 1) Under semiarid conditions, green manures allow carbon sequestration in soils, which can help to mitigate climate change effects. 2) With the methodology used, the carbon capture ability of sorghum (*Andropogon sorghum sudanensis*) was verified. 3) Fallow with weeds showed a high capacity for SC storage. Therefore, proper management is important to mitigate climate change effects. 4) The results presented here were obtained over a short time, and suggest that probably the previous management might have had some effect on the more recalcitrant carbon fraction contents. Despite that, differences during the experimentation year were observed on SOC. Further studies are necessary to investigate the long-time treatments' effects. 5) The results of this study demonstrate the importance of maintaining plant cover and implementing green manures in the Colombian Caribbean region.

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