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Soil Organic Carbon Dynamics in Two Rice Cultivation Systems Compared to an Agroforestry Cultivation System

Ibonne Geaneth Valenzuela-Balcázar ^{1,2,*} , Efraín Francisco Visconti-Moreno ¹ , Ángel Faz ² and José A. Acosta ²

¹ Faculty of Agricultural and Environmental Sciences, Universidad Francisco de Paula Santander, Av. Gran Colombia No. 12E-96 Barrio Colsag, 540001 San Jose de Cucuta, Colombia; efrainfranciscovm@ufps.edu.co

² Sustainable Use, Management and Reclamation of Soil and Water Research Group, Universidad Politécnica de Cartagena, Paseo Alfonso XIII 48, 30203 Cartagena, Spain; angel.fazcano@upct.es (Á.F.); ja.acosta@upct.es (J.A.A.)

* Correspondence: ibonnegeanethvb@ufps.edu.co

Abstract: After changes in tillage on croplands, it is necessary to assess the effects on soil organic carbon (SOC) dynamics in order to identify if soil is a sink or emitter of carbon to the atmosphere. This study was conducted in two plots of rice cultivation, where tillage and water management changes occurred. A third plot of native forest with Cacao trees was used as reference soil (agroforestry). For SOC balance estimation, measurement of organic carbon (OC) inputs was determined from necromass, roots, microbial biomass, and urea applications. CO₂ and CH₄ emissions were also measured. Results showed that the change in the use of irrigation and tillage in rice cultivation did not cause significant differences in OC inputs to soil or in outputs due to carbon emissions. Further-more, it was found that both irrigation and tillage management systems in rice cultivation compared with agroforestry were management systems with a negative difference between OC inputs and outputs due to CO₂ emissions associated with intense stimulation of crop root respiration and microbial activity. The comparison of SOC dynamics between the agroforestry system and rice cultivation systems showed that an agroforestry system is a carbon sink with a positive OC dynamic.

Keywords: carbon sequestration; greenhouse gas emissions; soil degradation; sustainable agriculture



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1. Introduction

Soil constituents such as clay, humus, and microorganisms are the most important components for terrestrial ecosystems due to its multiple ecosystem services. The ability of soil to fulfill its functions depends on its physical, chemical, and biological properties [1,2]. Intensive agricultural use of soils threatens productivity and ecosystem functionality mainly due to a decrease in soil organic carbon (SOC) content [3,4] caused by a decrease in the contributions of organic residues and an increase in gas emissions [5–10]. According to Smith and collaborators in 2018, agricultural soils changes in SOC are determined by the cumulative contributions of organic carbon (OC) from the crop, and when there are high returns driven by nitrogenous fertilizers and the fallow frequency is low, it can favor an increase in SOC [11]. Nevertheless, this is a complex and dynamic process. In 2013, Saljnikov and collaborators pointed out that 55 to 70% of the carbon in organic residues reaching the soil is lost due to gaseous emissions into the atmosphere, and 5 to 15% is incorporated to the microbial biomass of the soil [12]. The balance between inputs and outputs of organic carbon in the soil constitutes an assessment methodology to identify its functioning as a sink or as a carbon emitter in the ecosystem, allowing the evaluation and comparison of the dynamics of organic carbon in soils under different use and management systems [12,13].

In 2010, Lal has pointed that in intensive cultivation, cropland soils contain 25 to 75% less SOC than their counterparts in undisturbed or natural ecosystems [14]. However, soils with long term rice cropping can significantly increase SOC stock [15]; this accumulation

of SOC in paddy soils of rice cropping systems may occur due to their high crop biomass production and lower decomposition rates because of long-time submergence, [16,17]. Despite high SOC storage capacity, it has been reported that rice cropping in paddy soils can produce high greenhouse gasses (GHG) emissions [18], because crop intensification with tillage, fertilizer application, irrigation, and improved cultivars can increase GHG emission [19].

Recently agroforestry has emerged as a cropping system that enhances SOC storage, since increases in C stocks on the surface are associated with a larger volume of organic residues from vegetation that returned to the soil [20]. The litter produced by agroforestry systems is the first of all factors that promotes the renewal of C stocks in the soil. It keeps the soil covered and protected from the direct impacts of rain and sun, thus maintaining a better moisture level in the soil, and soil biota in turn provides C and nutrients released by decomposition and contributes to the formation of new SOMs that are the other main factors that enhances SOC [21].

On the other hand, the role of microorganisms in SOC dynamics has evolved from a pool concept to emerging theories of microbial production of SOM, resulting in the consideration of microbial biomass as a SOC source, a situation significantly evident when increased plant residue inputs also provide more substrate for soil microorganisms, resulting in a more active and more abundant microbial community [22–24].

In Colombia, rice (*Oryza sativa*) is the third agricultural product in extension after coffee (*Coffea arabica*) and corn (*Zea mays*), representing 13% of the country's harvested area. The Norte de Santander department groups a production area of 40,000 hectares, where the Zulia river irrigation district concentrates approximately 38,000 ha [25].

The soils of the Zulia river irrigation district are agricultural soils with a history of rice production with more than 40 years, time through which cultivation practices have been dominated by the intensive use of agricultural machinery in the mode of tillage in flooded soil (muddy), the intensive use of fertilizers and agrochemicals, as well as flood irrigation. In 2015 Valenzuela and collaborators concluded that soil degradation at the Zulia river irrigation district, due to deterioration of its physical properties, generates a loss of productivity that reduced yields from 7 t ha⁻¹ to approximately 5.5 t ha⁻¹ [26]. Since the last five years, in order to counteract the problems of soil degradation, a new system of rice cultivation has been introduced consisting of tillage in partially dry soil with no flood irrigation for a rainfed-like system. However, the effect on soil properties and constituents after its implementation is unknown.

In the search for sustainable agricultural systems, it is important to evaluate the behavior of organic carbon in soil. Most sustainability evaluations assume that organic matter is necessary to achieve soil productivity, and that increasing organic matter inputs favors organic carbon storage in soils [19]. Therefore, a recommended methodology to evaluate the impact of a management practice is to monitor the change in SOC compared to the change when that practice is not implemented [2,27,28]. Therefore, this study evaluates the changes in SOC dynamics caused in rice cultivation after modifying tillage and irrigation.

2. Materials and Methods

2.1. Description of the Study Site

The study area was located in the Zulia River Irrigation District at a village named Las Vacas of Cucuta municipality, Norte de Santander department, Colombia, with geographic reference coordinates of 08°12'33" North and 72°31'13" West, and an altitude of 70 m.a.s.l. The annual mean temperature is 29 °C, the average annual precipitation is 1900 mm, and according to Holdridge the biome is classified as Tropical Dry Forest [29]. Records from the local meteorological station registered that accumulated precipitation during the first growing cycle was 776.2 mm, and during the second growing cycle it was 417 mm.

The study was carried out in three contiguous plots of a soil classified as *Typic Udi-fluvents* (USDA Soil Taxonomy, 2010). Two plots correspond to rice cultivation, with an

approximate area of 2 hectares each, and the third is a 3 hectares plot of native forest with Cocoa (Cacao trees), all have more than 40 years under their respective crop (Figure 1). In one of the rice cultivations, plot changes in the tillage and irrigation management were carried out one year ago.



Figure 1. Satellite image of the study site taken on January 2016 from Sentinel.

The plot using forest with cocoa was used as reference soil and consists of tropical trees with a predominance of tall native species such as the following: Ceiba (*Ceiba petandra*), Jobo (*Spondias mombin*), Roble (*Tabebuia rosea*), and Higuieron (*Ficus luschnathiana*); all of them serve as shade for Cacao trees (*Theobroma cacao*). The management of the agroforestry system consists of reduced intervention, with cocoa tree maintenance pruning once a year and harvesting of fruits twice a year. No fertilizer applications were performed; there is no use of herbicides, insecticides, or fungicides.

Rice cultivation systems were studied during two consecutive crop cycles and in two plots to compare different tillage systems and irrigation water management. The traditional rice cultivation system, which has more than 40 years in use, was identified as irrigated rice and consisted of intensive mechanized tillage in flooded soil (called muddy shake) and flood irrigation with periodic replacement of water. The modified rice cultivation system, which has only one year in use, was identified as rainfed rice and consisted of mechanized tillage in partially dry soil without flood irrigation. Other agronomic practices were common in the two rice cultivation systems, characterized by a broadcast manual sowing with pre-germinated seed of the Fedearroz 2000 variety. Fertilizer application was also manual and based on urea, potassium chloride, and formulas 24-0-17 and 12-25-16 to contribute 150 kg ha^{-1} of N, 80 kg ha^{-1} of P, and 120 kg ha^{-1} of K, as recommended by Fedearroz (Rice farmers federation of Colombia). Applications of selective pre-emerging and post-emerging herbicides and chemical pest and diseases controls were manual with back spraying machines. Grain harvest was mechanized and packed in sacks of 60 kg, which were transported out of plots by tractor with a cart. After the mechanized harvest operation, the crop residues (chaff) were burned.

2.2. Sampling Design and Analytical Methodologies

The experiment was carried out for ten continuous months from August 2016 to May 2017, where a systematic strategy was performed to sample topsoil (0 to 10 cm depth) in each plot, which consisted of three equidistant points on a diagonal transect. At each sampling point, the intersection and ends of an imaginary cross measuring one meter long on each side served to take five subsamples of disturbed soil to form a composite sample of surface soil. At each point, two undisturbed samples were also taken with metal cylinders

of 5 cm height and 5 cm diameter. Sampling was carried out simultaneously in the three plots every 30 days during two consecutive cycles of rice cultivation, beginning on August 2016 in the rest stage before tillage of the first cycle, the second stage was September 2016 after tillage and sowing, the third stage was October 2016 after tillering, the fourth stage was September 2016 during flowering, and the fifth stage November 2016 was immediately after harvest. Sampling was carried out in the same manner during the second cycle on January, February, March, April, and May 2017.

In the field, surface soil temperature was measured with a mercury thermometer, and volumetric moisture content was measured with a dielectric sensor. The distribution of soil mineral particles was determined by the Bouyoucos method. Bulk density (Bd) and porosity were measured using metallic cylinder Uhland type [30]. The water content at -33 kPa was measured with Richards chambers of Soil Moisture Equipment Corp [31]. Soil microbial biomass (MBOC) was measured indirectly using the method of substrate-induced respiration (glucose) in disturbed soil samples that were kept refrigerated (4 °C) from sampling until their analysis [32], and it was expressed as milligrams of MBOC kg^{-1} of soil. The determination of SOC was performed by a modified method of Walkley and Black [33]. Soil pH and electric conductivity (EC) were measured in a suspension 1:1 of soil and water. For the cation exchange capacity (CEC) of soil, the method of ammonium acetate 1N pH 7 was used [33].

2.3. Measurement of the Organic Carbon of the Necromass

The biomass of vegetation contributes organic carbon of soils through the necromass. In order to measure the necromass on soil, all vegetation residues found aboveground were collected in ten sampling points randomly distributed in each of the studied plots. The necromass collection was performed on the same dates of soil sampling using frames of 0.25 m². On each sampling day, a portable digital scale was used to determine the total fresh weight of necromass collected. The samples were homogeneously mixed and then three subsamples were taken of approximately 300 g, which were oven dried at 72 °C until constant weight to determine the dry weight of the necromass and calculate the percentage of dry matter [34]:

$$\%DM = \frac{\text{weight of dry sample}}{\text{weight of fresh sample}} \times 100 \quad \text{and} \quad BN = \frac{Wm \times DM(\%)}{100}$$

where %DM is the percentage of dry matter in the necromass, BN is the total biomass of the necromass, and Wm is the total fresh weight of necromass of each sample.

In order to estimate organic carbon stored in the biomass of the necromass, the following equation was used based on biomass contains about 50% of organic carbon [35–37].

$$\text{Organic carbon of Necromass} = BN \times 0.5$$

2.4. Measurement of Organic Carbon from Roots

Plant roots represent another important input of organic carbon to the soil. In order to measure the contribution of roots in each plot, in the sampling of the fifth stage and in the same ten necromass sampling locations, surface soil samples were collected to separate roots by water washing and sieving (4.1, 2.36, and 1.18 mm of mesh opening). Then, the collected roots were oven dried at 72 °C until constant weight. The organic carbon of roots was assumed to consist of 50% carbon [35–37].

2.5. Measurement of Organic Carbon Losses from Gas Emissions to the Atmosphere

Soil organic carbon losses were measured by using fluxes of CH₄ and CO₂ between the soil and the atmosphere using modified Static Chamber methodology [13,18,38]. The static chambers designed for this study consisted in containers of cylindrical PVC with dimensions of 25 cm in diameter and 35 cm in height, which were placed simultaneously at the time of taking the air samples on a PVC base of 25 cm in diameter and 5 cm in

height that remained buried in the soil throughout the period of the experiment. The union of both parts was secured by a plastic rubber to avoid gas escape. In order to achieve thermal insulation of the chambers, they were coated with an insulating membrane of 1 cm thick aluminized polyethylene foam. In the upper part of the chamber, a small sampling port was fitted with a plastic septum through which the gaseous samples were extracted. Gas samples were taken during 40 min at intervals of 0, 10, 20, and 40 min after camera installation. Gas sample collection was carried out with a 20 mL plastic syringe equipped by a valve to prevent gas escape. This allowed a 20 mL sample of which only 15 mL was stored in a glass tube (vial) of 20 mL vacuum.

Subsequently, vials properly sealed and packed were sent to the Stables Isotope lab of the International Center for Tropical Agriculture (CIAT) in order to be analyzed on a Shimadzu GC-14° gas chromatograph with flame ionization detector (FID) and electron capture detector (ECD) equipped with a pre-column and a Porapak Q column (80–100 mesh) of 1 m and 2 m length, respectively. For carbon dioxide analysis, an infrared CO₂ analyzer with NaOH and silica gel was used to retain carbon dioxide and moisture from air. The analysis time for each sample was 2 min. The flux for the gases was calculated from the CH₄ and CO₂ concentration data obtained from four measurement intervals using the following equation [13,18]:

$$\text{Flux}_{(\text{Gas})} = \frac{\Delta C_i \text{ concentration}}{\Delta t_i \text{ time}} \cdot V_{\text{chamber}} / A_{\text{area}} = \frac{(C_2 - C_1)}{(t_2 - t_1)} \cdot H_a$$

where Flux (Gas) is the flux of CH₄ or CO₂ in (mg m⁻² h⁻¹); V_{chamber} and A_{area} represent the volume and the cross-sectional area of the chamber in m³ and m², respectively; H_a is the height of the chamber over the air-soil interface in meters; and ΔC_i/Δt_i can be calculated by linear regression as the slope of the concentration vs. time curve in which t_i represents sampling time (in hours) and C_i is the concentration of CH₄ or CO₂ in mg m⁻³, measured in interval “i” with the following equation:

$$C_i \text{ (mg m}^{-3}\text{)} = C_{\text{chromatograph (ppm)}} \cdot \frac{PM \times P}{0.082 \times T_{\text{field}}}$$

where C_{chromatograph} is the concentration in ppm-volume (ml m⁻³) of each gas, reported in the chromatographic analysis. T_{field} is the temperature in the chamber at the time of sampling in K. P is the atmospheric pressure in atm. PM is the molecular weight of each gas in g mol⁻¹.

2.6. Calculation of the Organic Carbon Budget in the Surface Soil

The dynamics of SOC can be estimated from the balance between inputs and outputs in the soil [13,17]. A decrease in total organic carbon in the soil occurs when there is a negative difference. In this study, in order to estimate the SOC budget in a rice cultivation cycle (5 months), the inputs of organic carbon were considered from the application of 200 kg ha⁻¹ of urea, the roots in the surface soil (0 to 10 cm), and the microbial biomass and necromass. Total CO₂ and CH₄ emissions of the five months cycle were expressed in kilograms per hectare and considered as OC outputs or losses, since losses due to erosion or leaching were considered negligible in this study.

This study considers MBOC as an input of SOC budget, since recent evidence points that microbial biomass residues (microbial necromass) can be accounted for such as SOC source [24]. In this sense, Miltner and collaborators in 2012 [23] suggest that 50% of biomass-derived C remains in soil, mainly in the non-living part of SOM (40% of the added biomass C), because cell wall envelopes of bacteria and fungi are stabilized in soil and contribute significantly to small-particulate SOM formation.

For the calculation of SOC budget, inputs and outputs were expressed in kilograms per hectare, which were achieved by estimating the weight of the surface soil from the average bulk density of each plot.

2.7. Analysis of the Data

Data were analyzed with the Stat graphics Centurion 16° statistical software using an analysis of variance (ANOVA), after checking the assumptions of normality with the Anderson–Darling test and the assumption of variance homogeneity using the Levene test. In the case of violation of these assumptions, data were analyzed using the the Kruskal–Wallis non-parametric test. In the comparison of means, the test of least significant difference was applied at a confidence level of 0.05% [4].

3. Results

3.1. Physical and Chemical Properties of the Studied Surface Soil

The soil of this study was classified as a *Typic Udifluvents* (USDA Soil Taxonomy, 2010), and it was a rice cultivation plot of clayey texture due to the predominance of clay, followed by significant proportions of silt. Conversely, the texture of soil used in agroforestry of cocoa was silty clay loam due to the predominance of silt (Table 1).

Table 1. Distribution of mineral particles and soil textural class in the studied plots.

Particle Size Fractions	Irrigated Rice	Rainfed Rice	Agroforestry
Sand (0.05 to 2.0 mm)	17.40	8.70	11.70
Silt (0.002 to 0.05 mm)	33.60	38.50	54.90
Clay (<0.002 mm)	48.98	52.80	33.40
Textural class	Clay	Clay	Silty clay loam

Surface soil (0 to 10 cm) of the studied plots showed important statistical differences in soil moisture at -33 kPa, soil surface temperature, bulk density (Bd), porosity, pH, electrical conductivity (EC), and cation exchange capacity (CEC) (Table 2). The forest with cocoa showed lower values of bulk density, together with higher percentages of total porosity and humidity at field capacity (-33 kPa). On the other hand, the plots destined for rice cultivation showed higher values of Bd, together with lower values of total porosity and humidity at field capacity (-33 kPa). Regarding soil moisture at the time of each sampling, soil of the plot with irrigated rice contained higher humidity, followed by the forest with cocoa with lower soil moisture in rainfed rice. For surface soil temperature, the lowest mean temperature was found in the forest with cocoa and the highest in the soil with rainfed rice.

Table 2. Physical and chemical properties of soil at a depth of 0 to 10 cm in each field.

Soil Properties	Irrigated Rice (<i>n</i> = 30)	Rainfed Rice (<i>n</i> = 30)	Agroforestry (<i>n</i> = 30)
Soil moisture at -33 kPa (%)	31.36 (4.04) a	36.72 (2.36) b	44.98 (3.59) c
* Soil moisture at field (%)	23.36 (9.14) a	18.72 (2.53) a	21.98 (7.69) a
* Soil surface Temperature ($^{\circ}$ C)	27.99 (1.06) b	28.58 (2.49) b	25.08 (1.05) a
Bd (Mg m^{-3})	1.28 (0.10) b	1.32 (0.12) b	1.16 (0.14) a
Porosity (%)	45.88 (5.47) a	47.12 (4.49) b	50.06 (4.22) b
pH (water 1:1)	5.27 (0.37) a	5.23 (0.36) a	5.62 (0.42) b
* EC ($\mu\text{S cm}^{-1}$)	93.79 (30.48) b	78.04 (27.29) a	117.21 (65.02) c
CEC (cmol kg^{-1})	9.95 (3.15) a	11.76 (2.59) b	13.76 (3.02) c

*: Non parametric analysis. (): standard deviation. Different letters represent significant difference of averages. Bulk density (Bd), electrical conductivity (EC), and cation exchange capacity (CEC).

The pH in the forest soil is moderately acidic, but in plots with rice it was strongly acidic. The surface soils of the three plots have low CEC, with the forest with cocoa being the soil with the highest value. In addition, EC in all batches was low.

3.2. Evaluation of Soil Organic Carbon (SOC), Organic Carbon (OC) from Microbial Biomass and Carbon from Necromass

The results of stable soil organic carbon (SOC) for ten continuous months in the three plots studied demonstrated a statistically significant effect for soil use factor, while the factors of crop cycle and sampling stage did not have a significant statistical effect on this soil parameter (Table 3).

Table 3. Soil organic carbon (SOC), organic carbon (OC) of microbial biomass and carbon of necromass with LSD comparisons at 95% confidence intervals.

Source of OC	SOC (%)	OC of Microbial Biomass (mg 100 g ⁻¹)	C of Necromass (g m ⁻²)
Soil Use (n = 30)			
Irrigated rice	2.84 (0.35) a	1.80 (0.62) a	62.64 (151.1)
Rainfed rice	2.89 (0.46) a	1.68 (0.67) a	57.49 (124.7)
Agroforestry	3.22 (0.56) b	1.91 (0.85) a	781.82 (424.7)
Crop Cycle (n = 45)			
Cycle 1	3.01 (0.47) a	1.87 (0.82) a	304.05 (375.9)
Cycle 2	2.96 (0.51) a	1.73 (0.60) a	297.25 (489.5)
Stage (n = 18)			
Stage 1	3.02 (0.47) a	1.60 (0.49) b	491.33 (727)
Stage 2	3.12 (0.32) a	1.21 (0.65) a	346.37 (463)
Stage 3	2.88 (0.55) a	1.53 (0.46) ab	201.87 (287.2)
Stage 4	3.06 (0.72) a	2.36 (0.61) c	168.10 (236.1)
Stage 5	2.83 (0.20) a	2.29 (0.62) c	295.57 (187.3)

(): standard deviation. Different letters represent significant difference of averages.

The interaction of the soil use system with the sampling stage is the only one to show a statistically significant effect on stable SOC (Figure 2). The forest with cocoa showed higher SOC contents than rice plots from stage 2 to stage 5. In the rice plots, a decrease in the SOC content was observed with progress in the stages, while in the forest with cocoa an increase in SOC was observed with the advance of stages.

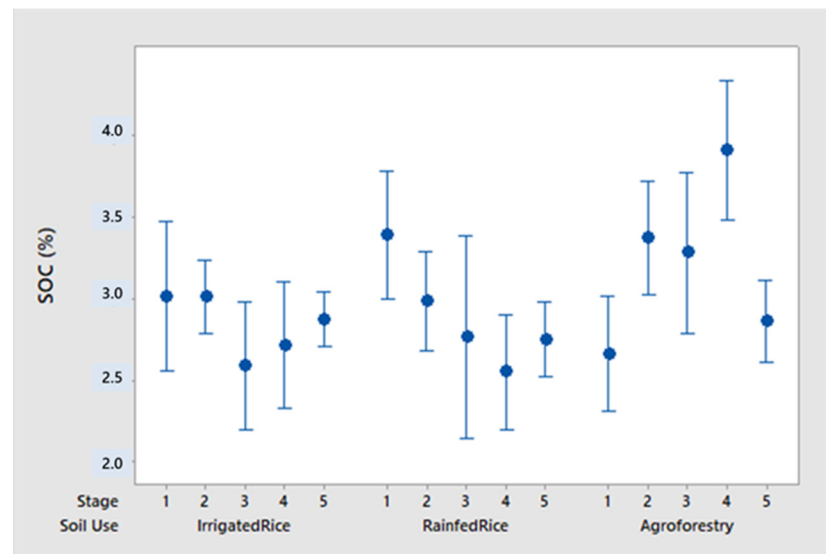


Figure 2. Interaction effect of the soil use and the stage on the soil organic carbon (SOC) ($n = 6$).

The analysis of variance for OC of the microbial biomass (MB) indicated that only the factor stage has a statistically significant effect on this variable. The soil use system and cultivation cycle had a significant interaction with the stage over the MB (Table 3).

Although there is no statistical difference, it was observed that the soil of forest with cocoa had the highest OC in the MB, followed by irrigated rice. The soil of rainfed rice resulted in less OC of MB (Table 3).

Due to the interaction of factors such as soil use and stage (Figure 3), the OC of MB behaves similarly in the uses of forest with cocoa and rice with irrigation, where there is a decrease from stage 1 to stage 2 for later increase, which is observed in the forest with cocoa with higher OC of MB. In the case of rainfed rice, the behavior is different, since there was a decrease from stage 1 to stage 2, while in stages 3 and 4 it increased, and then it decreased in stage 5. This difference in behavior of OC of MB in rainfed rice is related with humidity and soil temperature conditions.

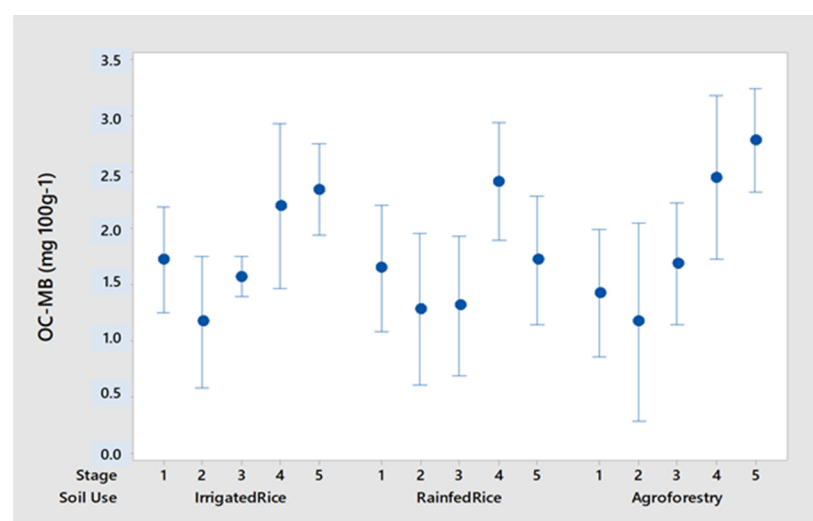


Figure 3. Interaction effect of the soil use and the stage on the organic carbon (OC) of microbial biomass (MB) ($n = 6$).

In the interaction of the factors such as crop cycle and stage of sampling (Figure 4), it was observed that the behavior of the OC of MB is different for each cycle, and the values were higher in the first cycle.

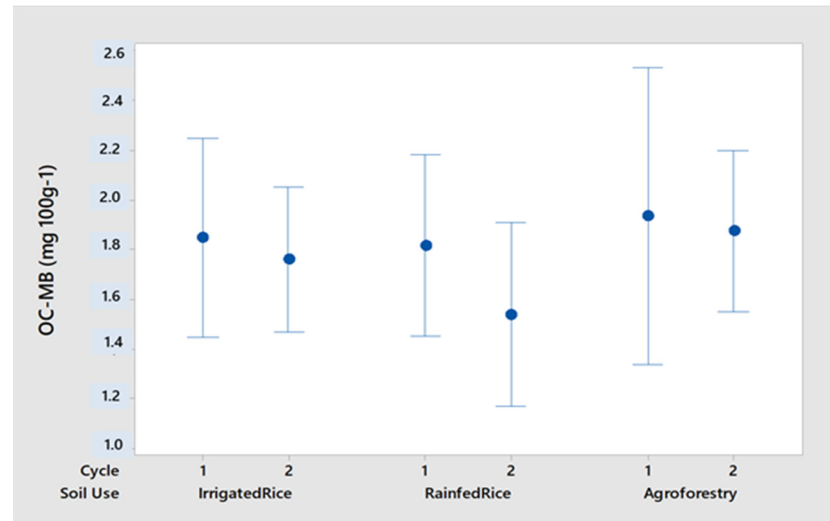


Figure 4. Interaction effect of the cycle and the stage on the organic carbon (OC) of microbial biomass (MB) ($n = 15$).

Concentrations of carbon in necromass above the soil (Table 3) indicated that the land use factor has a statistically significant effect on the carbon of the necromass, with the use of forest with cocoa having the highest carbon of the necromass (Figure 5). In the case of the effect of the sampling stage factor on the carbon of the necromass, non-parametric analysis of the medians revealed that stage 1 is the one with the least carbon in the necromass, and stage 5 is the one with the highest amount of carbon in the necromass (Figure 5).

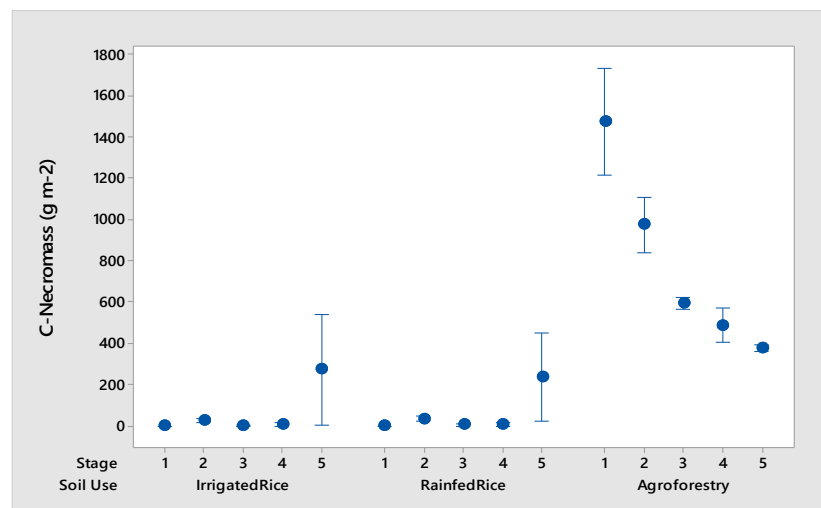


Figure 5. Effect of the soil use and stage on the carbon of the necromass ($n = 6$).

3.3. Assessment of Carbon Emissions into the Atmosphere

Statistical analysis of the collected data showed different behavior between the two gases according to the soil use system. A statistically different behavior was found between the cocoa forest and two rice lots. It was observed that the two rice plots had higher CO₂ and CH₄ emissions than the agroforestry system (Table 4).

Table 4. Non-parametric comparisons of medians (Kruskal–Wallis) for CO₂ and CH₄ emissions by type of soil use.

Soil Use	<i>n</i>	Flux CO ₂ mg m ⁻² h ⁻¹	Flux CH ₄ mg m ⁻² h ⁻¹
Irrigated rice	30	325, 79a	0, 15a
Rainfed rice	30	383, 45a	0, 14a
Agroforestry	30	125, 33b	0, 02b

CO₂ Flux was 61.5% higher in irrigated rice and 67.3% higher in the rainfed rice field compared to CO₂ Flux in the forest with cocoa. Moreover, evidence showed that rainfed rice produces slightly higher emissions than irrigated rice. For CH₄ Flux, we found that the forest with cocoa has significantly lower emissions than the rice lots, and 13.3% and 14.3% of emissions were generated in irrigated rice and rainfed rice, respectively. Moreover, irrigated rice produces slightly higher CH₄ emissions than rainfed rice.

3.4. Balance of Inputs and Outputs of Organic Carbon in the Surface Soil

The carbon budget in surface soil was estimated with the sum of inputs expressed in kilograms per hectare corresponding to the OC of roots, the OC from fertilization of rice with 200 kg ha⁻¹ of Urea, the OC of the microbial biomass, and OC of the necromass. The total outputs or losses were represented by the sum of the CH₄ and CO₂ emissions, and the difference between inputs and outputs is calculated for each studied soil use system (Table 5).

Table 5. Organic carbon (OC) budget of surface soil in the studied soil use systems.

Soil Use	Bulk Density (Bd) Mg m ⁻³	Inputs of OC (kg ha ⁻¹)				Outputs of OC (kg ha ⁻¹)				Difference (kg ha ⁻¹)
		Root-C	Urea-C	Microbe Biomass-C	Necromass-C	Inputs Sum	CH ₄ -C Loss	CO ₂ -C Loss	Outputs Sum	
Irrigated Rice	1.3	1766	40.0	23.1	626	2455	27.7	15,271	15,299	-12,843
Rainfed Rice	1.3	1920	40.0	22.1	574	2556	270.3	15,232	15,502	-12,945
Agro Forestry	1.2	987	0.0	22.1	7818	8827	51.6	8772	8824	3.6

The total contribution of organic carbon reports a different behavior between rice plots and the forest with cocoa, since irrigated rice had 72.2% less inputs and rainfed rice had 71.0% less. This was due to the fact that the OC contributed by the necromass was higher in the forest with cocoa, and it is a scarce contribution in the rice plots, representing 8.0% and 7.4% in irrigated and rainfed rice, respectively. The contribution of OC by roots in the rice fields is higher than the contribution of OC of the necromass, and when comparing between the types of soil used, it was observed that the contribution of the fine roots of the forest in the superficial soil is 44% less than irrigated rice and 48% less than rainfed rice.

Microbial biomass produced similar inputs in the three plots, representing the lowest OC input in the rice plots. With respect to OC emissions, it was found that CO₂ emissions are the most important in the three types of use: it was 99.8% of the total in irrigated rice, 98.3% of the total in rainfed rice, and 99.4% of the total in the forest with cocoa. When comparing CO₂ emissions between the three uses, it was observed that the rice fields have very similar high CO₂ emissions, and the forest has lower emissions, representing 43% of the previous ones. The difference between the inputs and outputs allowed observing that the rice lots have a negative difference, which means that they are soil use systems that emit carbon into the atmosphere mainly in form of CO₂, while the cocoa forest has SOC dynamics with positive difference, representing a sink of organic carbon.

4. Discussion

4.1. Evidence of Physical and Chemical Degradation of Soil

The soil studied is of incipient evolution with alluvial origins from hydromorphic sediments deposited in the flood plain of the lower basin of the Zulia river. In the forest with cocoa, the physical-chemical properties of the soil arise from this pedogenetic process. In the case of plots with rice, a significant negative effect on bulk density and porosity was reported, which showed physical degradation due to soil compaction and an acidification process (Table 2). Degradation has been reported by several authors [26,39], who diagnosed loss of porous space due to compaction by evaluating the physical properties of soils in rice cultivation, resulting in increased bulk density. Therefore, changing the management system of rice with flood irrigation is justified [40,41]. However, results showed that after the first year of changing to rice with tillage in almost dry soil and restriction of flood irrigation, soil properties such as total porosity, bulk density, and pH have not been improved. Thus, further evaluation should be carried out in order to reveal possible changes resulting from changes in soil management. According to Busari and collaborators in 2015, changes in soil tillage system impact soil physical conditions. The rate and quantity of the impact depend on the particular tillage system chosen and the time elapsed [42].

4.2. Evaluation of Stable Organic Carbon in the Soil

Results indicated that rice plots have a significantly lower SOC content compared with the forest with cocoa (Table 3). This is in line with the numerous studies that indicate a decrease in SOC due to monoculture of rice and other crops under intensive agricultural use [17,43]. This remarkable difference is due to both the difference in the amounts of OC that enter the soil due to contributions from necromass, roots, fertilizers, and microbial biomass (Table 5) and the differences in OC losses due to gas emissions [13,27].

When observing the interaction of the factors of soil use and sampling stage on SOC content (Figure 2), it can be observed that the forest with cocoa shows an increase from the initial stage to the final stage; on the contrary, in the two rice plots, the content of SOC is lower in the last stage, which confirms that the two rice cultivation systems are losing SOC throughout the crop cycle, while the cocoa forest gained SOC, indicating that the forest functions as a carbon sink [44,45]. However, in order to find changes in the content of SOC caused by the modification of management in tillage and irrigation in rice, it is necessary to use longer periods of time [11,28].

4.3. Carbon from Microbial Biomass

The total amount of microorganisms present in the soil represents the living fraction of its organic matter and is very sensitive to environmental conditions or changes due to management [46]. Microbial biomass is considered as a labile fraction of SOC and is an important reservoir of nutrients for plants, and it also has important functions in the soil, among which highlight waste recycling [47]. Moreover, soil microorganisms contribute to SOC directly with the formation and degradation of microbial biomass [23,24,48].

The stage factor has a statistically significant effect on the carbon of the microbial biomass, showing a variable behavior for the five stages (Figure 3). In stage 1, there were higher values than stage 2 because it corresponds to the fallow period, while the sampling of the second stage was conducted after a decrease in the substrate for microorganisms due to burning of the crop residues, tillage, and planting [49]. Then, in stages 3, 4, and 5 there was a significant increase in the carbon of the microbial biomass related to plant root growth [50,51]. This corresponds with the statement that increases in the rhizosphere promote and increase in the microbial community, resulting in both increased microbial activity and microbial biomass [24].

During each crop cycle, soil moisture conditions fluctuated monthly, since in the first cycle the rainfall was higher than in cycle 2, generating an increase in soil moisture that produced greater microbial activity in the soil, which agrees with Gómez and Paolini who indicated that higher humidity conditions promote the change of the latent state of the

microbial cells to a metabolically active state, as well as the greater growth of plants, which has effects of increasing the dynamics and activity of microbial populations [50].

Variations in moisture content of the soil not only affect the nature of the microbial populations, but it can alter the amount of nutrients and the physical structure of the environment of the microorganisms [52]. In addition, we observed that between stage 3 and 4, the farmer conducting fertilization, which produces a bio-stimulation of the microorganisms and brings greater activity with them. Thus, chemical fertilization promotes a greater proliferation of roots, exudates, and accumulation of organic residues in the soil, favoring the total quantity of microorganisms in the soil [53].

4.4. Necromass Carbon

The decomposition of necromass in the soil constitutes the main pathway for nutrients to enter the soil and is one of the key contributions of SOC [54]. Together with the recycling of organic matter and nutrient, other benefits are generated to the soil, such as increased activity of microorganisms and improvement of physical and chemical conditions [3]. In the agroforestry system of the forest with cocoa, necromass production is fourteen-fold higher than in rice cultivation (Table 3), which represents the main SOC input for the soil [36]. Therefore, the main impact on the dynamics of the SOC generated by the use of rice cultivation in this soil is the drastic decrease in the contributions by the necromass.

Regarding the cultivation stage, it was observed that at the end of the rice cultivation cycle (Stage 5), the contribution of necromass significantly increased, which represents an OC available to be incorporated into the soil at the moment of tillage, resulting in an increment of microbiological activity and improving soil conditions. However, due to burning of the residues of the rice crop, this was not achieved, representing a very harmful practice that alters the dynamics of SOC and produces soil degradation.

4.5. Carbon Losses Due to Emissions to the Atmosphere

Results showed that rice soil in both systems behaved similarly to a CO₂ and CH₄ source (Table 4). For CH₄, the emission is due to the anaerobic conditions developed in the irrigated rice system, which generates the proliferation of anaerobic methanogenic organisms (strict or optional), which further facilitates the anaerobic degradation activity of organic matter, triggering greater production of CH₄ [55]. This agrees with Irisarri and collaborators who reported the relationship between flooding conditions and CH₄ emissions in a system of mechanized rice planting and irrigation [18]. The greater the thickness of the layer of water placed on the soil in crops, the greater the CH₄ reduction potentials at subsoil level [7]. With respect to the cocoa agroforestry system (Table 4), there is complete agreement with Kasimir and collaborators who found that forest and agroforestry ecosystems are an effective tool for reducing carbon emissions into the atmosphere [56].

Dioxide carbon emissions represent the highest carbon outputs, and regarding the soil use system, the rice in both systems showed the highest CO₂ fluxes. The soil with rice had significantly higher root biomass in the surface soil and an active growing cycle; these high CO₂ emissions are attributed to the respiration of plant roots (autotrophic respiration) [57].

4.6. Soil Organic Carbon Budget in the Studied Land Use Systems

As other studies [7,8], our results revealed that rice cultivation systems present the highest amounts of OC outputs and a negative budget (Table 5), which indicated that the rice crop had the highest carbon loss due to high CO₂ emissions from soil microbial activity and mainly associated with greater respiration of the crop's roots, as pointed out by Zornoza and collaborators in 2018 who observed a relationship in greenhouse gas emissions with crop stimulation through fertilization and irrigation water [51].

Moreover, when interpreting the positive balance of the forest with cocoa (Table 5), it was observed that 99.9% of the inputs are lost, with CO₂ emissions responsible for 99.4% of these losses, indicating that intense biological activity around the decomposition and

mineralization of the abundant organic residues is taking place, and it is favored in turn by the conditions of high humidity and favorable soil temperature [58].

5. Conclusions

The change in the use of irrigation and tillage implemented for a year in rice cultivation at the Rio Zulia irrigation district has not caused a significant difference in OC inputs to soil, since irrigated rice had 72.2% less inputs and rainfed rice had 71.0% less inputs. Neither outputs due to carbon emissions in the form of CH₄ and CO₂ had significant differences.

Furthermore, it was found that rice cultivation is a soil use system with higher gross losses of OC (−12,843 kg ha^{−1} in irrigated rice and −12,945 kg ha^{−1} in rainfed rice) acting as a source of greenhouse gases mainly due to CO₂ emissions related to intense stimulation of crop root respiration and in a minor range to soil microbiological activity.

The comparison of SOC dynamics between the agroforestry system of forest with cocoa and the rice cultivation systems allowed observing that the agroforestry system is a carbon sink with a positive OC budget (3.6 kg ha^{−1}) associated with the significant contribution of OC from necromass (7818 kg ha^{−1}), which is enough to store SOC, even though there was also significant CO₂ emission associated with the decomposition and mineralization of that organic matter from vegetation residues.

Comparison of the SOC budget in the surface soil between the rice cultivation systems and the agroforestry system is a useful methodology to understand the significant difference in SOC content in favor of a higher content in the forest soil with cocoa.

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