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Natural Sciences

Original article

Spatio-temporal variability of organic matter content in a vertisol planted with sugarcane under different management systems

Variabilidad espacio-temporal del contenido de materia orgánica en un vertisol plantado con caña de azúcar bajo diferentes sistemas de manejo

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Abstract

In soils cultivated with sugarcane, organic carbon content is strongly influenced by crop residues and increases with the number of ratoons. Our objective in this study was to analyze the spatio-temporal variability of organic matter content in a pelic vertisol soil planted with sugarcane under different management systems in areas of the Provincial Station of Sugarcane Research in Holguín, Cuba. We used a split-plot experimental design with three treatments and four subtreatments. Harvests were collected with a sugarcane harvester in plant cane and four ratoons. The sampling was done before planting the ratoons and after the harvest, managing harvest residues and applying fertilizers in each case. We determined the soil organic matter content, and the exploratory data analysis was performed using the Statistica 7 software. The experimental semivariograms were fitted using the appropriate theoretical models, and the semivariograms and kriging were performed using Surfer 8 software. Soil organic matter content decreased in the plant cane below the values before planting. It reached stability in successive ratoons, increasing its percentage after the fourth ratoon's harvest without reaching the initial levels. The improvement was more noticeable with crop residue conservation and the use of organic fertilization. Crop residue conservation in the field reinforced by organic fertilization proved to be appropriate for protecting soil from the deterioration of its chemical fertility.

Keywords: Conservation of agroecosystems; Management of crop residues; Fertilization.

Resumen

En suelos cultivados con caña de azúcar el contenido de carbono orgánico está fuertemente influenciado por los residuos de cosecha y aumenta con el número de retoños. El objetivo de nuestro estudio fue analizar la variabilidad espacio-temporal del contenido de materia orgánica en un vertisol pélico sembrado con caña de azúcar bajo diferentes sistemas de manejo en áreas de la Estación Provincial de Investigaciones de la Caña de Azúcar en Holguín, Cuba. Se empleó un diseño experimental de parcelas divididas, con tres tratamientos y cuatro subtratamientos. Las cosechas se recolectaron con cosechadora de caña en la planta de caña y en cuatro retoños. El muestreo se hizo antes de la siembra y después de la cosecha de cada retoño, manejando los residuos de la cosecha y aplicando fertilizantes en cada caso. Se determinó el contenido de materia orgánica del suelo y se hizo un análisis exploratorio de los datos con el *software* Statistica 7. Los semivariogramas experimentales se ajustaron mediante los modelos teóricos apropiados y los semivariogramas y el kriging se hicieron con el *software* Surfer 8. El contenido de materia orgánica del suelo disminuyó en las plantas de caña por debajo de los valores anteriores a la siembra y alcanzó cierta estabilidad

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en los retoños sucesivos, aumentando su porcentaje después de la cosecha del cuarto retoño, aunque sin alcanzar los niveles iniciales. La mejora fue más notoria con la conservación de los residuos de cosecha y la aplicación de fertilización orgánica. La conservación de los residuos de cosecha en el campo, reforzada por la fertilización orgánica, resultó una vía apropiada para la protección del suelo ante el deterioro de su fertilidad química.

Palabras clave: conservación de agroecosistemas; manejo de residuos de cosecha; fertilización.

Introduction

Organic carbon is the most important component to sustain soil quality due to its role in supporting the chemical, physical, and biological properties of soils (**Dhaliwal *et al.***, 2019). Conservation agriculture practices and various traditional production systems can significantly increase the organic carbon in soils, reinforcing their resistance to the impact of rainfall, improving the infiltration rate and the amount of available water, increasing the content of microbial biomass, decreasing erosion, and mitigating greenhouse gas emissions (**Cotler *et al.***, 2016).

On soils planted with sugarcane, the organic carbon content is strongly influenced by harvesting, which increases as the number of ratoons increases. Soil organic carbon increases along the successive harvests, reducing the maximum bulk density and increasing the optimum soil water content. In the subsurface horizons, where conventional tillage systems form "plow floors" immediately below the tillage layers, the increase in organic carbon improves soil physical conditions (**Cavalcanti *et al.***, 2019).

The assessment of soil fertility status is a significant aspect of sustainable agricultural production, as it is a determining factor in crop yield (**Basumatary *et al.***, 2021). Soil organic matter, 60% of which consists of organic carbon, has a direct impact on nutrient transformations in the soil (**Dhaliwal *et al.***, 2019).

Current farmer residue management practices, particularly pre-harvest burning, have significant negative environmental impacts. Sustainable management of sugarcane residues could help address various challenges in the sugarcane industry, including the high cost of irrigation (**Chipfupa & Tagwi**, 2024). As the issues related to sugarcane harvesting are complex, their thorough understanding is required for policymaking (**Chaya**, 2024).

Crop residues are generally burned in developing countries, with the subsequent environmental, economic, social, and health effects (**Kumar *et al.***, 2020). In the case of sugarcane, its leaf biomass can be burned in the field, before or after harvest. However, if the crop is harvested without burning, crop residues represent an important source of waste that provides many short- and long-term ecosystem services, including the improvement of soil chemical, physical, and biological properties (**Carvalho *et al.***, 2017). Their removal usually has negative effects on soil and plant development (**Lisboa *et al.***, 2018), while their burning causes soil degradation, increases erosion risks and soil temperature, and deteriorates soil microfauna (**Lin & Begho**, 2022).

There are many ways to incorporate nutrients into the soil. Organic fertilization is a sustainable alternative because, although chemical fertilization is essential, it increases the risk of environmental contamination (**Araújo *et al***., 2020). Sugar agroindustry residues have been used as soil amendments in sugarcane agroecosystems due to their predominantly organic composition (**Quiroz & Pérez**, 2013).

Soil is a heterogeneous, diverse, and dynamic system, and, therefore, studying its changes in time and space is essential (**Kavianpoor *et al.***, 2012). These changes are influenced by the interaction between formative factors and agroecosystem management (**Siqueira *et al.***, 2018). Spatial variability affects soils the most, which explains the many studies exploring technologies to improve soil management, greater efficiency and profitability of agricultural production, and less aggressive practices for the environment (**Jaramillo**, 2012).

Spatial variability depends on the soil property under analysis. Besides, chemical properties are more variable than physical properties, and soil properties have less variability under natural conditions than when subjected to agricultural use (**Obando *et al.***, 2006) given that different cropping systems cause changes in soils' physical, chemical, and biological properties that can alter their quality (**Carvalho *et al.***, 2014). Properties most affected by soil management are those with the greatest variability (**Obando *et al.***, 2006).

Advances in regionalized variables theory associated with soil studies have resulted in statistical tools that help to evaluate substantial aspects of the spatial variability of soil properties. When the value of a property depends on the distance and direction of its location with respect to a neighboring site, we are dealing with a spatially dependent variable. Here, we used a set of statistical tools known as geostatistics (**Jaramillo**, 2012). Such geostatistical analysis can be represented through soil parameter maps that facilitate their interpretation (**Molin *et al.***, 2006). In this framework, our objective was to analyze the spatio-temporal variability of organic matter content in a pelic vertisol planted with sugarcane under different management systems.

Materials and methods

The experiment consisted on the planting of sugarcane (variety C8612) on a pelic vertisol (**Hernández *et al.***, 2015; **Hernández *et al.***, 2019) of soft limestone, carbonated, shallow to moderately deep, moderately humified, little eroded, carbonated, clayey, with an effective depth of 55 cm and a slope of 0.5-1%. The plot was located in inland areas of the Cristino Naranjo Experimental Block belonging to the Provincial Station of Sugarcane Research in Holguín, Cuba. The area has an average air temperature ranging from 22-26 °C, the annual accumulated precipitation is between 800 and 1400 mm, it has a tropical savanna climate of the Aw type (**Pérez & Hidalgo**, 2016), according to the Köppen-Geiger climate classification (**Kottek *et al.***, 2006; **Peel *et al.***, 2007).

We used a split-plot experimental design (OCC1 experiment) with three treatments, four subtreatments, and four replications for a total of 48 plots of 6.4 x 10.0 m, with four furrows each seprated 1.60 m one from the other, with the centroid located at 20°45′14″N and 76° 22′ 25″W. **Table 1** shows the treatments and subtreatments.

Harvests were collected with a sugarcane harvester on tires on the plant cane and four ratoons. The six samplings were done before planting (beginning of the cycle) and after the harvest of each ratoon, managing harvest residues and applying fertilizers in each case. We chose a point located approximately in the center of each 64 m^2 plot, between the second and third furrow.

Soil samples were taken with a Dutch auger at a depth of 0-20 cm (in the A horizon), and the organic matter content was determined by the Walkley-Black method. For the classification, we used the categories applied by **Cairo & Fundora** (2005): very low (< 1.5%); low (1.5-2%); medium (2-4%); high (4-8%), and very high (> 8%).

Table 1. Conformation of treatments and subtreatments

Subtreatments	Treatments		
	A (Crop residues burning)	**B (Crop residue removal)**	**C (Crop residue conservation)**
I	Organic fertilization (30 t ha^{-1} of sugarcane sludge)		
II	Organic-mineral fertilization (18 t ha^{-1} of sugarcane sludge + 100 kg ha^{-1} of nitrogen)		
III	Mineral fertilization (100 kg ha^{-1} of nitrogen)		
IV	Unfertilized		

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We performed an exploratory data analysis using the main position and statistical dispersion with the Statistica 7 software. Semivariograms were determined as a function of distance. Experimental semivariogram fitting was done according to the appropriate theoretical models. The experimental semivariogram γ*(h)* was:

$$\gamma(h) = \frac{1}{2Np(h)} \sum_{i=1}^{Np(h)} [Z(x_i) - Z(x_i + h)]^2, (1)$$

where *Np(h)* is the number of pairs of observations compared at each distance, *Z(xi)* is the value of the variable at site *xi*, and *Z(xi + h)* is the value of the variable at a site located at a distance *h* from site *xi*. Semivariograms and kriging were performed using the Surfer 8 software.

Results and discussion

Table 2 shows the main position and statistical dispersion. In the experimental area, the highest soil organic matter content (highest mean) was found just before planting the sugarcane crop (1.99%). There was a general downward trend throughout the cycle, especially in the plant cane (1.74%), although gradually, in the 1st, 2nd, and 3rd ratoons, there was a slight increase and a certain degree of stabilization (1.84, 1.79, and 1.79%, respectively). In the 4th ratoon, the increase in soil organic matter continued (1.89%), although without reaching the initial values.

These results are lower than those observed by **Martín *et al.*** (2023), who found that the total organic carbon in sugarcane areas was 11.7 g kg^{-1}, equivalent to 2.02% of organic matter in the soil, when determining the organic carbon fractions of the soil in the first 20 cm of depth in a chromic vertisol under different land uses in Mayarí (Holguín). They are also lower than those found by **Cobo *et al.*** (2024), who found that soil organic matter ranged from 1.62 to 4.00%, with an average of 2.67% when evaluating the influence of limiting soil factors on the availability of microelements in vertisols planted with sugarcane in eastern Cuba.

When examining the long-term effects of land-use changes on soil structure and distribution of soil organic C and N content among different organic matter (SOM) fractions in east-central tropical tropical Mexico, **Anaya and Huber-Sannwald** (2015) found that where sugarcane cultivation had a low impact on agroecosystems (due, among other factors, to keepong soil surfaces covered with plant residues), soil physical disturbances were fundamentally reduced, so that the effects of cultivation on soil organic carbon (SOC) and N stocks depended mainly on organic matter input and physicochemical mechanisms of SOM stabilization. After 50 years of traditional sugarcane cultivation, SOC stocks returned to sizes similar to those of nearby forests.

Table 2. Main position and dispersion statistics of soil organic matter in a vertisol planted with sugarcane under different management systems before planting and in each of the ratoons

	Mean	Median	Standar error	Minimun	Maximun	Variance	Standar deviation	C. V.[1] (%)
Before planting	1.99	2.00	0.021	1.66	2.18	0.021	0.145	7.30
Plant cane	1.74	1.74	0.013	1.58	2.06	0.009	0.093	5.36
1st ratoon	1.84	1.85	0.013	1.65	2.06	0.009	0.093	5.07
2nd ratoon	1.79	1.80	0.013	1.56	1.94	0.008	0.088	4.90
3rd ratoon	1.79	1.84	0.023	1.47	2.13	0.024	0.156	8.72
4th ratoon	1.89	1.91	0.017	1.69	2.13	0.014	0.119	6.33

[1]C. V.: Coefficient of variation

In all cases, they observed close mean and median values, which indicated no extreme observations caused the mean to shift. It is important to note that the greatest difference between the values was found in the 3rd ratoon. The highest standard error (0.023%) was also found in this same ratoon, followed closely by the standard errors determined before planting and in the 4th ratoon (0.021 and 0.017%, respectively). Lower values were found in the plant cane, and in the 1st and 2nd ratoons (0.013% for all three).

The lowest minimum value was observed in the 3rd ratoon, followed by the 2nd ratoon and the plant cane. As for organic matter values at the beginning (before planting) and at the end (4th ratoon) of the cycle, it was evident that, regardless of the behavior of the corresponding means in each ratoon, at the end of the cycle, the minimum was higher than at the beginning. The highest maximum value was found before planting (2.18%), followed by soil organic matter content in the 3rd and 4th ratoons (2.13% each). Lower percentages were observed in the soil, in the plant cane, and in the 1st ratoon (2.06% in both). In the 2nd ratoon, the percentage of organic matter was below 2%, i.e., low, according to the categories applied by **Cairo and Fundora** (2007) for clay soils.

Statistical dispersion (variance and standard deviation) showed that in the 3rd ratoon, there was a greater dispersion of soil organic matter percentages with respect to the mean. Also, the coefficient of variation showed that there was a greater dispersion of the data around the mean (8.72%) and that the probability of finding an organic matter value close to this was lower in the ratoon. However, all coefficients of variation, including that of the 3rd ratoon, were below 30%, which is considered the maximum acceptable limit for agronomic research (**Espino & Arcia**, 2009).

Figure 1 shows the semivariograms obtained by fitting the experimental models to the corresponding theoretical model. In almost all cases, the most adequate theoretical model was the spherical, except in the 1st and 3rd ratoons, where the exponential was used.

According to **Jaramillo** (2012), these two models are those that best fit the soil properties with spatial dependence. In all cases, although less noticeable in the 2nd ratoon, there was an adequate spatial structure, which can be appreciated, according to **Acevedo *et al.*** (2015), by the clear way in which the semivariance values increase.

Semivariance values, which were independent from sampling distance (nugget effect), were close to each other before planting in the plant cane and the 1st and 4th ratoons. More distant from these values was the nugget effect in the 2nd and 3rd ratoons; given that it had

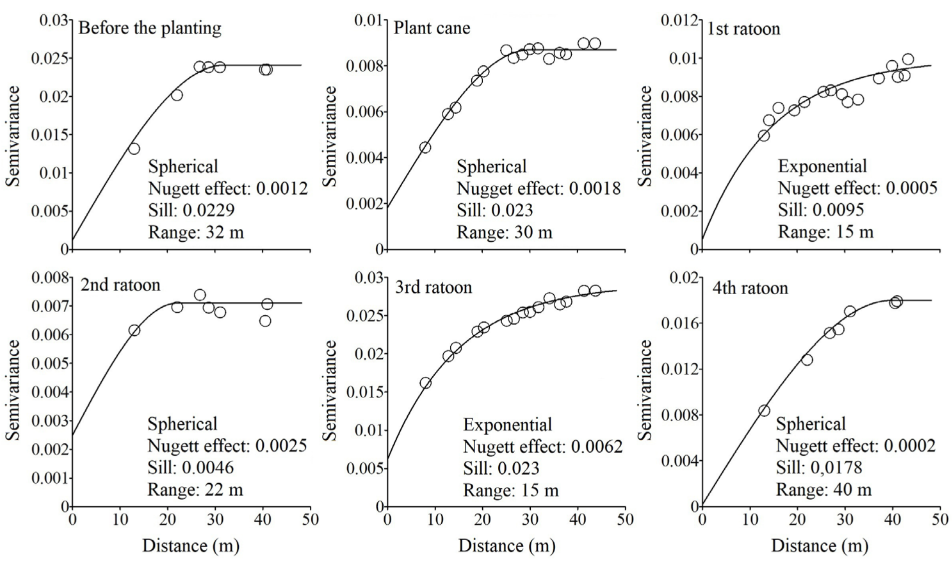

Figure 1. Semivariograms of organic matter in a vertisol planted with sugarcane under different management systems before planting and in each of the ratoons

the highest value, in the latter, organic matter suffered the dominant effects of short-range processes, while the variance became constant (sill) at values close to each other before sowing, in the 3rd and 4th ratoons.

Before planting and at the plant cane, the sill had similar amounts. The distance from which the variance stabilized (range) decreased up to the 3rd ratoon, thus decreasing the distance up to which there was spatial dependence between the organic matter samples taken. However, in the 4th ratoon, this parameter increased sharply, exceeding the previous values.

Figure 2 shows the spatio-temporal behavior of soil organic matter content in the OCC1 experiment. At the beginning of the planting cycle (before planting), the organic matter content in the whole area reached values between 1.66 and 2.18%, classified as low and medium.

After the harvesting of the plant cane, the management of the straw cover, and the application of the corresponding type of fertilization, a decrease in the percentage of organic matter was observed in the whole area of the experiment. The deterioration of soil organic matter was more noticeable in a wedge covering two thirds of the lower and middle parts of treatment A (crop residue burning), in the unfertilized subtreatment (IV) of treatment B (crop residue removal), and in the first two replicates of treatment C (crop residue conservation), with mineral fertilization (III) and with no fertilization.

In a field experiment of six years of successive annual sugarcane crops planted in a rodhic eutrudox with 20.4 °C mean annual temperature and and 1420 mm of rainfall, **Soltangheisi *et al.*** (2021) observed that by completely removing the crop residues of each year from the field, the initial soil organic matter content decreased from 3.97 to 3.45%.

In these areas, the strips in treatments B and C, where organic fertilization was applied (subtreatment I), the tendency was to maintain slightly higher percentages of soil organic matter. Regardless of the fact that only the soil organic matter content was classified as medium in the last repetition of crop residue burning with the application of organic fertilization, in the rest of the experiment, the percentage of organic matter was low.

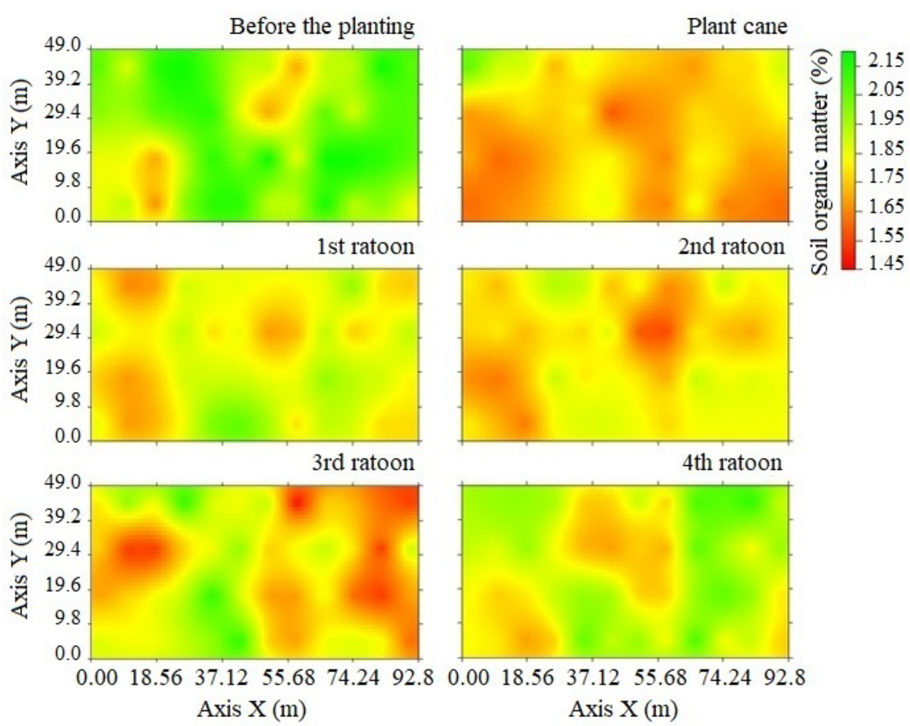

Figure 2. Soil organic matter kriging in a vertisol planted with sugarcane under different management systems before planting and in each of the ratoons

In the 1st ratoon, a recovery of soil organic matter values was seen, especially in the conservation strip of crop residues with organic fertilization. Although the highest values were those in the plots belonging to the first replicate of treatment B with organic and organic-mineral fertilization, only in the latter zone did the percentage of soil organic matter reached a medium level; in the rest of the experiment, despite the improvement, it continued to be low.

In the 2nd ratoon, there was a decrease in soil organic matter content in all three treatments, less noticeable where crop residue conservation was combined with organic fertilization. It was accentuated towards the center of treatment B with mineral fertilization and (especially) without fertilization, and in treatment A.

In the 3rd ratoon, an increase in soil organic matter content was registered at the boundary between treatments A and B, where the percentage of soil organic matter was classified as low to medium. However, in the fourth replicate of unfertilized treatment B, the lowest soil organic matter content of the experiment was 1.47%, i.e., very low. In treatment C, the soil organic matter content decreased in the strips with organic-mineral and mineral fertilization (1.54%, the lowest value in this treatment) and without fertilization. However, where organic fertilization was applied, the value of organic matter tended to maintain a certain degree of stability over time.

In the 4th ratoon, a general improvement of the soil organic matter content was observed in the whole area of the experiment, especially in a diagonal band from the 1st replicate of treatment B with organic fertilization (soil organic matter content, medium) to the upper left part of the experiment, where soil organic matter decreased but widened in area at the furthest end of treatment A.

The most outstanding recovery was seen in treatment C, where the percentage of soil organic matter was classified as medium in the entire strip with organic fertilization, and in some parts where organic-mineral and mineral fertilization was applied. In these subtreatments there were numerous sampling points with organic matter values classified as moderate. Less notable was the improvement found where no fertilization was applied (subtreatment IV).

When evaluating the impact of different sugarcane straw removal rates (total removal, 0 Mg ha^{-1}; high removal, 5 Mg ha^{-1}; low removal, 10 Mg ha^{-1}, and no removal, 15 Mg ha^{-1} of dry straw maintained on the soil surface) on the quantity, quality, and stability of soil organic carbon (SOC) up to 0.3 m depth in a clayey rhodic eutrudox soil over six years, **Pimentel *et al.*** (2024) found that total and high removal decreased SOC stocks at depths of 0.0-0.1 m and 0.0-0.3 m, whereas, without removal, the SOC accumulation rate was 1.42 Mg ha^{-1} $year^{-1}$ as compared to the baseline. Low removal increased particulate organic matter (46.2%) and mineral-associated organic matter (12.4%) in the surface layer compared to total removal.

In a long-term experiment with plant sugarcane planted in a chromic vertisol in southern Africa, **Graham *et al.*** (2002) observed that the green harvesting of sugarcane with conservation of crop residues in the field was an effective way to counteract the losses of organic matter that conventional sugarcane cultivation normally causes in the soil, especially when it is burned before harvest.

Medorio *et al.* (2020) pointed out that burning and removing crop residues, among other agricultural practices in sugarcane agroecosystems, decreased soil organic carbon concentrations. Similarly, **Graham and Haynes** (2006) stated that, during burning, the sugarcane root system concentrated below the stump and the soil in the space between rows received little organic matter. The lower content of total and labile organic matter reduces microbial activity and decreases the stability of soil aggregates, thus increasing soil compaction, runoff, and erosion in the areas.

On the other hand, **Graham and Haynes** (2006) concluded that with green sugarcane harvesting and harvest residues on the soil, roots proliferated and redistributed towards the space between rows in the first 10 cm of depth. This resulted in an increased organic matter content, microbial activity, and structural stability, which reduced the effects of compaction and erosion and kept the soil protected with crop residues. Thus, green harvesting of sugarcane improved soil quality, particularly in the space between rows, and, in the long term, it may be the most sustainable management system for sugarcane.

Conclusions

The burning, removal, or conservation of crop residues, and the application of mineral or organic fertilizers, decreased the soil organic matter content in the plant cane below pre-planting levels. It reached certain stability levels in subsequent vines and increased its percentage after the fourth shoot harvest, although it did not return to its initial levels. This improvement, at the end of the cycle, was most noticeable in treatment C (conservation of crop residues), especially where organic fertilization was applied. The conservation of crop residues in the field, reinforced by organic fertilization, proved to be an appropriate means of protecting the soil from the deterioration of its chemical fertility.

Author contributions

JAVG contributed to the project idea and design, supervised its implementation, participated in the field and laboratory work, wrote the article, reviewed its content, and designed the graphics. GMG participated in the field and laboratory work and reviewed the article content. YCV participated in the field and laboratory work and reviewed the article content.

Conflict of interest

The authors declare no conflict of interest that may affect the publication of this study.

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