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Soil organic carbon dynamics in land-use systems in the tropical dry forest of Colombia

Dinámica del carbono orgánico del suelo en sistemas de uso del suelo en el bosque seco tropical de Colombia

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ABSTRACT

Soil organic carbon (SOC) is a crucial reservoir that facilitates climate change mitigation through its sequestration. The SOC stock was estimated in the top 30 cm in the predominant land use systems (LUS) (agriculture, grasslands, and forestry – forestry plantations, gallery forests, and natural regeneration) in the Centro Universitario Regional del Norte (CURDN), located in the dry zone of northern Tolima, Colombia. The bulk density (BD) and SOC concentration were estimated at this depth in a sampling. Information on the latter variable was also taken from a study in the same area in 2007. The effects of possible changes in land use on SOC stock between 2007 and 2021 were estimated, calculating a change rate between the two years. A significant effect of land use on the variables analyzed was found: agriculture presented the highest BD and lowest SOC concentration, while livestock production reached the highest SOC concentration and stock (1.45% and 63.2 Mg C/ha, respectively). The SOC stock, after 14 years, increased in all LUS, mostly in livestock production (150%), resulting in a SOC capture rate of 3.0 Mg/ha/year. Changing livestock to other uses can cause emissions of up to 60.6 Mg CO_2/ha and up to 9.3 Gg CO_2 in the total area of the CURDN. These results are the basis for LUS management for climate change mitigation through SOC conservation and sequestration.

Keywords: bulk density; climate change; CO_2; emissions; land use change; mitigation

RESUMEN

El carbono orgánico del suelo (COS) es un importante reservorio que permite mitigar el cambio climático a través de su secuestro. Se estimó el almacenamiento de COS en los primeros 30 cm de profundidad en los sistemas de uso del suelo (LUS) predominantes (agricultura, pasturas, silvicultura: plantaciones forestales, bosques riparios y regeneración natural) en el Centro Universitario Regional del Norte (CURDN), ubicado en la zona seca del norte del Tolima, Colombia. A esta profundidad, se estimó la densidad aparente (DA) y la concentración de COS con un muestreo. La información sobre la última variable se complementó con un estudio realizado en la misma zona en 2007. Se estimó el efecto de posibles cambios en el uso del suelo sobre el almacenamiento de COS entre 2007 y 2021, calculando la tasa de cambio entre los dos años. Se encontró un efecto significativo ($p < 0,05$) del uso del suelo sobre las variables analizadas: la agricultura presentó la mayor DA y la menor concentración de COS; mientras que la ganadería alcanzó la mayor concentración y almacenamiento de COS (1,45% y 63,2 Mg C/ha, respectivamente). El almacenamiento de COS, después de 14 años, aumentó en todos los LUS, principalmente en ganadería (150%), resultando en una tasa de captura de COS de 3,0 Mg/ha/año. El cambio de usos ganaderos a otros usos puede provocar emisiones de hasta 60,6 Mg CO_2/ha y hasta 9,3 Gg CO_2 en toda el área del CURDN. Estos resultados son la base para la gestión de SU para la mitigación del cambio climático a través de la conservación y secuestro de COS.

Palabras clave: cambio climático; cambio de uso del suelo; CO_2; densidad aparente; emisiones; mitigación

INTRODUCTION

Soil is one of the key components that humanity can use to mitigate climate change, being the second largest carbon sink after the oceans (Cantú & Yáñez, 2018; Rani, 2021; Carvajal-Agudelo & Andrade, 2021). This component can interact directly with the atmosphere and vegetation, allowing it to capture and conserve large amounts of carbon, the main greenhouse gas (GHG) (Food and Agriculture Organization of the United Nations [FAO], 2017; Cantú & Yáñez, 2018). GHG, intensified by technological advances, population, and industrial activities, has reached alarming levels in the atmosphere. In 2018, CO_2 hovered around 407.8 ppm, and for 2019 the increase was higher, more than in previous years, reaching 410.5 ± 0.2 ppm (World Meteorological Organization [WMO], 2018; 2019). Likewise, the global mean temperature has broken records since the second half of the 20th century, demonstrating the accelerating increase in climate change (Crutzen, 2006; Intergovernmental Panel on Climate Change [IPCC], 2021; WMO, 2021).

The carbon cycle is recognized for its importance to global ecosystems, due to its relationship with soil quality and plant productivity, as well as its crucial impact on the fight against climate change (Dad, 2019; Wiltshire & Beckage, 2022). Soil can sequester up to 1.2 Gt C/year, i.e., more than 10% of global fossil fuel emissions (Lal, 2004). For this reason, sustainable sequestration and productive soil management can play a significant role in mitigating climate change by reducing GHG emissions into the atmosphere, while improving food security and soil quality (FAO, 2017; Dad, 2019).

Sequestration, by removing atmospheric carbon, is one of the most economical and least demanding technologies of CO_2 removal (Keel *et al.*, 2019). Plants capture CO_2 from the atmosphere through photosynthesis, creating complex organic molecules and forming biomass, which is transported to the soil by senescence and becomes part of the soil, contributing greatly to carbon sequestration (FAO, 2017; Sharma *et al.*, 2021). Understanding soil organic carbon (SOC) stocks and how different land use systems affect them is crucial for effectively managing all ecosystem services (Carvajal-Agudelo & Andrade, 2021).

SOC stocks are influenced by their use and management practices (Lal, 2008). Carbon sequestration significantly improves soil quality, positively increases crop yields, improves bulk density (BD) and moisture retention, and mitigates climate change (Lal, 2004; FAO, 2017; Carvajal-Agudelo & Andrade, 2021). This creates opportunities to offset GHG emissions by carbon sequestration and ensure food and water supply for all populations involved (FAO, 2017; Lal, 2004). The objective of this study was to estimate the SOC stock and the potential impact of changes in land use systems after 14 years on this variable in the Centro Universitario Regional del Norte, Armero-Guayabal, a dry zone in the north of the department of Tolima.

MATERIALS AND METHODS

Study area

The study was conducted at the Centro Universitario Regional del Norte (CURDN) of the Universidad del Tolima, located in the north of the department of Tolima in Colombia (4°59'57.50" N. and 74°54'52.74" W) (Figure 1). The study area corresponds to a tropical dry forest with a mean annual temperature of 27°C, a mean relative humidity of 71%, a mean annual precipitation of 1,738 mm, and an altitude between 275 and 350 m (Universidad del Tolima, 2021).

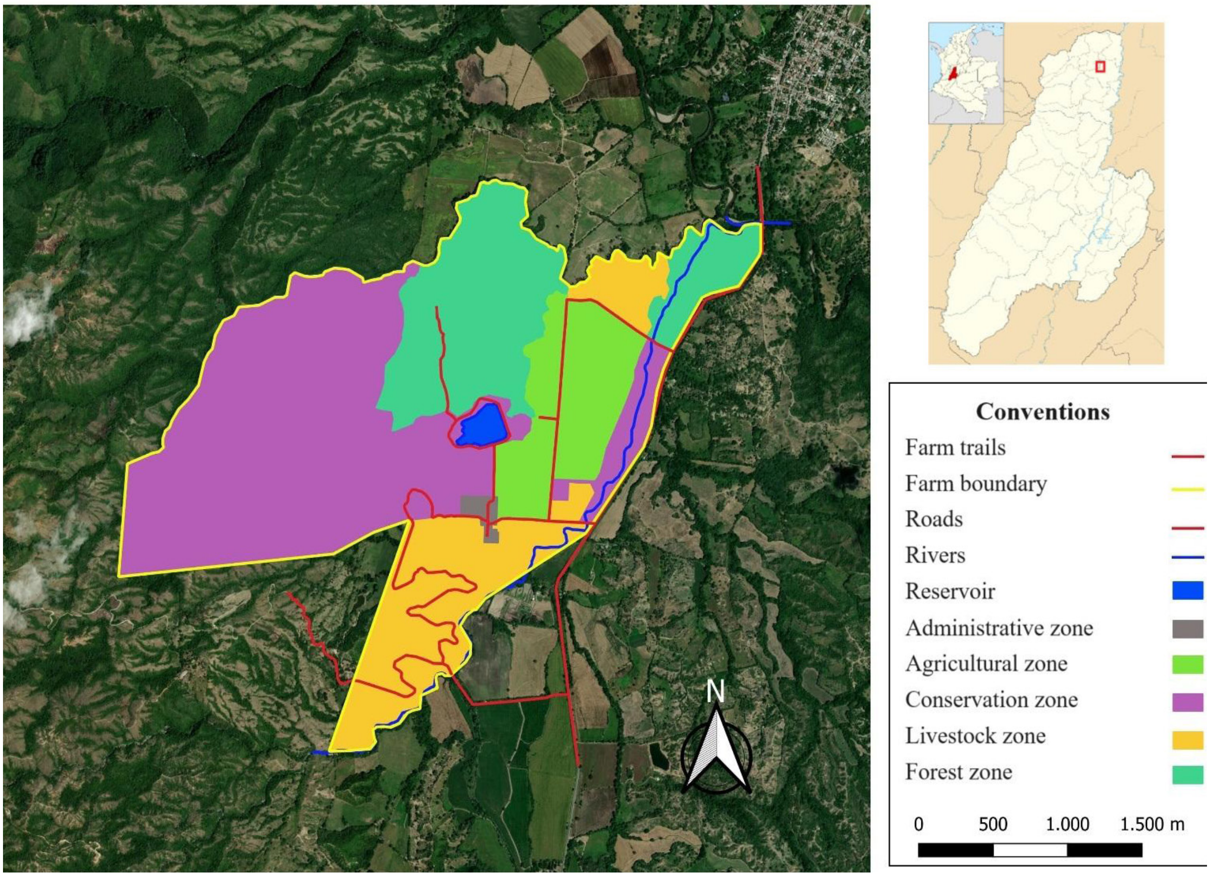


Figure 1. *Location and land use systems of the Northern Regional University Center (CURDN) of the University of Tolima, municipality of Armero-Guayabal, Tolima, Colombia, 2021.*

The CURDN presents a remarkable diversity of relief, which gives rise to a wide variety of soil types, including the following taxonomic units: *Typic Haplustept, Duric Haplustolls, Vertic Haplustepts, Fluventic Haplustolls, Aquic Haplustolls*, and *Typic Ustorthents,* with slopes ranging from 1 to 50%. These soils exhibit different characteristics: the flat areas are characterized by deep, fertile soils, while the hills are dominated by steep and shallow soils. In addition, this farm has diverse land use systems, classified according to activities: agricultural, forestry, livestock production, and conservation of soils.

Land use systems. The four types of land use systems (LUS) present in the CURDN were evaluated: agriculture, grasslands, and forestry, which is composed of forestry plantation and gallery forests and natural regeneration (Table 1). This classification is used by the AFOLU (agriculture, forestry, and other land uses) sector by the IPCC (2019). A sampling scheme that includes 21 soil phases with their respective LUS was established. In each soil phase, three randomly selected replicates were established throughout the CURDN. An unbalanced, completely randomized statistical design was used since the number of replicates was not equal in all treatments or LUS.

Soil organic carbon stock (SOC). The SOC stock was estimated at a depth of 0-30 cm (IPCC, 2003; Andrade-Castañeda *et al*., 2016). Two samples per sampling unit were collected to determine BD by the cylinder method (IPCC, 2003; Andrade-Castañeda *et al*., 2016). One composed soil sample, from 10 subsamples, was collected per sampling unit to estimate SOC concentration by the Walkley & Black (1934) method at the Laserex Laboratory of the University of Tolima.

Impact of land use change on carbon fixation or CO_2 emissions. A simulation was carried out to estimate the possible changes in SOC stock by land-use changes. Scenarios in which land use is changed were modelled, with a corresponding change in carbon stock. It was assumed that with a land use change, the SOC stock change according to the estimations from this study. In this case, carbon stock estimates were estimated based on soil mass and not soil volume, using the lowest value of BD (Lorenz & Lal, 2016; FAO, 2017; Rojas *et al*., 2018; Carvajal-Agudelo & Andrade, 2021). Differences in SOC stock between future and current uses were estimated and multiplied by 3.67 to convert them to CO2. Positive values imply an increase or additionality of SOC, while negative values reflect CO2 emission (Sánchez *et al*., 2003; Andrade-Castañeda *et al*., 2016; Carvajal-Agudelo & Andrade, 2021). These projections considered a change from the total area of each land use in the CURDN to the others.

Temporal dynamics of soil organic carbon. SOC dynamics were estimated by taking SOC concentration data from the study conducted in 2007. This calculation was made assuming that the BD of each phase did not change during this period, i.e., SOC stock was estimated based on the same soil mass. The rate of change corresponded to the change in SOC stock between 2007 and 2021, the elapsed time.

Data analysis

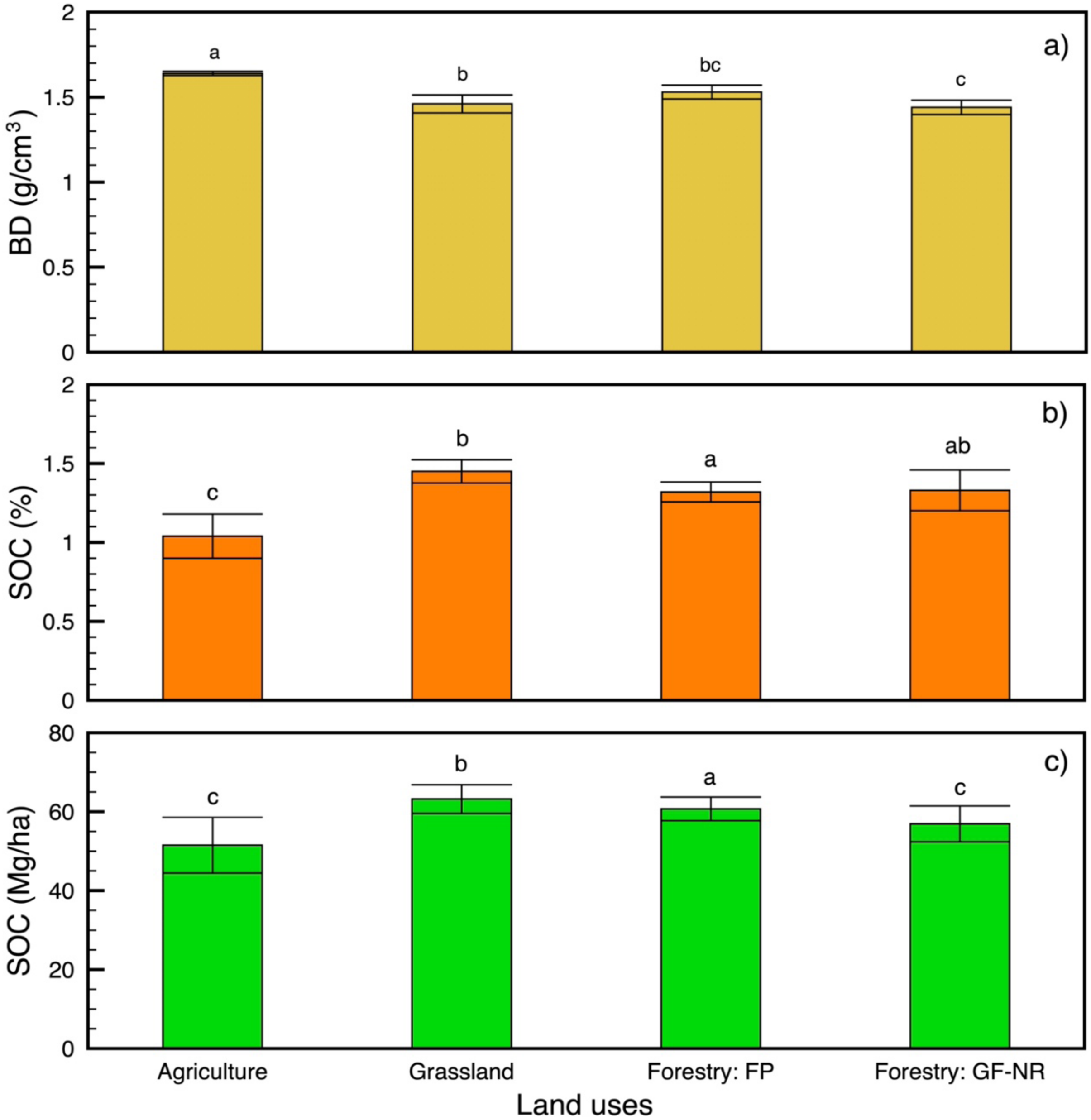
The Shapiro-Wilks test was performed on all variables to verify whether they met the assumption of normality. Variables that presented normal distribution were analyzed by analysis of variance and LSD Fisher mean comparison tests to see statistical differences between pairs of treatments (LUS). Variables that were not normally distributed were transformed and analyzed to determine if they reached normality; if not, they were analyzed using the Kruskal-Wallis nonparametric test of variance. All statistical analyses were performed with the InfoStat program.

Table 1. *Land use characteristics of the Northern Regional University Center, Armero-Guayabal, Tolima, Colombia, 2021.*

Land use systems	Total area (ha)	Soil characteristics	Activities	Management between 2007 and 2021
Agriculture	80	Alluvial plains and terraces, with flat soils and fertile valleys, with taxonomic groups *Aquic Haplustolls* and *Typic Ustorthents*, without evident erosions and slopes ranging from 1 to 3%, very fertile and deep soils.	Production of grasses, *Oryza sativa,* and *Gossypium hirsutum* L., depending on the time of closure; you can also find sowing of *Sorghum bicolor*, *Zea mays*, *Glycine max,* and *Sesamum indicum*.	Conventional farming system, with multiple passes of plowing. Reduced tillage with incorporation of crop residues in 2021.
Grasslands	119	Foothill areas and alluvial plains with accumulation glaciers, with flat and sloping terrain, with taxonomic groups *Duric Haplustolls, Vertic Haplustepts,* and *Fluventepts Haplustolls,* with no signs of erosion and slopes between 1 and 7%.	Cattle and goat breeding and exploitation	Extensive livestock farming system. Voisin 2021 grazing system.
Forestry: Forestry plantations	60		*Gmelina arborea* *Tectona grandis* Riparian forests	Forest systems with little or no intervention.
Forestry: gallery forests and natural regeneration	431	Mountain areas, very shallow soils, with high hills and isolated hills, taxonomic group *Typic Haplustepts,* with moderate erosion and slopes between 7 and 50%.	Mosaic of pastures with natural areas of gallery forest and secondary vegetation.	No intervention given the conditions of the terrain, which are not conducive to any type of activity.

RESULTS

Soil organic carbon stock (SOC). The evaluated LUS presented significant differences (p < 0.05) in their BD, with values between 1.44 and 1.64 g/cm3. Agriculture had the highest BD, which was significantly higher (p < 0.05) than the others, exceeding by 7, 12, and 14% the forestry plantations, grasslands, gallery forests, and natural regeneration, respectively (Figure 2a).

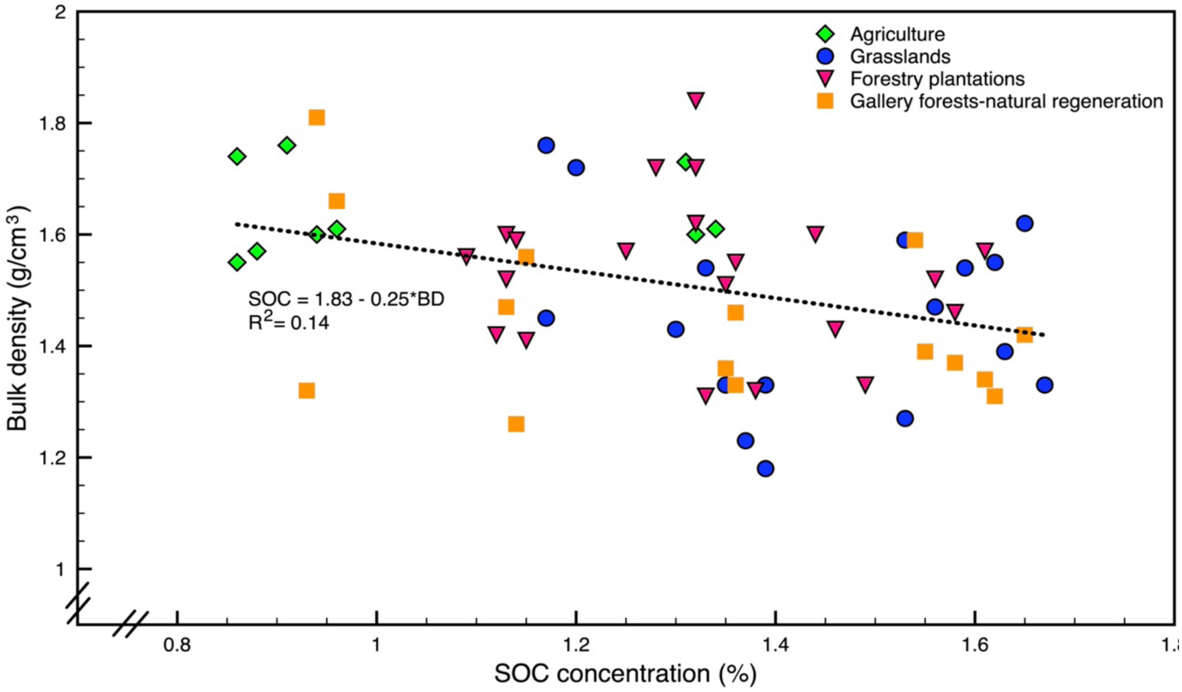


The error bars correspond to the standard error. and common letters are not significantly different (*p*>0.05). BD: Bulk density; COS: soil organic carbon. FP: forestry plantations; GF-NR: gallery forests-natural regeneration.

Figure 2. *a) BD, b) SOC concentration, and c) SOC stock in the different land use systems of the Centro Universitario Regional del Norte, Armero-Guayabal, Tolima, Colombia, 2021.*

SOC concentration presented, like BD, significant differences ($p<0.05$) among the LUS. This variable showed a range between 1.04 and 1.45% in the top 30 cm of depth. The grassland system presented the highest concentrations of SOC ($p < 0.05$), which exceeded 9, 10, and 39% of those found in the forestry (gallery forests-natural regeneration), forestry plantations, and agriculture, respectively (Figure 2b).

An inverse relationship was found between BD and SOC concentration (Figure 3). Although it is not a very close relationship (r = 0.37), a pattern towards a reduction in BD with increases in SOC concentration was observed in the different LUS. This relationship indicates a reduction of 0.25 g/cm3 per 1% increase in SOC concentration.

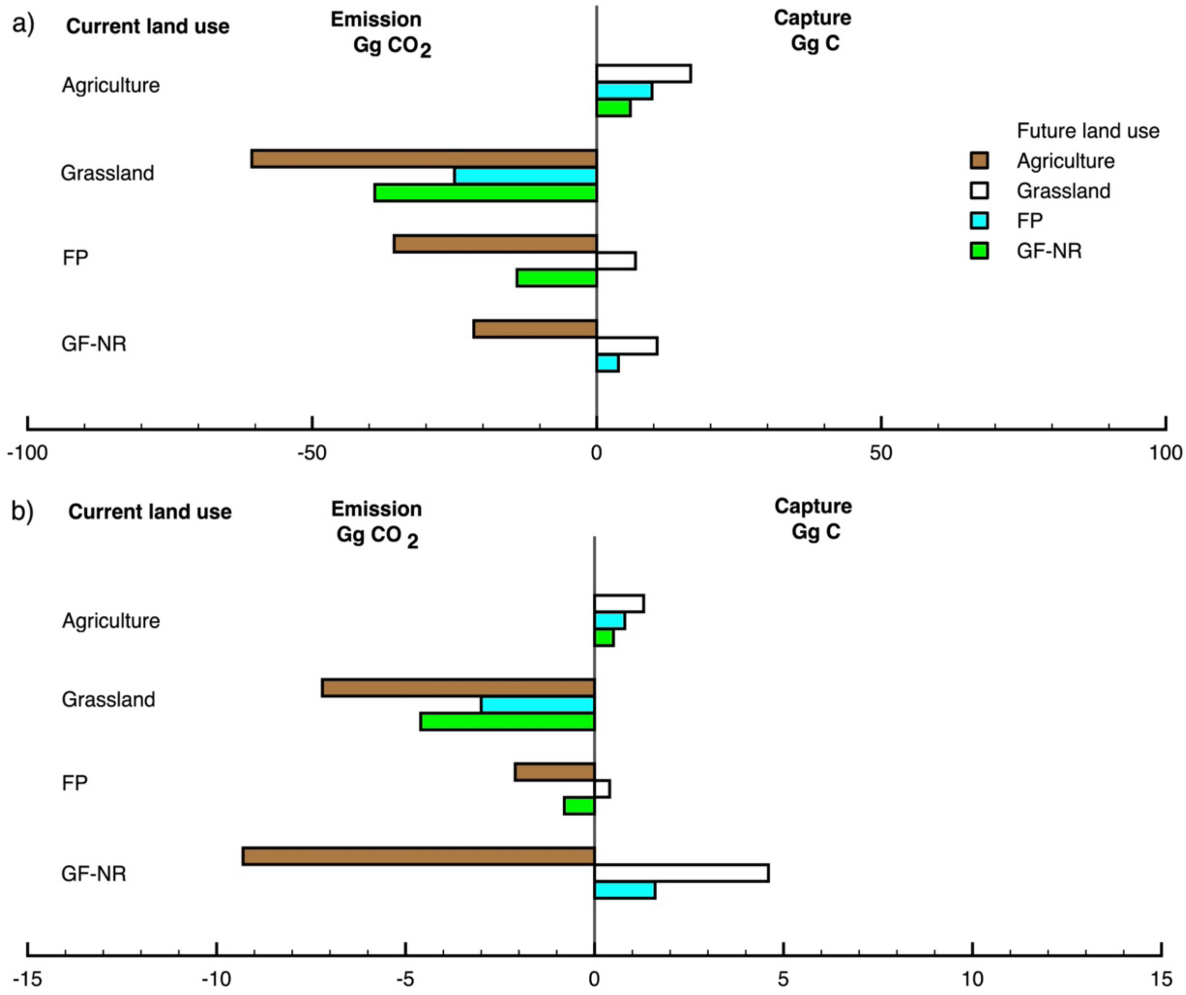


COS: soil organic carbon; BD: bulk density.

Figure 3. *Relationship between SOC concentration and bulk density (BD) in the different use systems of the Centro Universitario Regional del Norte, Armero-Guayabal, Tolima, Colombia, 2021.*

In the same way, significant differences ($p < 0.05$) were detected in SOC stock among the LUS. The grassland, with Voisin rational grazing system, registered the highest carbon stock with 63.2 Mg/ha (Figure 2c) because of its highest SOC concentrations. Grassland systems had more SOC than the other systems, exceeding forestry plantations, gallery forests-natural regeneration, and agriculture by 4, 11, and 23%, respectively (Figure 2c).

Impact of land use change on carbon sequestration and CO2 emissions. This simulation found that when switching from agriculture to grassland systems, an increase or additionality of carbon of 16.1 Mg/ha can be generated. In contrast, the inverse change can generate net emissions of 60.6 Mg CO_2/ha. Another positive land use change, in terms of carbon sequestration, is to modify agriculture or gallery forest-natural regeneration use to forestry plantations, as this would increase SOC by 9.7 and 3.8 Mg/ha, respectively. The abandonment of agricultural areas, allowing assisted natural regeneration, generates an additional carbon sequestration of 5.9 Mg/ha, while the incorporation of new areas into agriculture generates CO2 emissions (Figure 4a).

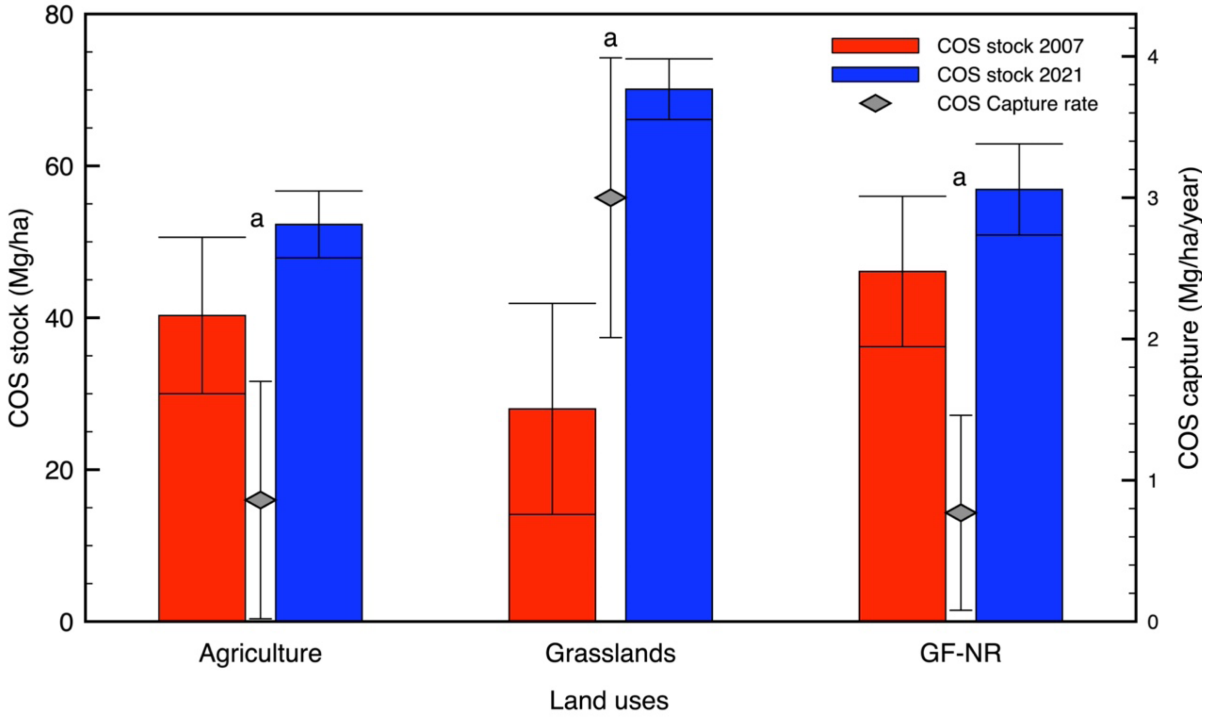


a) Per unit area; b) in total for the farm; SOC: soil organic carbon. FP: forestry plantations; GF-NR: gallery forests-natural regeneration.

Figure 4. *Simulated impact of land use change on soil organic carbon stocks (SOC) and associated CO_2 emissions or sequestration at 0–30 cm depth in soils of the Centro Universitario Regional del Norte (CURDN), Armero-Guayabal, Tolima, Colombia, 2021.*

On the other hand, Figure 4b presents the estimated changes in LUS when the entire area of each land use is altered. In these results, the best positive change is when the entire conservation area is changed to livestock production, which would capture a total of 4.6 Gg C (Figure 4b). In contrast, the worst change would be when the entire conservation area shifts to agriculture, which generates about 9.3 Gg CO_2 of emissions (Figure 4b).

Temporal dynamics of soil organic carbon. The study of the temporal dynamics of SOC showed that grassland systems presented the highest increase in SOC stock, rising from 28.0 to 70.1 Mg/ha in 2007 and 2021, respectively, representing a 150% increase in 14 years. Increases of 24 and 31% were estimated in gallery forests-natural regeneration and agriculture, respectively (Figure 5). The highest SOC capture rate was estimated to occur in grasslands (3.0 Mg/ha/yr), which was almost four times higher than in conservation and three and a half times higher than in agriculture, respectively (Figure 5).



SOC: soil organic carbon.

Figure 5. *Temporal dynamics of SOC in different land uses after 14 years at a depth of 0 to 30 cm in the soil of the Centro Universitario Regional del Norte, Armero - Guayabal, Tolima, Colombia, 2021. GF-NR: gallery forests-natural regeneration.*

DISCUSSION

Soil organic carbon stock (SOC). It is to be expected that agricultural activity increases soil BD, as was found in sugarcane, where it increased from 1.22 to 1.37 g/cm3 at 10 cm depth with the use of heavy machinery (Sánchez *et al.*, 2003). Several authors have found an impact of the vegetation type of land use systems on BD, thus, monocultures of semiannual species commonly present higher values than land use systems that have a high abundance and diversity of woody species, such as forest plantations, forests, and forestry plantations and gallery forests-natural regeneration (Rojas *et al.*, 2018, Zúñiga Ugalde *et al.*, 2018). This trend was also found by Castillo-Valdez *et al.* (2021), who reported a BD in soils without agricultural use of 1.28 g/cm3 compared to soils with flowers and vegetables (1.4 g/cm3).

Contrary to what was reported in the study and other investigations, Andrade-Castañeda *et al.* (2016) found that forests presented a higher BD than the surrounding edges and agricultural matrix (1.7, 1.1, and 1.0 g/cm3, respectively), possibly due to organic management in agricultural production areas. Contreras-Santos *et al.* (2019) recorded values like this research, where pastures without trees presented 1.54 g/cm3 at the same depth, which decreased to 1.22 g/cm3 in silvopastoral systems. This shows the importance of using this type of system for the improvement of edaphic properties. On the other hand, anthropic disturbances have caused the degradation of soil properties. Thus, Andrade *et al.*

(2022) have found the lowest BD in natural ecosystems of the Santuario de Flora y Fauna Iguaque (0.69 g/cm3), due to the low anthropic disturbances that the soil has had in several years.

On the other hand, in Mexico, trends in SOC concentration at the same depth (30 cm) have been recorded with results of 1.3, 1.8, 2.2, and 2.3% in agricultural soils, plantations, pastures, and shrubland, respectively (Cantú & Yáñez, 2018). In contrast, in natural ecosystems of the department of Boyacá, in Colombia, SOC concentrations of 5.5% have been estimated, given that the soils and their vegetation have not been intervened for more than 45 years and that very low temperatures reduce mineralization (Andrade *et al.*, 2022). However, in areas surrounding the present study, values higher than those found in the present study were recorded, with variations between 1.5 and 2.6% in the first 20 cm of soil in rice crops and pastures in tropical dry forest (Andrade-Castañeda *et al.*, 2016). SOC is strongly related to soil type, landscape morphology, management practices, crops, and climate (Hao *et al.*, 2002; Devi, 2021).

The inverse relationship between SOC concentration and BD has been established by other authors in different life zones (Rojas *et al.*, 2018; Zúñiga Ugalde *et al.*, 2018; Andrade *et al.*, 2022). This small relationship between these variables may be determined by the mineral content of the soil (Gosselink *et al.*, 1984); however, this inverse relationship is a great indicator of the recovery and improvement of soils and the synergy of SOC capture with soil quality, since capturing carbon in soils improves their physical conditions.

The grassland system presented the highest values in SOC stock; this can be attributed to the higher turnover (regrowth and senescence) of fine roots that pasture soils have (Andrade *et al.*, 2008; Contreras-Santos, 2019) helped by the Voisin rational grazing (Seó *et al.*, 2017). In addition, it should be noted that carbon accumulation depends on soil use history and age of current use (Ayala-Aragón & Almanza-López, 2021); slope and soil management exert a significant effect on SOC accumulation. Hao *et al.* (2002) estimated that controlled application of cattle manure can significantly increase SOC stocks and, combined with other parameters such as no-tillage and crop rotation, can even improve fertility.

Contreras-Santos et al. (2019) reported values very close to the findings of this study, with carbon storage of 62.8 Mg/ha in silvopastoral systems, which contrasts with the 38.3 Mg/ha estimated in pastures without trees in the municipality of Cereté (Córdoba). Andrade-Castañeda *et al.* (2016) estimated that the interfaces in the same area of the present study, rice-riparian forest and pasture-riparian forest, contained 65.6 and 61.3 Mg/ha, respectively. The lower SOC values in agricultural soil would be due to the use of tillage with agricultural machinery combined with soil erosion, which exposes soil organic carbon to further mineralization (Sánchez *et al.*, 2003; Andrade *et al.*, 2008). This decrease in SOC in agricultural systems exposes the true potential of these soils to sequester carbon (Ayala-Aragón & Almanza-López, 2021).

Impact of land use change on carbon sequestration and CO2 emissions. Modification of current soils used in grassland systems, including their management with the Voisin rational grazing (Seó *et al.*, 2017) in the CURDN could contribute to fixing more carbon in the soil (Haddaway *et al.*, 2015; Carvajal-Agudelo & Andrade, 2021). According to Contreras-Santos *et al.* (2019), the best soils for carbon sequestration were those with silvopastoral systems, mainly in upper layers, because the roots of shrubs and trees accumulate carbon, which improves their physical conditions. Andrade-Castañeda *et al.* (2016) found that the greatest changes in SOC stock in the same area of the present study occur when changing from pasture to forest, making it possible to reduce emissions of approximately 35.8 Mg CO_2/ha.

At the farm level, the most positive change for SOC would be to change the areas dedicated to conservation to livestock production, which would generate an addition of 4.6 Gg C. However, this change should be analyzed carefully since it only considers SOC and leaves aside other important ecosystem services provided by conservation areas, such as water regulation (Jiménez *et al.*, 2019), soil improvement (Castillo-Valdez *et al.*, 2021), and all those derived from biodiversity conservation (Jullian *et al.*, 2018; Andrade *et al.*, 2018). The worst land use change would be if all conservation areas were converted to the agricultural systems found on the farm, as it would cause emissions of the order of 9.3 Gg CO_2. Policies and management strategies should create incentives so that these changes that cause CO_2 emissions to the atmosphere do not occur.

Improving carbon stock in different land uses requires the adoption of friendly practices. For example, the grassland system could increase SOC by combining plant species, which increases root biomass, reduces bulk density, and improves soil aeration and water infiltration (Gosselink *et al.*, 1984; Haddaway *et al.*, 2015; Contreras-Santos *et al.*, 2019). The agricultural system is a potential asset for carbon sequestration; in this system, crop rotation, zero tillage, incorporation of livestock manure, and efficient management oriented to carbon sequestration should prevail (Devi, 2021). The integration of practices that contribute to improving SOC stock and biodiversity is essential in the maintenance and regulation of ecosystem services (Centro de Monitoreo de la Conservación Mundial del Programa de las Naciones Unidas para el Medio Ambiente [UNEP-WCMC], 2016; Seó *et al.*, 2017; Weil & Brady, 2017; Burbano-Orjuela, 2018). Therefore, the understanding of land use changes will allow the development of strategies to reverse degradation and desertification processes and to improve soil ecosystem functions (Bolívar Gamboa *et al.*, 2021; Muñoz-Rojas *et al.*, 2021). These results provide important bases for the management of land use systems, emphasizing climate change mitigation through the capture of SOC.

Temporal dynamics of soil organic carbon. The average accumulation rate for CURDN soils ranged from 0.9 to 3.0 Mg/ha/year, relatively high values compared to the SOC sequestration rate in rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) crops in China, which ranged from 0.03 to 0.20 Mg/ha/year in treatments with chemical fertilizers and manure aggregates. In contrast, Keel *et al.* (2019) reported carbon losses at an average rate of 0.29 Mg/ha/year in different agricultural treatments in Switzerland.

Ogle *et al.* (2005) found that the transition from conventional tillage to zero tillage resulted in an increase in SOC by a factor of 1.23, i.e., an increase of 23% in humid tropical climates after 20 years of implementation. In Egypt, farming systems of clover (*Trifolium alexandrinum* L.), sugar beet (*Beta vulgaris* L.), and rice (*Oryza sativa* L.) showed increases in carbon sequestration as crop years increased. This is mainly due to agricultural practices such as the return of plant residues to the soil and the incorporation of organic matter (Keel *et al.*, 2019; Arshad *et al.*, 2020); in addition, minimum or zero tillage increases water and moisture retention, which favors microbial activity (Shen *et al.*, 2023), which may explain the increase in carbon stocks found for the agricultural systems in the present study. Agricultural management and climatic and edaphic conditions influence the dynamic processes of carbon stock (Ogle *et al.*, 2005; Keel *et al.*, 2019).

Livestock systems in tropical regions can contribute significantly to soil carbon sequestration and mitigate the effects of climate change (Gaitán *et al.*, 2016). Good pasture management, including Voisin rational grazing for livestock use, can accumulate significant amounts of SOC in deep layers (Seó *et al.*, 2017; Ayarza *et al.*, 2022). Livestock excretion provides nutrients to the soil and supplies organic matter (Oliveira *et al.*, 2022), stimulating the growth and proliferation of microorganisms that help carbon accumulation in these systems (Oliveira *et al.*, 2022; Shen *et al.*, 2023).

CONCLUSIONS

Livestock systems presented comparative advantages for SOC stock in surface layers. Land use changes alter the SOC stock, causing higher sequestration, such as when areas are converted to grasslands (under Voisin rational grazing), or strong CO2 emissions when areas are incorporated into agriculture. The analysis of the temporal dynamics of SOC also showed positive results in grassland systems under current management, causing them to incorporate SOC at a rate of 3.0 Mg/ha/year. Additional incentives should be created to encourage systems that further mitigate climate change by capturing or conserving large amounts of SOC.

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CONFLICT OF INTEREST

The manuscript was prepared and reviewed by the authors, who declare that no conflict of interest would jeopardize the validity of the results presented.

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