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Research article

Potential of silvopastoral systems for the generation of ecosystem services in an Andean landscape in Tolima, Colombia

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Abstract

Livestock production systems have a great social, economic and environmental importance. The present research seeks to estimate the potential of the generation of ecosystem services (ES) of silvopastoral systems (SPS) in an Andean landscape in the municipality of Roncesvalles, Tolima, Colombia. Two main research hypotheses were established: 1) land use systems have an impact on ES, and 2) carbon in fine roots is correlated with some edaphic variables, which in turn are indicators of ES. Some ES indicators were selected, such as soil bulk density (BD), total porosity (P), soil organic carbon (SOC) stock and fine root biomass density. Pits were made in the selected areas and samples were taken with an auger and cylinder at two depths: 0 to 10 and 10 to 20 cm to analyze them. Higher SOC stock was estimated at a depth of 10 to 20 cm, while at depth 0 to 10 cm, a higher P was found. No statistical differences ($p > 0.05$) in the carbon of fine roots between the treatments were detected, but there were greater values in the 0-10 cm depth than at 10-20 cm (20–30 and 6–8 t/ha, respectively). No statistical differences ($p > 0.05$) in the other edaphic variables were detected between systems, but significant differences ($P < 0.05$) were found between soil depths. Fine roots were found to have a positive impact on ES generation, as they improve soil quality indicators such as BD, P and SOC stock. These results show an improvement in soil conditions when establishing the SPS, which in turn generates ES.

Keywords: Bulk density, Carbon sequestration, Fine roots, Porosity, Silvopastoral systems

Introvduction

Livestock is a globally important production line, on which 1.3 billion people depend, accounting for 40 and 20% of agricultural production in developed and developing countries, respectively, and using 30% of the land (FAO, 2018). The high food demand required by the world's growing population, coupled with the increasing wealth of developing countries, will drive demand for food (Daszkiewicz, 2022). According to the National Livestock Census (ICA, 2022), there were 633,841 farms and 29,301,392 animals in Colombia, which represents an increase of 4.7% compared to the previous year.

The accelerated growth of the agricultural and livestock industry observed in recent years positions Colombia as an ideal territory to produce different crops (OECD, 2015). The country has the fourth-largest livestock herd in the Americas (+28 million head), and the 14th largest in the world (Parodi, 2022). However, improper livestock management causes negative impacts on the environment, such as deterioration of water resources, soil degradation, greenhouse gas emissions and reduction of biodiversity (Caballero 2019; Gerber *et al*., 2013).

Silvopastoral systems (SPS) combine woody perennial species with herbaceous forages and animals under an integrated management system. SPS offer benefits such as improvement in forage production, soil water storage and animal welfare and increased carbon sequestration; however, they face some main barriers: high initial costs, competition between trees and grass, and regulatory and knowledge gaps for adoption (Poudel *et al*., 2024). These systems could be considered as a nature-based solution (NbS) to address the challenges of modern agriculture (de Faccio Carvalho *et al*., 2024). In this context, FAO (2016) recommends establishing policies based on incentives associated with environmental criteria that stimulate the protection and restoration of soils through payment models for environmental services (ES) or ecosystem services in SPS, and their linkage to mechanisms to promote compliance with environmental standards. This paper uses indicators of physical and chemical soil improvements and climate change mitigation.

According to IDEAM (2015), approximately 15 million hectares (13.3% of the total area) of the country has soils with livestock vocation, of which more than 5 million have degradation processes associated with land use change, overgrazing and poor management. In Colombia, research on the impact of SPS has increased in recent decades, focusing on the improvement of animal production, economic income of producers and beneficial impacts on the soil (Céspedes and Vargas, 2021; Ruiz, 2022; Buitrago *et al*., 2018; Contreras *et al*., 2019). However, there are still gaps in the knowledge of the impact of SPS on the generation of ecosystem services (ES). Similarly, little is known about the impact of fine roots on the generation of ES in these land use systems.

The results of this research will improve our understanding of the environmental impact of SPS and the role of fine roots, to promote them as an option for modernizing livestock farming in the department.

Materials and Methods

Study area: The research was carried out in the Cucuanita and El Paraíso micro-watersheds of the municipality of Roncesvalles, department of Tolima, located in the middle part of the eastern margin of the Andean Central Cordillera of Colombia (4°01′552″–4°04′210″N and 75°38′454–75°42′18″W). This municipality is at an average altitude of 2640 m, has a total of 6331 inhabitants and an average temperature of 12°C on a high plateau, with moderate to strongly undulating topography (Gobernación del Tolima, 2015). This life zone corresponds to a humid high Andean forest with a rainfall of 2000 to 3500 mm/year with a bimodal regime presenting the rainy season in March-May and September-November and a dry season in December–February and June–August.

Farm selection: Farms were selected from producers interested in participating in the research and having at least one of the land use systems to be worked: 1) conventional semi-intensive livestock farming with high demand of chemical inputs with use of SPS (HOLIC), 2) organic semi-intensive livestock farming with low demand of chemical inputs with use of SPS (LOLIC), 3) extensive livestock farming without trees (ECM) and 4) forests (F). Five replicates were selected for each land use system, which were selected to ensure that they were representative.

The characteristics of each of the production systems studied are presented. HOLIC: systems with a high load of manure, chemical fertilizers and management of SPS. LOLIC: systems that employ minimal use of chemical fertilizers and promote the use of organic fertilizers in areas that implement SPS. ECM: areas dedicated to grazing with large areas without SPS where cattle are extensively managed. F: native wooded areas with minimal or no anthropic intervention adjacent to grazing areas and belonging to the land of the farms evaluated. The stocking rate was 1.2 and 0.8 animal units/ha for SPS and ECM, respectively. These systems manage animals of the same size. All plots had a minimal area of 0.5 ha. The systems were dominated by *Pennisetum clandestinum*, *Lolium multiflorum* and *Holcus lanatus*; whereas the most abundant tree species were *Weinmannia tomentosa*, *Juglans neotropica*, *Quercus humboldtii*, *Alnus acuminata*, *Myrcianthes leucoxyla* and *Baccharis latifolia*.

Analysis of soil properties: In each repetition, soil samples were taken at two depths: 0 to 10 and 10 to 20 cm. Bulk density (DB), total porosity (P), soil organic carbon (SOC) stock and carbon in biomass of fine roots were analyzed. The sampling was carried out once at the beginning of the rainy season to reduce its effects on treatments.

Bulk density (DB): This soil property was estimated with the cylinder method of known volume (98.2 cm^3) in two pits per replicate, according to the recommendations of Andrade and Ibrahim (2003). Samples were taken at the two depths mentioned above. From each cylinder, the sample was extracted and analyzed by drying it to constant weight (105ºC) at Laboratorio de Fisiología Vegetal de la Universidad del Tolima.

Total porosity (P): Total porosity was estimated from the BD and real density (RD) values of the soils, using the following equation. RD was estimated with the use of the pycnometer technique at laboratory.

$$P = \left(1 - \frac{BD}{RD}\right) * 100 \qquad \text{Equation 1}$$

Where; P: Total porosity (%); BD: Bulk density (g/cm^3); RD: Real density (g/cm^3)

Soil organic carbon (SOC): SOC stock was estimated considering BD, SOC concentration and depth (0-10 and 10-20 cm), following recommendations from Andrade and Ibrahim (2003). The proportion of coarse soil fragments (diameter > 2 mm) was not considered, due to the fact observed in sampling that this variable was less than 5% in volume. The SOC concentration was estimated by taking a composed sample, consisting of 10 subsamples taken with a helical auger, for each repetition. These samples were analyzed by the method of Walkley and Black (1934) at the Laserex Laboratory of the Universidad del Tolima.

$$SOC = SOCc * BD * D * (1-CF) \qquad \text{Equation 2}$$

Where: SOC: Soil organic carbon stock (t/ha); SOCc: Soil organic carbon concentration (%); BD: Bulk density (g/cm^3); D: Soil depth (cm); CF: Coarse soil fraction

Carbon in fine roots: Five soil samples were taken per replicate with a 98.2 cm^3 cylinder auger, per replicate. The first sample was taken at the base of a tree, the second at the crown edge and the other three in the open pasture, away from the tree canopy. In the ECM and F, the samples were selected randomly. Sampling was carried out at the same two depths: 0 to 10 and 10 to 20 cm.

The samples were washed to separate the fine roots from soil, passing the samples through meshes with sieves of different widths (0.5 and 1 mm) and pressurized water in the Laboratorio de Fisiología Vegetal de la Universidad del Tolima. Fine roots (less than 2.0 mm in diameter) were selected and dried to constant weight at 65°C, following the methodology employed by Andrade *et al.* (2008). The dry samples were weighed on an analytical balance (0.01 g accuracy) to estimate biomass, then converted to carbon using a fraction of 0.47 (IPCC, 2003).

Impact of land use change on SOC: A simulation of the potential impact of land use changes on SOC stock and its implications for carbon sequestration or CO_2 emissions was carried out. In this case, the SOC stock of all systems was estimated using the estimated average BD in the forest; in other words, SOC was estimated by soil mass instead of soil volume. In this case, the SOC stock was estimated with the lowest BD (forests) for all treatments. The change in SOC was estimated as the difference between the SOC stock from future use and the current use. SOC values were converted to CO_2 by multiplying by 3.67.

Statistical analysis: An analysis of variance and a Fisher's mean comparison test were performed with a significance of $\alpha = 0.05$. These analyses were carried out after checking the normality of the data with a Shapiro-Wilks test. Variables that were not normal were transformed to achieve normality. Correlation and linear regression analyses were performed between fine root carbon and BD, P and SOC stock at the two depths to estimate the impact of fine roots on SE supply. Statistical analyses were performed in Infostat software.

Results and Discussion

Bulk density (BD): Statistical differences ($p<0.05$) in BD were detected between depths, being 41% higher at 10-20 cm than at 0 to 10 cm (0.62 *vs* 0.44 g/cm^3, respectively). At 0 to 10 cm, only statistical differences ($p<0.05$) were found between systems F and HOLIC-LOLIC (0.32 and 0.45 to 0.56 g/cm^3, respectively). In contrast, at 10 to 20 cm, no significant differences ($p>0.05$) were detected between the land use systems (Fig 1) in this variable, although it is observed that the LOLIC system outperformed the other systems by 39% (Fig 1).

Despite no significant differences ($p>0.05$) in BD between treatments, F tended to have the lowest BD, which is a valuable indicator of soil health (0.32 g/cm^3). However, livestock systems did not have a negative impact on this indicator, as they did not cause an increase, which leads to soil compaction, as stated in other studies (Abarca *et al*, 2018; Simon *et al*, 2022). According to Molina Benavides and Sánchez Guerrero (2017), the BD in cattle ranching with different densities of trees and forests in high mountain landscapes in Valle del Cauca, Colombia, was similar, indicating low impact of cattle ranching in these systems. Contreras *et al*. (2020) state that the positive effects of SPS on soil are observed in slightly deeper layers (20 and 30 cm). Other authors have claimed that SPS improve soil properties, such as reductions in penetration resistance (Buitrago *et al*., 2018), mainly at layers beyond 20 cm depth. This property is highly related to BD.

Total porosity (P): At the 0 to 10 cm depth, porosity was significantly higher ($p<0.05$) than at 10 to 20 cm, exceeding it by about 9% (74.3–85.2 vs. 66.0–76.6%, respectively). Although no statistical differences ($p>0.05$) were detected among systems at both depths, F at 0 to 10 cm showed slightly higher porosity, exceeding that found in ECM, HOLIC and LOLIC by 3, 8 and 15% (85.2 *vs* 82.5 *vs* 78.6 and 74.3%, respectively). This trend varied somewhat between 10 and 20 cm, with ECM showing the tendency to have the highest values, followed by F, HOLIC and LOLIC (76.7 *vs* 76.6 *vs* 73.9 *vs* 66.0%, respectively) (Fig 2). In general, P was 74% higher at 0 to 10 than at 10 to 20 cm. Contreras *et al.* (2021) state that good aeration quality and low compaction are observed when the P

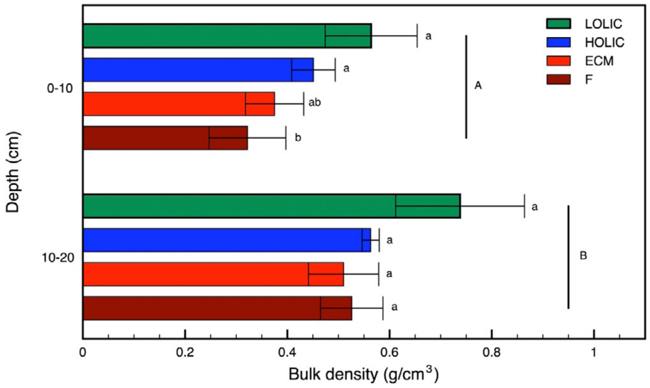

Fig 1. Bulk density in the treatments of forest (F), semi-intensive organic or low chemical input demand livestock with SPS (LOLIC), semi-intensive conventional livestock with high chemical input demand with SPS (HOLIC) and extensive livestock without trees (ECM) on cattle farms in Roncesvalles, Tolima, Colombia [Error bars correspond to standard error and different lowercase letters indicate statistical differences ($p<0.05$) between systems at the same depth. Different uppercase letters indicate statistical differences ($p<0.05$) between depths].

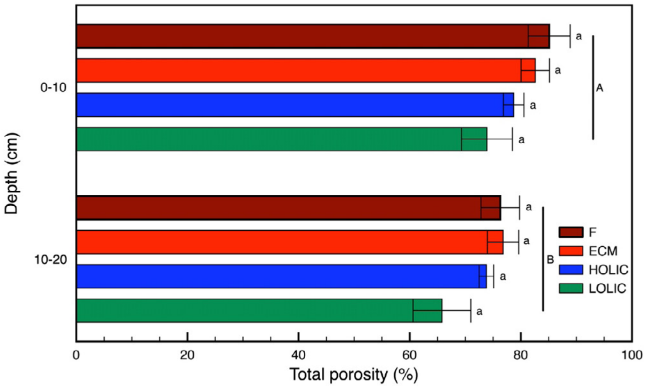

Fig 2. Total porosity in the treatments of forest (F), semi-intensive organic or low chemical inputs with SPS (LOLIC), semi-intensive conventional livestock with high chemical inputs with SPS (HOLIC) and extensive livestock without trees (ECM) in cattle farms in Roncesvalles, Tolima, Colombia [Error bars correspond to standard error and different lowercase letters indicate statistical differences ($p <0.05$) between systems at the same depth. Different uppercase letters indicate statistical differences ($p <0.05$) between depths]

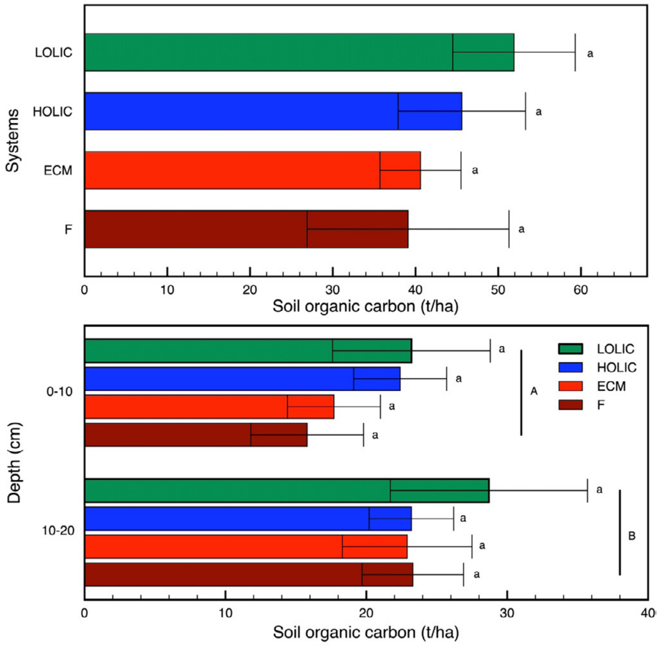

Fig 3. Soil organic carbon stock in the treatments of forest (F), semi-intensive organic or low chemical input demand livestock with SPS (LOLIC), semi-intensive conventional livestock with high chemical input demand with SPS (HOLIC) and extensive livestock without trees (ECM) in livestock farms in Roncesvalles, Tolima, Colombia [Error bars correspond to standard error and different lowercase letters indicate statistical differences ($p <0.05$) between systems at the same depth. Different uppercase letters indicate statistical differences ($p <0.05$) between depths]

percentage is higher than 50%; lower values indicate low oxygen diffusion, low infiltration, and high surface runoff. Porosity is an indicator variable of soil quality, although high BD values reduce methane emission into the atmosphere (Espinosa *et al*,, 2020). In line with these results, Molina Benavides and Sánchez Guerrero (2017) affirm that low stocking rates and organic matter input mitigate the negative changes that livestock farming could have on BD and porosity.

Soil organic carbon (SOC): No statistical differences ($p >0.05$) were detected between systems at the two depths (Fig 3); however, SOC stock in the LOLIC system exceeded HOLIC, ECm and F by 14, 28 and 33% (51.9 vs. 45.6 vs. 40.6 vs. 39.1 t C/ha, respectively). These values considered the BD of each land use, i.e., they were estimated based on a different soil volume for each use. The depth with the highest SOC stock was 10 to 20 cm ($p <0.05$) (Fig 3).

At depths of 10 to 20 cm, SOC stock was 24% higher than that found at 0 to 10 cm (24.5 *vs* 19.8 t C/ha, respectively). From 0 to 10 cm, the descending order in SOC stock was: HOLIC, LOLIC, ECM and F (22.2 *vs* 21.5 *vs* 17.5 *vs* 15.7 t/ha, respectively); the order changed at 10 to 20 cm: LOLIC, F, HOLIC and ECM (27.8 *vs* 23.3 *vs* 23.0 *vs* 22.3 t/ha, respectively) (Fig 3). Despite not detecting statistical differences ($p >0.05$) between systems, the fact that LOLIC presented a SOC stock that surpassed 24% that presented in the other systems (28.7 *vs*. 23.3 *vs*. 22.9 *vs*. 22.9 t C/ha, respectively), stands out (Fig 3).

In all management systems, SOC stock was estimated to be higher at a depth of 10 to 20 cm. In this study, SPS were estimated to contain more SOC than treeless livestock (ECM) and natural forests with no statistical differences ($p >0.05$). These results agree with those reported by Contreras *et al*. (2020), who state that SPS stored more SOC than traditional livestock grazing without trees (60.6 and 65.1 *vs*. 38.3 t C/ha). This is possibly due to tree diversity and composition of fine roots, contributing to higher atmospheric organic carbon capture. However, these results should be viewed with caution, as they are estimates based on the BD of each land use, which leads to calculations based on volume and not soil mass, as recommended by several authors (Chamba, 2024; De la Cruz, 2022; Allauca and Ayala, 2021). It is also important to consider capturing carbon in other components and other ecosystem services provided by forests (Andrade *et al*., 2014).

In the present study, no statistical effect ($p >0.05$) of land use systems on fine root carbon was found. However, greater fine root accumulation was observed in the 0 to 10 cm depth than in the 10 to 20 cm (20–40 and 6–8 t/ha respectively), which agree with the findings of Contreras *et al*. (2020), who observed that as depth increases, fine root biomass decreases in all treatments, especially in the treeless pasture with no significant differences ($p >0.05$). However, in SPS, even at soil depths of 20 and 30 cm, abundant fine roots were found, which may be due to the penetration capacity of primary roots, which in turn explains the higher SOC at 10 to 20 cm (Acevedo and Arévalo 2020; Andrade *et al* 2013; De la Cruz, 2022; De la Cruz, 2023).

When estimating SOC stock with the same soil mass and simulating land use changes, forests are the best performers in SOC capture. Deforestation and conversion to livestock systems would cause emissions of 2.9 to 20.2 t CO_2/ha, which would contribute to increasing global climate change (Zuluaga, 2020; Pérez *et al*, 2023; Galeas, 2020). Extensive livestock farming (ECM) also proved to be an important system for mitigating climate change as it is the system with the highest SOC stock, which is consistent with the findings of other authors (Andrade *et al*., 2013; Abril *et al*., 2023). This underlines the importance of well-managed livestock production systems to generate ES.

According to FAO (2024), the lack of incentives to improve management practices and the current difficulty in accurately monitoring stock and SOC changes are some of the reasons for not being included in the Paris Agreement climate plans, so local analyses will contribute to strengthening research material on SOC and rangelands.

Carbon in fine root biomass and its impact on SE: No statistical differences (p >0.05) were detected in fine root carbon between treatments at the two depths. However, at 0 to 10 cm there was almost four times more fine root carbon than at 10 to 20 cm (26.0 *vs.* 6.9 t C/ha, respectively) (Fig 4). The HOLIC system presented a tendency to have higher carbon in fine roots from 0 to 20 cm, which was 2, 6 and 28% greater than that found in F, ECM and LOLIC (75.5 *vs* 74.0 *vs* 71.0 *vs* 58.9 t C/ha, respectively) (Fig 4).

In all cases, it is observed that carbon in fine root biomass has a positive impact on SE supply at both depths (Fig 5). That is, increasing carbon in this component increases the SE supply from reduced BD and increased P and SOC concentration. Models were developed that predict SE indicator variables with better fit at depths of 0 to 10 cm than at 10 to 20 cm ($0.85 < R^2 < 0.92$ vs. $0.57 < R^2 < 0.72$, respectively) (Fig 5). The steeper the slope (negative or positive) of the estimated line, the greater the impact of fine roots on these ES indicators. Forests present the best edaphic SE indicators; however, livestock systems are not dramatically affecting these indicators (Fig 5).

Fine roots are important for plant growth and soil health due to their importance in acquiring water and nutrients (Strand *et al*., 2008), improving soil biological activity (Campos *et al*., 2017; McCormack *et al*., 2017) and carbon capture (Andrade *et al*., 2008). This variable can be used as an indicator of the supply of ES (Freschet *et al* 2021). SPS can enhance agro-ecosystem sustainability (de Faccio Carvalho *et al.* 2024), which can be monitored by fine roots. Bieluczyk *et al.* (2024) argued that integrated pasture systems increased fine root production and turnover, which implies a faster recycling of nutrients from fine roots.

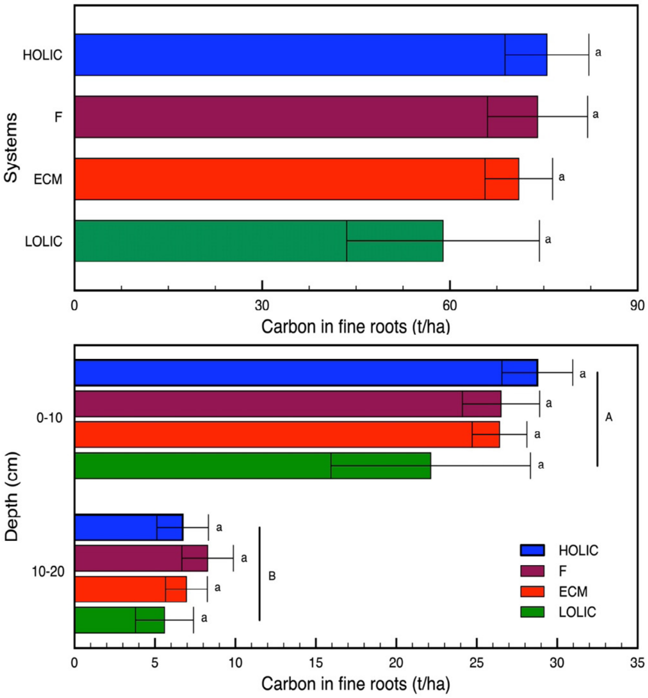

Fig 4. Carbon in fine root biomass in the treatments of forest (F), semi-intensive organic or low chemical input demand livestock with SPS (LOLIC), semi-intensive conventional livestock with high chemical input demand with SPS (HOLIC) and extensive cattle ranching without trees (ECM) in cattle farms in Roncesvalles, Tolima, Colombia [Error bars correspond to standard error and different lowercase letters indicate statistical differences (p <0.05) between systems at each depth. Different uppercase letters (P<0.05) indicate statistical differences between depths.

***Impact of land use change on SOC*:** The simulation of the impact of land use change on SOC capture or CO_2 emission yielded contrasting results. Deforestation would cause large emissions, so these values would be between 2.9 and 20.2 t CO_2/ha if these areas were converted to ECM or LOLIC, respectively (Fig 6). Changing ECM to either form of intensive livestock farming would also cause emissions in the order of 0.7 to 17.2 t CO_2/ha (Fig 6). Promoting natural regeneration, i.e., switching from pasture to forest, would capture SOC in the order of 0.8 to 5.5 t C/ha (Fig 6).

Estimates of potential change of SOC stock due to land use change are a strategy for estimating mitigation or carbon additionality of improved practices (Black *et al* 2021). In any case, F contains the largest amount of SOC, which is why projects of Reducing Emissions from Deforestation and Forest Degradation (REDD+) seek to conserve them so that they do not emit CO_2 (Zambrano-Cortés and Behagel, 2023). Livestock systems with high levels of SOC are also important to conserve that carbon, so that they do not contribute more emissions to the atmosphere (Carvajal-Agudelo and Andrade, 2020; Andrade *et al*., 2024).

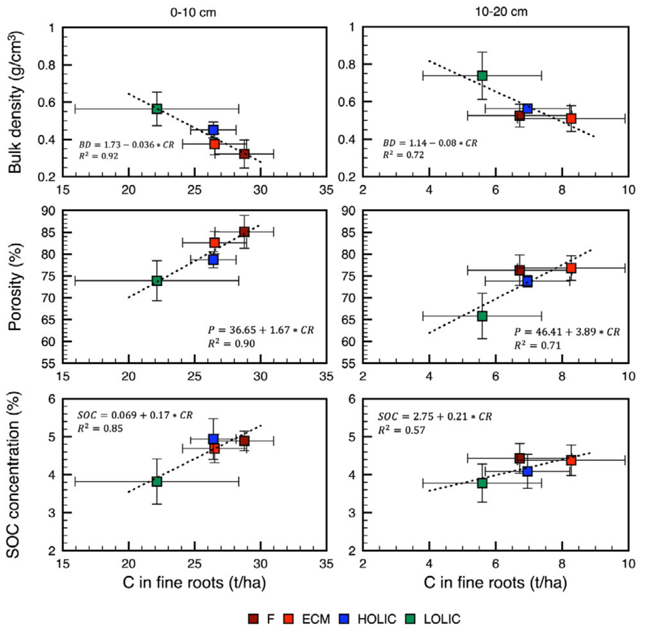

Fig 5. Relationship between carbon in fine roots and indicator variables of ecosystem services in forest (F), semi-intensive organic or low chemical input demand livestock with SPS (LOLIC), semi-intensive conventional livestock with high chemical input demand with SPS (HOLIC) and extensive cattle ranching without trees (ECM) in cattle farms in Roncesvalles, Tolima, Colombia [Error bars correspond to standard error. Dotted lines represent the linear models to estimate the variables of ES as a function of carbon in fine roots. R^2: coefficient of determination]

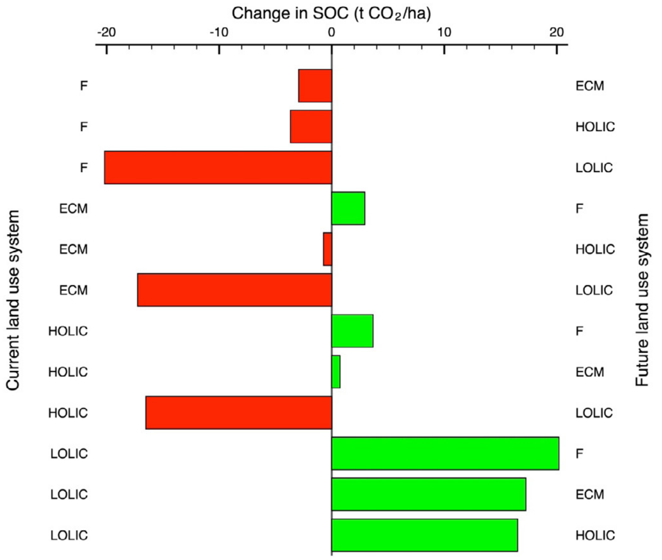

Fig 6. Impact of land use change on soil organic carbon (SOC) stock forest (F), semi-intensive organic or low chemical input demand livestock with silvopastoral systems (SPS) (LOLIC), semi-intensive conventional livestock with high chemical input demand with SPS (HOLIC) and extensive cattle ranching without trees (ECM) in cattle farms in Roncesvalles, Tolima, Colombia [Red bars indicate SOC losses, *i.e.* CO_2 emission, while green bars refer to SOC gains or carbon additionality]

Conclusion

Forests had the lowest bulk density, which is a valuable indicator of soil health; however, livestock systems did not have a negative impact on increasing this soil variable significantly. A similar situation was observed for total porosity. This contradicts the arguments about soil degradation often attributed to livestock farming.

Livestock systems have high densities of carbon in fine roots, mainly in their upper layers, at the level of what is found in forests. This demonstrates the dynamics of soil organic carbon and probably other nutrients necessary for healthy ecosystems and production systems. Forests are important stores of soil organic carbon, which should be encouraged through incentives.

Livestock systems, mainly using SPS, are presented as an option to reduce or mitigate the negative impacts of traditional livestock farming without trees.

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