



Carbon balance in dairy cattle silvopastoral production systems in Colombia's Andean-Amazon region

Henry Mavisoy[✉] · Adrian Rolando Riascos Vallejos[✉] · Edwin Castro Rincón[✉] · Juan Pablo Narváez-Herrera[✉] · Lorieth Rosas · Adriana del Socorro Guerra Acosta[✉] · Adrián Antonio Riascos Salcedo[✉] · Disney Magali Aguillon Alban · Carlos Chingal · David Fanguero[✉] · André M. de Almeida[✉]

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Abstract Silvopastoral systems (SPS) are recognized for their potential to sequester carbon (C) and mitigate greenhouse gas (GHG) emissions in livestock production. However, the extent to which small-scale dairy farms in the Andean region can offset emissions through SPS remains unclear. This study assessed the C capture of SPS to mitigate greenhouse gas emissions in small-scale dairy farms in Colombia's Andean-Amazon region. The average annual carbon increment (AACI) in living biomass (above and below ground) was evaluated in woodlots (WL), live fences (LF), and topsoil of pastures (TP) at plot and farm levels. The carbon footprint (CFP) was calculated using a cradle-to-gate

approach with biophysical allocation for fat and protein corrected milk (FPCM) and expressed per product ($\text{MgCO}_2\text{-eq MgFPCM}^{-1}$) and area ($\text{MgCO}_2\text{-eq}\cdot\text{yr}^{-1}\text{ ha}^{-1}$) across 30 farms categorized by high, medium, and low SPS coverage. At plot level, AACI values were $4.54 \pm 0.57\text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (LF), $3.20 \pm 0.61\text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (WL), and $0.24 \pm 0.08\text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (TP). At farm-level AACI was 4.43 ± 0.96 , 1.28 ± 0.41 , and $0.24 \pm 0.08\text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ for high, medium, and low SPS coverages respectively. Between 78 and 86% of AACI was attributed to *Eucalyptus globulus* (LF). CFP per product averaged $1.24 \pm 0.16\text{ MgCO}_2\text{-eq MgFPCM}^{-1}$. Total emissions per farm averaged $28.27 \pm 2.58\text{ MgCO}_2\text{-eq}\cdot\text{yr}^{-1}$ and per area $3.35 \pm 0.32\text{ MgCO}_2\text{-eq}\cdot\text{yr}^{-1}\text{ ha}^{-1}$, with no differences across SPS coverages. Carbon balance was negative regardless

David Fanguero and André M. de Almeida have contributed equally to this work.

H. Mavisoy (✉) · D. Fanguero · A. M. de Almeida
LEAF - Linking Landscape, Environment, Agriculture and Food, School of Agriculture, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal
e-mail: karolhenry@edu.ulisboa.pt

H. Mavisoy · A. R. R. Vallejos · J. P. Narváez-Herrera · L. Rosas
Centro Agroforestal y Acuícola Arapaima, Servicio Nacional de Aprendizaje SENA, 861020 Puerto Asís, Putumayo, Colombia

E. C. Rincón
Corporación Colombiana de Investigación Agropecuaria Agrosavia, Centro de Investigación Obonuco, Pasto, Nariño, Colombia

A. del Socorro Guerra Acosta · A. A. R. Salcedo
Instituto Tecnológico del Putumayo ITP 861040, Programa Ingeniería Ambiental, Sede Sibundoy – Ampliación Colón Putumayo, Sibundoy, Colombia

D. M. A. Alban · C. Chingal
Fundación Sachamates, 861020 Sibundoy, Putumayo, Colombia

D. Fanguero · A. M. de Almeida
Associated Laboratory TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal

of SPS coverage. The mitigation potential of SPS were 63%, 26%, and 4% for high, medium, and low SPS coverage. The required area to offset emissions ranged from 11.5 ha⁻¹ considering the soil AACI to 1.2–10.2 ha⁻¹ based on the AACI of SPS. Small dairy farms (9.11 ± 0.75 ha⁻¹) in the Andean-Amazon region can mitigate total emissions using a SPS coverage over 13% together with optimized feeding practices, lactation and weaning periods.

Keywords Agroforestry · Climate change · Ecosystem services · Greenhouse gases emissions mitigation · Low carbon livestock

Abbreviations

AACI	Annual average carbon increment
CFP	Carbon footprint
FPCM	Fat and protein corrected milk
GHGE	Greenhouse gas emissions
LAB	Living above-ground biomass
LBG	Living belowground biomass
LCA	Life Cycle Assessment
SPS	Silvopastoral systems
WLs	Woodlots
LFs	Live fences
Ac	<i>Alnus acuminata</i>
Am	<i>Acacia melanoxylum</i>
Eg	<i>Eucalyptus globulus</i>
Fch	<i>Fraxinus chinensis</i>
Pr	<i>Pinus radiata</i>
Sh	<i>Salix humboldtiana</i>

Introduction

The farm to market component of the global supply chain contributes with $2.7 \pm 0.4\%$ of global human-induced greenhouse gas emissions (GHGE), with 80–90% of these emissions occurring at the farm level (Gerber et al. 2010). Latin America and the Caribbean (LAC) accounts for 28% of the world's cattle inventory (FAO 2022), 23% of global beef production, and 11% of milk production (OECD & FAO 2022). Of the 8.1 gigatons of CO₂-equivalent (Gt CO₂eq) emitted globally by livestock, 1.9 Gt CO₂eq comes from the LAC region, largely due to specialized beef production, making it the highest-emitting region in the world (Singaravadivelan et al. 2023). In response to these challenges and following the

United Nations Conference on Climate Changes in 2007, several South American nations (Colombia, Costa Rica, Guatemala, Honduras, and Mexico) have promoted Nationally Appropriate Mitigation Actions (NAMAs) specific to the cattle production sector on a national scale (FAO 2023). These initiatives aim to achieve sustainable production, reduce the GHGE, and enhance carbon sequestration through the management practices such as rotational systems, pasture improvement, and the implementation of silvopastoral systems (SPS). However, despite these efforts, measurement, reporting, and verification (MRV) of trees population used in agroforestry is poorly characterized (Rosenstock et al. 2019), hindering the promotion of targeted mitigation strategies such as carbon sequestration and their contribution to reduce carbon footprint, particularly on small scale dairy farms.

The environmental costs of dairy production systems have been extensively studied using standardized Life Cycle Assessment (LCA) methodologies allowing the evaluation of the carbon footprint (CFT) as CO₂-eq per functional unit (FU) of fat and protein corrected milk (kg FPCM) or per area (ha). Globally, the average milk CFT in 2015 was estimated to be 2.5 kgCO₂-eq kgFPCM⁻¹ (FAO & GDP 2018). There is a consensus on a reverse relation between milk yields and carbon footprint at the farm level. Indeed, farms with high-yield cows tend to have lower carbon footprints, applicable across grazing-based, semi-grazing, and zero-grazing systems in different regions (Gerber et al. 2011; Lorenz et al. 2019; Mazzetto et al. 2022; Velarde-Guillén et al. 2022). In tropical regions, dairy production systems are primarily pasture-based with low input and productivity. However, these systems are often located within agricultural landscapes with tree coverage that can vary between 5 and 80% and represent carbon stocks ranging from 6 to 274 Mg-C-ha⁻¹ (Zomer et al. 2016). A small number of studies have conducted integrated life cycle assessments that account for both farm emissions and carbon sequestration from trees and soil (Schettini et al. 2021; Brook et al. 2022; Andrade et al. 2024). Such integrated approaches are very useful, as they identify the technological factors needed to optimize productivity, while determining also the levels of silvopastoral cover required to balance emissions and carbon fixation.

Determining the minimal area of silvopastoral coverage necessary to mitigate the carbon

footprint is essential for rural planning, particularly in countries that have adopted NAMAs and actively promote the adoption of silvopastoral systems. The balance between carbon sequestration from silvopastoral biomass and emissions from dairy farms has seldom been studied, particularly in tropical regions. Carbon stocks and sequestration in SPS through the annual average carbon increment (AACI) in aboveground biomass are widely variable, depending on the complexity of its structure, that is, tree density, basal area, height, and tree diversity (Soto-Pinto et al. 2010; Feliciano et al. 2018a, b). These characteristics can significantly influence the potential of SPS to offset GHGE from dairy farms. In Costa Rica, for instance, carbon footprint per area (CFP) can be offset by 21–37% with 30% SPS coverage on the farm, mainly by planting live fences of native tree species (*Erythrina* spp., *Trichanthera gigantea*, and *Gliricidia sepium*) (Brook et al. 2022). In contrast, in Brazil, the offset potential can exceed emissions, generating carbon surpluses, with 58% coverage in SPS with exotic species, such as *Eucalyptus grandis* × *Eucalyptus urophylla* in a system where the mitigation potential can reach values as high as 131% (Schettini et al. 2021).

This study aims to evaluate the annual average carbon sequestration in the living biomass of live fences, woodlots, and topsoil (0–30 cm deep) at plot level, as well as the contribution of these components of silvopastoral systems to offsetting the carbon footprint of small dairy farms in the Andean-Amazon transition region, which are representative of the diverse agroecological conditions found in the tropical Andes. The analysis identifies the land area and specific attributes of silvopastoral systems required to achieve carbon-neutral dairy production systems (where emissions and removals are balanced). The study also considers the impact of the heterogeneity in species composition (native vs. exotic) and silvopastoral configurations, including live fences, scattered trees, fodder banks, intensive silvopastoral systems and fallows. Additionally, this study highlights key aspects for mitigating the carbon footprint, considering both per area unit and per product unit. We discuss the technological and ecological aspects that should be considered to promote carbon footprint reduction through silvopastoral systems in small dairy farms in the Andean-Amazon

region, which can serve as a reference for other tropical regions.

Materials and methods

Study location

This research was conducted on the southwestern dairy chain of Colombia located at the Andean-Amazon transition region, more, specifically in the subregion of the Sibundoy Valley (9482 ha, 2000 m above sea level—m.a.s.l), in the flatlands of the Sibundoy (−76° 54′ 58.72″ W, 1° 10′ 59.39″ N) and San Francisco (−76° 56′ 38.45″ W, 1° 9′ 22.10″ N) municipalities. Soils are predominantly Inceptisols and Histosols, with precipitation ranging between 1000 and 1500 mm per year, and an average annual temperature of 15.5 °C (INCODER & IGAC, 2015). The climate is temperate mesothermal with no dry season and classified as Cf according to the Köppen classification (Kottek et al. 2006). According to ICA, (2022), UPRA, (2021), SAGAN, (2024), and (Maviso et al. 2025) this subregion has a variable herd size of $16,054 \pm 385$ heads (2018–2021), 97% of which is dedicated to specialized dairy production. The predominant breeds are creole Holstein, Jersey, and Brown Swiss, with smaller proportions of Girolando and unspecified crossbreeds. Reported daily milk production in the Sibundoy Valley subregion in 2023 was 25,766 L/day from 1,299 dairy farms, 85% of which were small farms with areas under 10 ha, these farms average a herd size of 14 head (50% lactating cows), achieving an average yield of 3,786 L/ha/year.

Network of farms and sampling plots

We established a network of 30 farms classified into high, medium, and low silvopastoral system coverage, with 10 farms in each category. The main characteristics of the dairy farms are detailed in Fig. 1. Initially, we identified dairy farmers' perceptions regarding the presence of trees on their farms, followed by field verification with each owner to determine the total farm area and the area occupied by silvopastoral systems. Farm area and SPS coverage were obtained using satellite imagery. The percentage of SPS coverage was calculated as the relative proportion between the total farm area and the area occupied by SPS.



Fig. 1 Representation of the main dairy farming systems based on silvopastoral coverage on the farm and predominant breeds. Holstein x Jersey cows with low silvopastoral coverage (A), Creole Holstein cows with intermediate silvopastoral

coverage and supplementation with salt and concentrate during milking (B), and Creole Holstein cows with high silvopastoral coverage (C) on farms in the Sibundoy Valley, Andean-Amazon region of Colombia

To carry out these procedures, we selected a study population of 95 farmers affiliated to two organizations: the *Asociación Agroambiental de Productores de Leche del Valle de Sibundoy (ASOVALLE)* in the Municipality of Sibundoy ($n=35$) and the *Asociación de Productores de Leche del Valle de Sibundoy (ASOPROLVAL)* in the Municipality of San Francisco ($n=60$), Department of Putumayo. Perceptions of SPS coverage levels on farms were obtained through a rapid diagnostic survey completed by 64 farmers (34 from ASOVALLE and 30 from ASOPROLVAL). Farmers reported the presence of three silvopastoral systems on their land: live fences (LF), woodlots (WL), and scattered trees (ST). For each system, farmers rated the coverage on their farm using a three-point scale: 3 (high: $\geq 50\%$ of the farm), 2 (intermediate: 33–50%), or 1 (low: $< 33\%$). Based on the sum of these ratings, farms were categorized into three levels of overall silvopastoral system coverage: high (7–9 points), intermediate (5–6 points), or low (1–4 points). For each coverage level, a group of 10 farmers voluntarily participated in the silvopastoral systems verification phase and the calculation of the carbon footprint through life cycle analysis. Within the 30 selected farms, silvopastoral systems were georeferenced with the assistance of the owners using a Garmin Map 65® GPS (Olathe, KS, USA). LF (live fences) were defined as linear systems with a density of 20 trees per 100 m and a minimum length of 20 m as suggested by Harvey et al. (2005) and León & Harvey. (2006), while WL (woodlots) were identified as areas larger than 1,000 m² with fast-growing planted trees used as a source of timber, where cattle benefit from shade and graze on spontaneous vegetation (Feliciano et al. 2018a, b). Since no areas

with scattered trees were identified, such system was excluded from the analysis.

To design the sampling plot network for carbon assessment in live biomass (above- and below-ground) within live fences, the following criteria were established based on adaptations of previous studies on linear plantations by Brook et al. (2022); Harvey et al. (2005); León & Harvey. (2006); Mancera et al. (2018):

- LFs were over 4 m in height and 50 m in length
- LFs must serve certain functions, such as paddock division, property boundaries, or road separation.
- If a LF within the 50 m section showed different ages, it was not considered for establishing a sample plot.
- A minimum distance of 50 m was allowed between plots.

To determine the area of the systems and the farms, we used the Bing Satellite extension in QGIS 3.34 Pizren and Google Earth® (up to November 2023). The LF area was estimated based on the length of each LF and the average crown width, calculated as the mean of the major and minor crown diameters of trees within the sample plots, as suggested by Brook et al. (2022) and León & Harvey (2006). SPS coverage was calculated as the SPS area-to-farm area ratio. Farms were categorized by SPS coverage as high (7–16%), medium (2–6.9%), and low ($> 2\%$), with 10 farms per level. For more detailed information regarding obtaining the silvopastoral coverage within each system and farm type, as well as the technological characteristics of the studied farms, kindly refer to our companion paper (Mavisoy et al. 2025).

Sampling approach was designed to capture the diversity and variability of silvopastoral systems arrangements across the three levels of coverage on farms. While the management practices for these systems were determined by the farm owners, the data collected represents the variability within the established plot network rather than adhering to a strict experimental design.

Assessment of carbon in living biomass and average annual carbon increment

We used 20-m transects for live fences and 20 m x 20 m square plots for plantations or continuous systems. To ensure that the inventory represented the heterogeneity of the systems found in each defined age range, we placed the sampling transect in the center of each system when it had a length of 50 m (minimum analysis length), two transects when the system length was up to 100 m, and three transects for systems longer than 150 m. In continuous plantations, we randomly located three subplots of 20×20 m. All individuals > 10 cm in diameter at breast height (DBH) were recorded. In the field, we recorded the common and scientific names of the species found. The total height was obtained using trigonometric calculations using an analog Suunto clinometer. We obtained structural variables such as basal area (cm²/m²) and tree density per plot (tree/plot) and extrapolated these to ha⁻¹ (tree/ha⁻¹).

Living above-ground biomass (LAB) of *Eucalyptus* and *Pinus* was estimated using allometric equations (Eq. 1 and Eq. 2) developed for Colombia by Smurfit-Kappa (2009). For other tree genera, we applied the equation (Eq. 3) developed for tropical species by Chave et al. (2014). Below-ground biomass (LBG) was estimated using Eq. (4) from Cairns et al. (1997).

$$\begin{aligned} &\text{Above ground biomass (kg), } E. globulus \\ &= 2713.4 / [1 + \exp(-(DBH - 38.5)/7.56)] \end{aligned} \quad (1)$$

$$\begin{aligned} &\text{Above ground biomass (kg), } P. radiata \\ &= 2280.9 / [1 + \exp(-(DBH - 37.7)/7.32)] \end{aligned} \quad (2)$$

$$\begin{aligned} &\text{Above ground biomass (kg) – general trees} \\ &= 0.0673(\rho \text{ DBH}^2 * H)^{0.976} \end{aligned} \quad (3)$$

Below ground biomass

$$\begin{aligned} &\text{– coarse roots (kg), general trees} \\ &= \text{EXP}(-1.805 + 0.926 \text{Ln}(\text{LAB})) \end{aligned} \quad (4)$$

where DBH is the diameter at breast height (cm), ρ is wood density (g/cm³), and H is total height (m). Wood density was obtained at the genus level from the database of Chave et al. (2009). The biomass for each plot was converted to carbon using the 0.48 factor suggested by Penman et al. (2003). The average annual carbon increment (AACI) at the system level was calculated by dividing the biomass by plot age, as reported by the farm owner. To estimate total carbon sequestration potential in C·ha⁻¹·yr⁻¹ of the living biomass at the farm level, we totaled the AACI of each system based on its specific area on each farm. We assumed that the AACI at the farm level reflected the variability of each previously characterized silvopastoral system.

The AACI in soils was obtained as an average of the 30 representative sites in pastures across farms using data from the Platform Global Soil Information System (GLOSIS) of the FAO (2024), which provides information on AACI for soils (0–30 cm deep) in different agricultural landscapes in Colombia. We discuss the limitations of soil carbon sequestration estimates due to the uncertainty associated with land use changes over time and the lack of information on long term land-use trajectories.

Greenhouse gases emission inventory

To obtain the emissions from enteric and manure CH₄ and the direct and indirect urine N₂O, we used specific Tier 2 emission factors developed for the southwestern dairy region from Colombia, which consider the genetic makeup, temperature stress, and feeding characteristics of the herd, and specific factors emissions for each pollutant as described in Table 1.

Primary information was obtained from a survey containing data on herd management, including cattle inventory categorized by sex and age, as well as calf and cow sales, feeding practices (supplementation with concentrate, salt and molasses), pasture fertilization practices (use of lime, urea, and fertilizers), and energy and fuel use (kWh and gasoline). This

Table 1 Factor emissions of CH₄, N₂O and CO₂ used in the inventory of GHG on and off farm in the LCA in dairy farms with silvopastoral systems in the Andean-Amazon region of Colombia

Pollutant	Unit	Factor emission	Reference
Herd management			
CH ₄ enteric fermentation			
High yielding cows (a)	kg·CH ₄ ·head yr ⁻¹	79.28	Moreno et al. (2021)
Replacement heifers (b)	kg·CH ₄ ·head yr ⁻¹	59.34	Moreno et al. (2021)
Preweaned calves (c)	kg·CH ₄ ·head yr ⁻¹	17	Moreno et al. (2021)
Fattening cattle (d)	kg·CH ₄ ·head yr ⁻¹	56.27	Moreno et al. (2021)
CH ₄ manure management			
High yielding cows	kg·CH ₄ ·head yr ⁻¹	6.97	Moreno et al. (2021)
Replacement heifers	kg·CH ₄ ·head yr ⁻¹	0.5	Moreno et al. (2021)
Preweaned calves	kg·CH ₄ ·head yr ⁻¹	0.18	Moreno et al. (2021)
Fattening cattle	kg·CH ₄ ·head yr ⁻¹	0.51	Moreno et al. (2021)
N ₂ O from urine and manure from grazing animals (direct)			
High yielding cows	kg·N ₂ O–N head yr ⁻¹	0.45	Torres et al. (2021)
Replacement heifers	kg·N ₂ O–N head yr ⁻¹	0.31	Torres et al. (2021)
Preweaned calves	kg·N ₂ O–N head yr ⁻¹	0.29	Torres et al. (2021)
Fattening cattle	kg·N ₂ O–N head yr ⁻¹	0.23	Torres et al., (2021)
N ₂ O from urine and manure grazing animals (indirect)			
High yielding cows	kg·N ₂ O–N head yr ⁻¹	0.2	Torres et al. (2021)
Replacement heifers	kg·N ₂ O–N head yr ⁻¹	0.13	Torres et al. (2021)
Preweaned calves	kg·N ₂ O–N head yr ⁻¹	0.06	Torres et al. (2021)
Fattening cattle	kg·N ₂ O–N head yr ⁻¹	0.14	Torres et al. (2021)
Off farm emissions			
Electricity	kg·CO ₂ eq·KWh input	0.23	UPME. (2021)
Urea	kg CO ₂ yr ⁻¹	0.2	De Klein et al. (2006)
Fuel	kg CO ₂ eq /lt	2.35	Carrasco (2015)
Lime	kg CO ₂ yr ⁻¹	0.1	ECOINVENT (2013)
Organic fertilizer	N ₂ O/kg N ₂	0.016	De Klein et al. (2006b)
	kg CH ₄ /kg	0.004	De Klein et al. (2006b)
Mineral Salt	kgCO ₂ eq kg ⁻¹ input	0.155	ECOINVENT (2013)

information was gathered based on records from the previous 12 months. We used GWP values suggested from the International Panel on Climate Change fourth assessment report (IPCC 2007) where CO₂ = 1; methane CH₄ = 25 and nitrous oxide N₂O = 298 for a 100-year time frame.

Carbon footprint calculation

For carbon footprint calculation, a life cycle analysis model “from cradle to farm gate” was set as described by the IDF (2015) following the recommendations of Mazzetto et al. (2022). Our analysis included upstream and on-farm sources as described in Fig. 2

and Table 1. The upstream resources included CO₂ from feed (mineral salt), soil management (organic fertilizer, urea and lime), fuel and energy usages. On-farms sources included enteric and manure methane, as well as direct and indirect urine, and manure N₂O.

Functional Units: The functional units used to express GHG intensities were defined as 1 kg of fat- and protein-corrected milk (FPCM) and 1 kg of beef from culled or surplus animals produced annually. The annual average milk fat and protein content was $3.8 \pm 0.18\%$ fat and $3.3 \pm 0.03\%$ protein for farms with high silvopastoral coverage, $3.9 \pm 0.14\%$ fat and $3.3 \pm 0.03\%$ protein for medium coverage, and $3.7 \pm 0.08\%$ fat and $3.3 \pm 0.02\%$ protein for

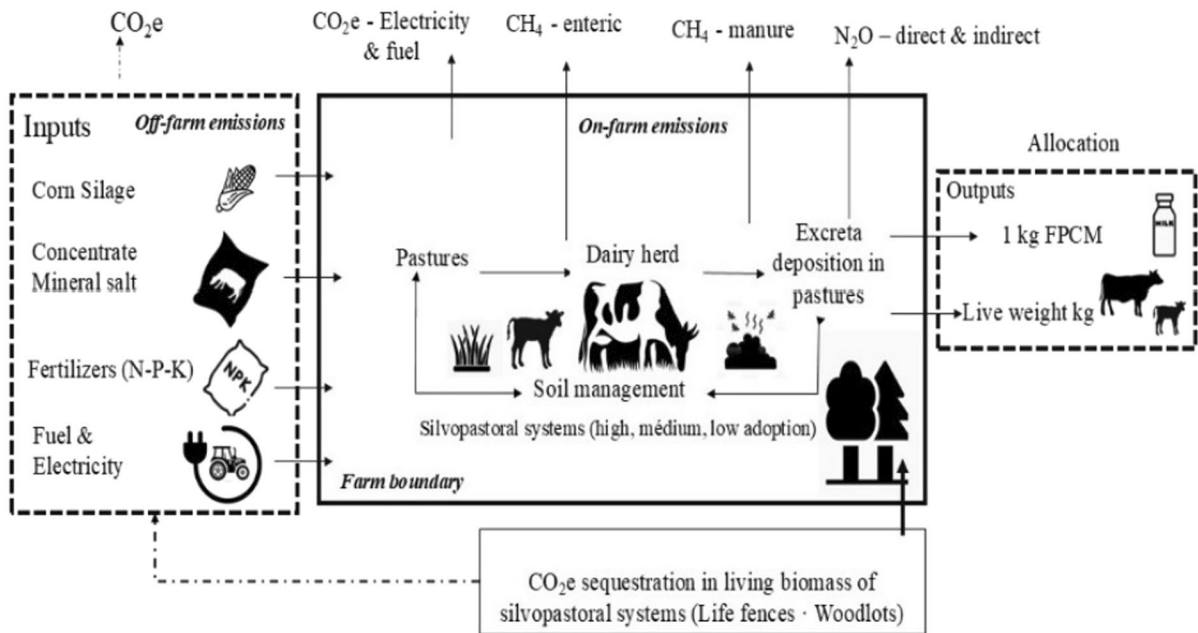


Fig. 2 Farm boundary systems used in the LCA include upstream and on-farm emissions to obtain the CFP allocated to 1-kg-FPCM and 1-kg-LW, and the sequestration of CO₂e in

the living biomass in the dairy silvopastoral systems with small cattle farmers in the Andean-Amazon Region of Colombia

low coverage. These values were obtained from monthly samples collected between November 2022 and November 2023, taken directly from milk tanks delivered to the collection center, following standard quality control practices. Analyses were conducted using a Milkotester® device (Belovo, Bulgaria). With these data, we applied the correction formula suggested by IDF (2015) $\text{FPCM (kg/year)} = \text{production (kg/year)} * [0.126 * \text{milk fat \%} + 0.0776 * \text{milk protein \%} + 0.2534]$. Milk yields on each farm were obtained from the number of lactating cows present on each farm, the daily milk productivity/cow/day and their lactation period. To obtain the live weight of the meat sold, we quantified the Animal Units (AU) that left the farm based on the equivalent of a 450 kg cow aged 3 years. One AU is equivalent to 3.3 male or female calves under 1 year old, 1.7 male or female calves aged 1 to 2 years, 1.3 heifers aged 2 to 3 years, 1.3 bulls aged 1 to 2 years, or 0.8 adult bulls, as suggested by González-Quintero et al. (2022).

Allocation: Because the study area is part of the national Colombia's dairy chain, in the highland

Region 1 (over 2000 m.a.s.l) or Andean Region, with specialized livestock farming, the main product is milk as well as calves and culled cows, therefore we used the biophysical allocation based on FPCM (Mg) and beef (Mg) from surplus animals produced per year. For this purpose, we applied the equation of Allocation factor for milk = $1 - 6.04 * \text{BMR}$ and allocation for meat = $1 - \text{milk allocation factor}$, where BMR is the ratio $\text{Mg} \cdot \text{live-weight-farm} \cdot \text{yr}^{-1} / \text{Mg} \cdot \text{FPCM} \cdot \text{farm} \cdot \text{yr}^{-1}$ as suggested by Thoma et al., (2013) and IDF (2015).

Carbon balance and scenario analysis

The carbon balance was calculated by the difference between the carbon sequestration, or the AACI of the living biomass (above and below ground) of silvopastoral systems at the farm level, and the total carbon emissions of the farm, both expressed in $\text{MgCO}_2\text{-eq} \cdot \text{yr}^{-1} \text{ ha}^{-1}$. To facilitate the carbon balance, the AACI in $\text{Mg} \cdot \text{C} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ was converted to $\text{CO}_2\text{-eq}$ at a molar ratio of 3.67, which corresponds to the molecular weight ratio of CO_2 (44 g/mol) to elemental carbon (12 g/mol), as suggested by Krug et al.,

(2006). To determine the relative mitigation potential of each farm, we quantified the proportion of C emissions offset by carbon capture from the silvopastoral systems respect to the total emissions. Additionally, we explored the neutral emissions scenarios by estimating the area and number of trees in silvopastoral systems and soil required to neutralize the 100% of the emissions generated. We also included for the scenario analysis, the annual AACI of silvopastoral systems as established by Colombia's bovine NAMA for the southwestern livestock region (CIPAV et al. 2021).

Statistical analysis

To analyze the structural aspects of SPS at the plot level (tree density and basal area), the age, and the AACI in aboveground, belowground, and for the total living biomass, we conducted a Kruskal–Wallis test with a 95% confidence interval, due to the unequal number of repetitions among groups. This method enables robust comparisons of median distributions without requiring homogeneity of variance or normality, making it suitable for non-experimental sampling and unequal sample sizes, as recommended by Di Renzo et al. (2008).

For the analysis of mean comparisons between the high, medium, and low silvopastoral coverage groups in terms of farm-level structural variables such as total farm area, percentage of silvopastoral systems coverage, total carbon uptake at the farm level, as well as the inventory of outputs (milk and beef), emissions, carbon footprint, and carbon balance, we conducted one-way ANOVA tests. When significant differences were identified, Fisher's LSD tests were performed at a 95% confidence interval. Normality and homoscedasticity of residuals were verified using Shapiro–Wilk tests ($p > 0.05$). We calculated the standard error and 95% confidence interval to quantify uncertainty associated to the means of the assessed variables.

Linear and non-linear regression analyses were conducted to evaluate the effects of milk production on CFT, the % of SPS coverage on carbon balance, and total basal area on carbon balance. Model selection was based on R^2 , statistical significance (p -value) and residual analysis (random distribution and homoscedasticity). Analyses were performed using InfoStat Software v2020 (InfoStat, Córdoba, Argentina).

Results and discussion

Carbon uptakes by soil and the SPS biomass

The AACI in soils of pastures was $0.7 \pm 0.01 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. We obtained a network of 56 temporary sampling plots from a total of 167 systems or segments identified in the 30 analyzed farms network. The mean characteristics of the silvopastoral systems and the ACCI in the above ground, belowground and the total biomass is presented in Table 2. The live fences averaged an ACCI of $4.54 \pm 0.571 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ and the woodlots $3.20 \pm 0.61 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (in average 91% in AGB and 9% in BGB). In both woodlots and live fences, the lowest AACI rates were observed in WL and LF of *A. acuminata*. The live fence of *E. globulus*, which had the highest AACI value ($6.26 \pm 0.92 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$), showed an AACI capacity eight times greater when compared to the WL and LF systems with *A. acuminata*.

Our results fall within the ranges of ACCI in silvopastoral systems in tropical contexts, which can vary between $0.21 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in tree-shaded pastures with *Leucaena leucocephala* (Montagnini et al. 2013) and $12.6 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in timber lots (Feliciano et al. 2018a, b). Our research highlights a noteworthy difference in ACCI between species of the *Eucalyptus*, *Fraxinus*, *Acacia*, and *Pinus* genera when compared to the native *Alnus* genus. Therefore, species selection in silvopastoral system directly influences carbon sequestration rates. It has been shown that, although rapid growth of exotic species like *Eucalyptus* can compete with native species, with proper management it is possible to maintain diversified systems between exotic and native species, ensuring carbon increases and restoration, allowing wood production and biodiversity conservation (Carpenter et al. 2004; Amazonas et al. 2018). Our results suggest that this approach shows high potential for small farms ($< 10 \text{ ha}^{-1}$) due to space constraints inherent to expanding silvopastoral systems areas.

Carbon uptakes at farm level

The total farm area, the proportion of silvopastoral coverage and the distribution of de ACCI at farm level in the different silvopastoral arrangements and species are described in Table 3. With $10.8 \pm 1.05\%$

Table 2 Total network of silvopastoral systems, number of sampling plots, main characteristics (age, density and basal area), and Annual Average Carbon Increment (AACI) in the aboveground biomass (AGB), belowground biomass (BGB), and total living biomass (LB) in woodlots of *A. acuminata* (WL-Aa), *E. globulus* (WL-Eg), and *F. chinensis* (WL-Fch), and live fences of *A. acuminata* (LF-Aa), *A. melanoxylum* (LF-Am), *E. globulus* (LF-Eg), *F. chinensis* (LF-Fch), *P. radiata* (LF-Pr), and *S. humboldtiana* (LF-Sh), and open pastures (OP) in dairy farms in the Sibundoy Valley, Andean Amazon Region

Parameter	Units	WL-Aa	WL-Eg	WL-Fch	LF-Aa	LF-Am	LF-Eg	LF-Fch	LF-Pr	LF-Sh
Total segments	Segments	1	2	1	25	7	108	10	5	8
Total segments	Segments	1	2	1	15	5	69	8	2	3
> 50 m length (LF) and > 1500 m ² (WL)										
Total plots assessed	Plots	3	6	3	5	3	20	8	5	3
Average age	Years	8 ^{cd} ± 0	17.0 ^{ab} ± 1.3	20.0 ^a ± 0.0	10.9 ^{bcd} ± 1.3	7.3 ^d ± 1.5	16.9 ^{abc} ± 1.9	18.6 ^{abc} ± 3.7	18.0 ^{ab} ± 2.0	12.3 ^{abc} ± 2.7
Density	tree/ha ⁻¹	766.7 ^{ab} ± 88	800 ^a ± 44	966.7 ^a ± 145	125.0 ^c ± 17	250 ^{bc} ± 38	278.7 ^{bc} ± 22	290.6 ^{bc} ± 40	250.0 ^c ± 37	116.7 ^c ± 22
Basal area	m ² /ha ⁻¹	3.1 ^c ± 0.4	15.9 ^a ± 2.3	18.7 ^a ± 3.9	6.3 ^{bc} ± 1.8	10.6 ^{abc} ± 3.6	18.9 ^a ± 2.4	14.9 ^{ab} ± 3.0	14.6 ^{abc} ± 2.9	8.5 ^{abc} ± 1.9
Average Annual Carbon Increment AACI										
AGB	Mg-C·ha ⁻¹ ·yr ⁻¹	0.68 ^c ± 0.09	3.78 ^{ab} ± 0.76	3.39 ^{ab} ± 0.77	0.75 ^c ± 0.21	5.35 ^{ab} ± 2.54	5.70 ^a ± 0.84	3.31 ^{ab} ± 0.77	2.77 ^{ab} ± 0.31	1.36 ^{bc} ± 0.14
BGB	Mg-C·ha ⁻¹ ·yr ⁻¹	0.08 ^c ± 0.01	0.38 ^{ab} ± 0.07	0.34 ^{ab} ± 0.07	0.08 ^c ± 0.02	0.55 ^{ab} ± 0.24	0.57 ^a ± 0.08	0.34 ^{ab} ± 0.08	0.29 ^{ab} ± 0.03	0.14 ^{cb} ± 0.01
LB	Mg-C·ha ⁻¹ ·yr ⁻¹	0.77 ^c ± 0.1	4.15 ^{ab} ± 0.82	3.74 ^{ab} ± 0.85	0.83 ^c ± 0.23	5.91 ^{ab} ± 2.78	6.26 ^a ± 0.92	3.65 ^{ab} ± 0.85	3.05 ^{ab} ± 0.34	1.50 ^{bc} ± 0.15

a, b, c Columns with different superscripts indicate significant differences ($p < 0.05$) according to the Kruskal–Wallis nonparametric analysis of variance

silvopastoral coverage and a total AACI rate of $4.43 \pm 0.96 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, farms with high silvopastoral coverage sequestered 18.5 times more C when compared to those with low silvopastoral coverage. At all levels, live fences of *E. globulus* accounted between 78 and 86% of the farm's carbon uptakes. The carbon uptake found in farms with high silvopastoral coverage in this study is comparable to those reported by Andrade et al., (2024), that established a carbon uptake of $6.9 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in livestock farms with SPS in Mexico, mainly consisting of pastures with trees, woody forage banks, and perennial crops.

On the other hand, our results highlight the influence of tree species and silvopastoral arrangements on carbon sequestration in specialized dairy production systems. For example, with live fences primarily consisting of native species such as *Erythrina fusca* and *Gliricidia sepium* in Costa Rica, a farm-level carbon sequestration potential of $1.43 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ was observed (Brook et al. 2022). Meanwhile, in Brazil, using alley cropping with *Eucalyptus grandis* x *Eucalyptus urophylla* in pastures, the carbon sequestration rate was $2.1 \text{ Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Schettini et al. 2021). In Costa Rica, the carbon sequestration in SPS mitigated between 27 and 34% of the carbon footprint with a silvopastoral coverage close to 30%, while in the dairy farm in Brazil, with coverage nearing 58%, a carbon surplus of 131.1% was recorded. These results

suggest that the percentage of silvopastoral coverage may be a predictor of carbon uptake and balance at the farm level. However, it is strongly influenced by tree species, making the development of specific carbon capture indicators for a given dairy-producing region crucial to providing tailored recommendations for mitigating greenhouse gases using silvopastoral systems.

The identification of the carbon accumulation rate in silvopastoral systems in livestock regions is a key aspect for analyzing the GHG mitigation at the farm level. However, it is necessary to deepen sampling schemes focused on the growth curves of tree species in different silvopastoral arrangements, incorporating aspects of species diversity and planting distances, to reduce uncertainties between farm coverage and basal area on the carbon balance. It is also necessary to create new alternatives to strengthen tree cover metrics at the farm level, especially in small properties where the coverage can be highly dynamic due to wood harvesting.

GHG emissions and carbon footprint

Farms averaged $23.8 \pm 2.9 \text{ Mg}\cdot\text{FPCM}\cdot\text{farm}\cdot\text{yr}^{-1}$ in milk yield and $0.6 \pm 0.1 \text{ Mg}\cdot\text{LW}\cdot\text{farm}\cdot\text{yr}^{-1}$ in live weight outputs. Total emissions averaged $28.3 \pm 2.6 \text{ MgCO}_2\text{-eq}\cdot\text{yr}^{-1}$ (69% enteric CH_4 , 10% soil management, 8% feed, 5% N_2O from urine and manure, and

Table 3 Total farm area, percentage of silvopastoral systems coverage and total C uptakes at farm level in the living biomass (aboveground + belowground biomass) in different silvopastoral systems and species in dairy farms in the Andean Amazon region of Colombia

	Units	Silvopastoral coverage		
		High	Medium	Low
Total farm area	ha^{-1}	$8.43^{ab} \pm 0.79$	$7.43^b \pm 0.6$	$11.48^a \pm 1.87$
% SPS coverage	%	$10.8^a \pm 1.05$	$3.2^b \pm 0.51$	$0.6^c \pm 0.16$
Uptakes C at farm level				
Woodlots				
<i>Alnus acuminata</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0 ± 0	0.01 ± 0.01	0 ± 0
<i>Eucalyptus globulus</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.32 ± 0.24	0 ± 0	0 ± 0
<i>Fraxinus chinensis</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.27 ± 0.27	0 ± 0	0 ± 0
Live fences				
<i>Alnus acuminata</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.06 ± 0.05	0.03 ± 0.02	0.01 ± 0.004
<i>Acacia melanoxylum</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.18 ± 0.18	0.06 ± 0.05	0.02 ± 0.02
<i>Eucalyptus globulus</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	$3.31^a \pm 0.9$	$0.99^b \pm 0.46$	$0.2^b \pm 0.08$
<i>Fraxinus chinensis</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.17 ± 0.14	0.14 ± 0.07	0.01 ± 0.01
<i>Pinus radiata</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.05 ± 0.03	0.03 ± 0.02	0 ± 0
<i>Salix humboldtiana</i>	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	0.07 ± 0.07	0.02 ± 0.02	0.01 ± 0.01
Total ACCI	$\text{Mg}\cdot\text{C}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$	$4.43^a \pm 0.96$	$1.28^b \pm 0.41$	$0.24^b \pm 0.08$

^{a,b,c} Rows with different superscript indicate significant differences ($p < 0.05$) according to Fisher LSD test

8% from other assessed components) as described in the Table 4. The unallocated carbon footprint was $1.5 \pm 0.2 \text{ MgCO}_2\text{-eq MgFPCM}^{-1}$, with allocation factors of 0.8 ± 0.031 for milk and 0.2 ± 0.031 for live weight. No significant differences were found in these parameters across farms with different levels of silvopastoral coverage. Regarding the carbon balance, all farms exhibited a negative balance, with a maximum emissions offset per area of 62.8% observed on farms with high silvopastoral coverage.

The carbon footprint in our network of farms averaged $1.24 \pm 0.16 \text{ MgCO}_2\text{-eq MgFPCM}^{-1}$ and was

within the ranges of carbon footprint in specialized milk production systems (1.0 to $2.3 \text{ MgCO}_2\text{-eq MgFPCM}^{-1}$) founded in the Andean region of Colombia (González-Quintero et al. 2022), and below of the national average ($3.8 \text{ MgCO}_2\text{-eq MgFPCM}^{-1}$) carbon footprint. Although the carbon footprint of silvopastoral systems for milk production has not been well studied, Ruiz-Llontop et al., (2022) found in the lowlands of the Andean Amazon region of Peru, a variable carbon footprint ranging between 1.76 to $3.09 \text{ MgCO}_2\text{-eq MgFPCM}^{-1}$ in farms with silvopastoral coverage between 13 and 37% respectively. Regarding

Table 4 Inventory of outputs (milk and beef), emissions, carbon footprint and carbon balance based on the difference between the Annual average carbon increment (AACI) in the

total living biomass and the total emissions in dairy farms with different levels of silvopastoral systems coverage in the Andean Amazon region of Colombia

Paremeter	Unit	Silvopastoral coverage level		
		High	Medium	Low
Milk outputs				
Milk yields cow	kg·FPCM·cow ⁻¹	3232 ± 425	3458 ± 512	2883 ± 290
Milk yield farm	Mg·FPCM·farm·yr ⁻¹	26 ± 6	23 ± 5	23 ± 5
Beef outputs				
Cows > 1 years old	Mg·LW·farm·yr ⁻¹	0.45 ± 0.15	0.61 ± 0.18	0.41 ± 0.1
Calves and heifers < 1 year old	Mg·LW·farm·yr ⁻¹	0 ± 0	0.08 ± 0.04	0.05 ± 0.04
Bulls > 1 year old	Mg·LW·farm·yr ⁻¹	0 ± 0	0.17 ± 0.17	0.17 ± 0.12
Outputs in live weight	Mg·LW·farm·yr ⁻¹	0.47 ± 0.15	0.62 ± 0.13	0.56 ± 0.13
Emissions				
Feed	Mg·CO ₂ eq·yr ⁻¹	2.9 ± 1.16	1.81 ± 0.46	1.91 ± 0.57
Soli management	Mg·CO ₂ eq·yr ⁻¹	3.54 ± 1.35	0.39 ± 0.37	4.24 ± 2.59
Fuel and energy	Mg·CO ₂ eq·yr ⁻¹	0.52 ± 0.06	0.59 ± 0.0035	0.54 ± 0.04
Enteric CH4	Mg·CO ₂ eq·yr ⁻¹	20.93 ± 2.63	16.08 ± 2.71	21.44 ± 2.68
Manure CH4	Mg·CO ₂ eq·yr ⁻¹	1.28 ± 0.18	0.99 ± 0.18	1.42 ± 0.19
Direct N2O urine and manure	Mg·CO ₂ eq·yr ⁻¹	1.6 ± 0.18	1.21 ± 0.21	1.65 ± 0.19
Indirect N2O urine and manure	Mg·CO ₂ eq·yr ⁻¹	0.64 ± 0.08	0.48 ± 0.08	0.66 ± 0.08
Total farm emission	Mg·CO ₂ eq·yr ⁻¹	31.41 ± 4.76	21.55 ± 3.48	31.85 ± 4.71
Carbon footprint				
Carbon footprint/area	MgCO ₂ -eq·yr ⁻¹ ha ⁻¹	3.79 ± 0.59	3.08 ± 0.59	3.17 ± 0.54
Carbon footprint/product (unallocated)	Mg·CO ₂ eq·Mg·CMPF	1.78 ± 0.42	1.26 ± 0.33	1.58 ± 0.21
Allocation factor of milk	Ratio	0.85 ± 0.05	0.82 ± 0.05	0.8 ± 0.06
Allocation factor of live weight	Ratio	0.15 ± 0.05	0.18 ± 0.05	0.2 ± 0.06
Carbon footprint milk allocated	Mg·CO ₂ eq·Mg·CMPF	1.44 ± 0.33	1.08 ± 0.35	1.19 ± 0.15
Carbon footprint meet allocated	Mg·CO ₂ eq·Mg·kg·LW	0.33 ± 0.16	0.18 ± 0.05	0.39 ± 0.14
Carbon balance				
Total uptakes	Mg·CO ₂ eq·yr ⁻¹ ·ha ⁻¹	17.01 ^a ± 3.44	4.14 ^b ± 1.00	0.78 ^b ± 0.30
Carbon balance—Farm	Mg·CO ₂ eq·yr ⁻¹ ·ha ⁻¹	-14.40 ^a ± 5.03	-17.42 ^a ± 3.48	-31.06 ^b ± 4.82
Relative mitigation	%	62.83 ^a ± 20.95	22.29 ^b ± 4.77	3.51 ^b ± 1.69

^{a,b,c} Rows with different superscript indicate significant differences ($p < 0.05$) according to Fisher LSD test

the distribution of the GHGE, our results are comparable to those in regional reports on dairy systems in Colombia and in the Andean Amazon region, where 69–83% of emissions on dairy farms are attributed to enteric CH_4 , (González-Quintero et al. 2022; Mazzetto et al. 2022 and Ruiz-Llontop et al., (2022)). These trends indicate that dairy farms with silvopastoral systems in the Andean Amazon region have the potential to reduce the carbon footprint per product by more than 40%, thanks to carbon sequestration in silvopastoral systems.

On the other hand, our study found that farm emissions averaged $28.3 \pm 2.6 \text{ Mg} \cdot \text{CO}_2\text{e} \cdot \text{yr}^{-1}$, while carbon uptake rates in SPS ranged from 2.6 to $23.0 \text{ Mg} \cdot \text{CO}_2\text{e} \cdot \text{yr}^{-1}$, depending on the type of silvopastoral system. Based on the carbon sequestration potential of each SPS, a minimum area between 1.2 and 10.8 ha is required to offset 100% of the emissions. These findings emphasize the importance of considering both the carbon footprint per product, which focuses on productive efficiency, and the carbon footprint per area, which highlights the role of silvopastoral system biomass in mitigating greenhouse gas emissions through carbon sequestration.

Additionally, we underscore that the integrated analysis of carbon footprint and carbon inventory is a valuable approach for incorporating technological advancements on dairy farms. Such integration can

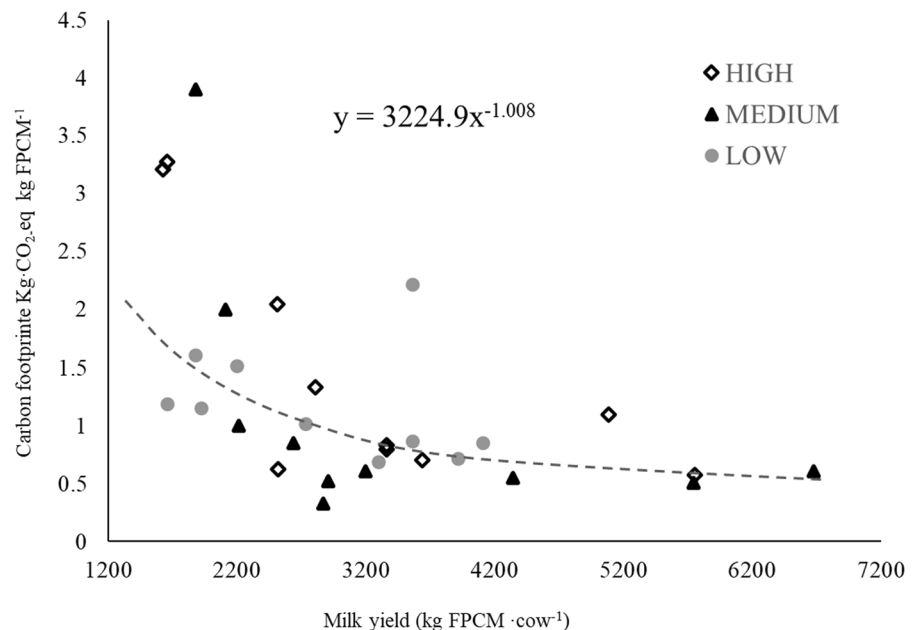
reduce the carbon footprint per product and enhance tree cover within farms. However, further efforts are needed to expand the carbon balance framework to include other environmental services—such as cultural, provisioning, regulatory, and support functions—as well as biodiversity conservation. These aspects, in turn, can influence animal welfare and the quality and quantity of milk production (Mancera et al. 2018).

Effect of yield on carbon footprint

We found a significant ($p < 0.05$) and reverse effect between milk yields per cow and carbon footprint per product (Fig. 3). Indeed, fifty percent of the farms had yields below the overall average of $3190.9 \pm 237.4 \text{ kg FPCM} \cdot \text{cow}^{-1}$, and only 13% reached yields higher than $5000 \text{ kg FPCM} \cdot \text{cow}^{-1}$. The levels of silvopastoral coverage did not influence milk yield, with farms displaying different scenarios of high and low productivity with high, medium, or low levels of silvopastoral coverage.

Although our study was conducted in the Sibundoy Valley subregion, without significant geographical or technological variations in highlands of tropical conditions, we observed a high heterogeneity regarding carbon footprint. This can be explained by the variability in livestock management practices found. We

Fig. 3 Effect of the yield on the carbon footprint ($r^2 = 0.45$, $p < 0.001$) in farms with different SPS systems coverage in the Andean Amazon Region of Colombia



observed that farms with higher productivity had lactation periods close to 360 days, weaning times of less than 69 days, and better feeding practices by supplementation. The increase in productivity has a significant impact on reducing carbon footprint, especially on low productivity farms. The transition from farms with cows producing 1,000 to 3,000 kg-FPCM-cow⁻¹ results in a 200% reduction in carbon footprint, while the transition from farms with cows producing 4,000 to 6,000 kg-FPCM-cow⁻¹ results in a 50% reduction in carbon footprint.

The significant effect of milk yield on carbon footprint found in our study is consistent with several studies that demonstrate that the reduction of carbon footprint in smallholder farms using grazing-based milk production systems is associated with the implementation of different management practices. These include pasture management, improved genetics, reproductive practices, such as artificial insemination, better infrastructure, machinery, equipment, and a high proportion of high-yield cows compared to dry cows (Lorenz et al. 2019; González-Quintero et al. 2022; Ruiz-Llontop et al. 2022; Velarde-Guillén et al. 2022; Mech et al. 2023; Andrade et al. 2024). These results highlight the importance of increased dairy herd management practices in decreasing the carbon footprint per product unit at all levels of silvopastoral coverage.

Our results highlight that small dairy farms can increase silvopastoral coverage from low (0.6%) to high (10.8%), primarily through live fences, without negatively impacting milk yield. This suggests that tree canopy shade over grazing areas did not reduce neither fodder quantity or quality, likely due to the wide spacing between live fences (> 20 m in our study). Dos Santos et al. (2023) reported that tree spacing between 9 and 20 m can limit *Urochloa decumbens* pasture yield, as photosynthetically active radiation may decrease by 46–60%, leading to a 58–86% reduction in dry matter production.

Despite potential shading effects, tropical pastures often show compensatory responses, such as increased chlorophyll and protein contents, reduced neutral detergent fiber, and improved digestibility, even under 65% shade interference (Casanova-Lugo et al. 2022; Paciullo et al. 2007). These effects are mainly due to the role of legumes and shade trees in nitrogen fixation, microclimate regulation, and soil biological activity stimulation, which collectively

enhance nutrient cycling (Cruz et al. 1999; Wong 1991). Nevertheless, given the high diversity of climatic and ecological conditions of the Andean region, further research is required in order to determine forage tolerance to shade and establish an optimal balance among tree coverage, carbon sequestration, forage productivity, and milk yield.

Effect of area and silvopastoral coverage on carbon balance

Figure 4 illustrates the relationship between carbon balance and two key structural indicators of silvopastoral systems: basal area (A) and silvopastoral coverage at the farm level (B). Both regressions revealed a non-linear relationship (second-degree polynomial).

In Fig. 4A, the regression analysis shows the effect of basal area (m²·ha⁻¹) on carbon balance (Mg CO₂e·yr⁻¹·ha⁻¹), with a moderate coefficient of determination ($r^2=0.3916$). This finding suggests that, while an increase in tree basal area contributes to GHG emissions mitigation, it does not necessarily ensure a positive carbon balance. Farms with low basal areas (2.2 m²·ha⁻¹) achieved neutral or positive carbon balances, whereas others with higher basal areas (6 m²·ha⁻¹) remained net carbon emitters. This variability underscores that the biomass accumulated on the farm may not be sufficient to fully offset emissions, particularly in farms with both high biomass and high emissions. Consequently, effective GHG mitigation in small farms requires addressing both productive efficiency by increasing milk yield through the reduction of technological gaps, as suggested by González-Quintero et al. (2022) and maintaining an optimal level of silvopastoral coverage that does not negatively impact pasture growth due to light competition.

On the other hand, and as shown in Fig. 4B, the regression analysis demonstrates that silvopastoral coverage (%) at the farm level explains a smaller proportion of the variance in carbon balance ($r^2=0.1803$), indicating its limited predictive power in assessing carbon mitigation potential. These findings highlight the complexity of carbon dynamics in tropical dairy systems, where isolated tree-based metrics must be complemented with broader farm-level variables to accurately capture mitigation potential. Furthermore, key determinants, such as weaning and lactation periods, milk yield, pasture management,

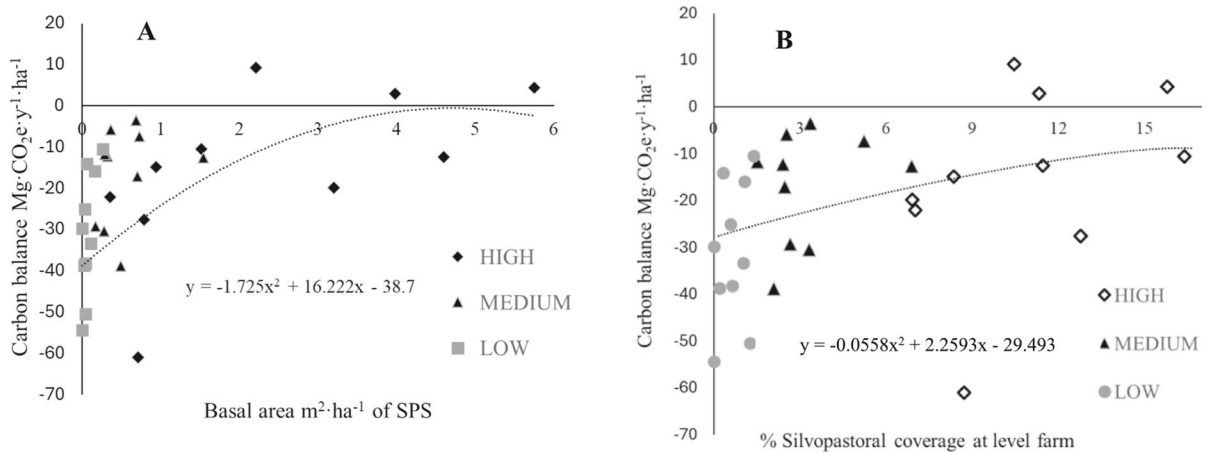


Fig. 4 Effect of the silvopastoral system basal area on the carbon balance ($r^2=0.3916$, $p<0.001$) (A), and Effect of the silvopastoral system coverage on the carbon balance ($r^2=0.1803$,

$p<0.001$) (B) in farms with different SPS systems coverage in the Andean Amazon Region of Colombia

and access to technical assistance, vary significantly across farms and play a pivotal role in shaping net GHG emissions (Mancera et al. 2018; Mavisoy et al. 2023, 2025; Ruiz-Llontop et al. 2022).

Therefore, enhancing the carbon balance in tropical dairy farms through silvopastoral systems requires integrating both biophysical indicators and management-related factors, ensuring a comprehensive approach to GHG mitigation and sustainable productivity.

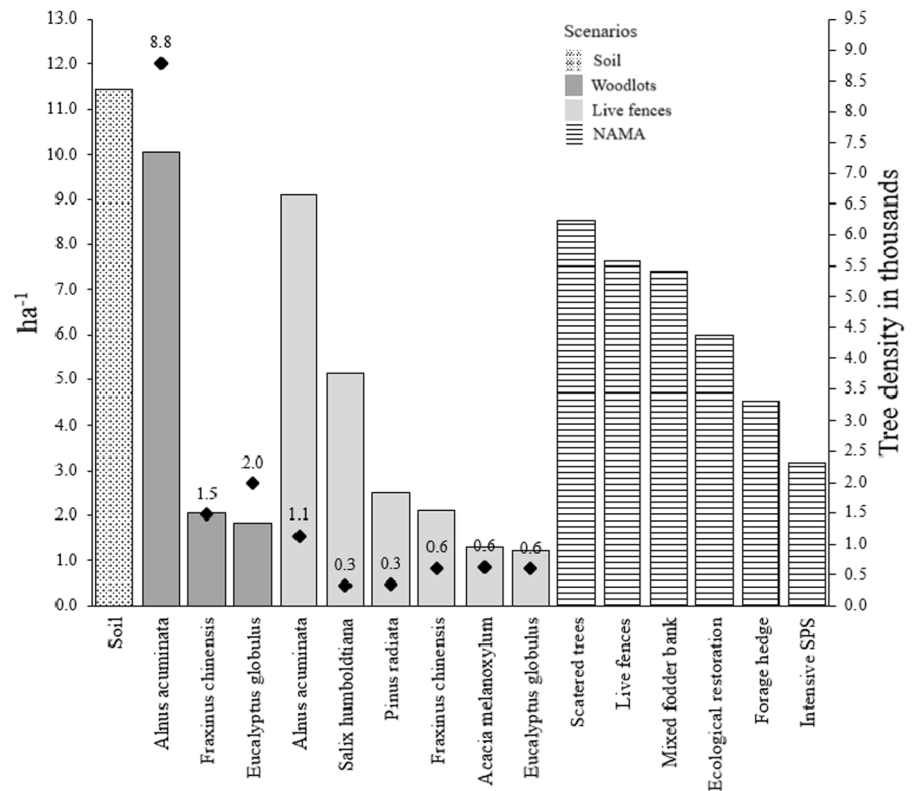
Scenario analyses

The area and the numbers of trees required to offset 100% of the emissions per farm under different scenarios is detailed in Fig. 5. Considering the average farm size in this study ($9.2 \pm 0.7 \text{ ha}^{-1}$) and the average of total emission of $28.3 \pm 2.6 \text{ Mg} \cdot \text{CO}_2\text{e} \cdot \text{yr}^{-1}$ per farm, scenarios show that all silvopastoral alternatives have greater potential for mitigating GHG emissions at the farm level, when compared to the scenario of carbon capture from treeless pasture soils. Additionally, under the conditions of the Sibundoy Valley, systems with introduced species such as *A. melanoxylum* and *E. globulus* require the least area, with a density of 600 trees per hectare. In contrast, live fences and woodlots with *A. acuminata* require the largest number of trees and area. On the other hand, if we consider the AACI established by NAMA for dispersed trees in pastures ($0.9 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$), live fences

($1.0 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$), mixed forage banks ($1.0 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$), ecological restoration ($1.2 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$), forage hedges ($1.7 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$) and intensive silvopastoral systems ($2.4 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$), the latter require less than half the area compared to the area required for dispersed trees in pastures.

Regarding carbon capture in pastures in the Sibundoy Valley (0–30 cm depth), which averaged $0.7 \pm 0.01 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$, it is above the national average ($0.239 \text{ Mg} \cdot \text{C} \cdot \text{yr}^{-1}$) projected for 2040 under the scenario of improved pastures with a 20% addition of organic matter (Araujo-Carrillo et al. 2021). This can be explained by soil composition in the Sibundoy valley, where flat areas have Histosols, which are rich in organic matter and prone to periodic flooding in the rainy season, whereas Inceptisols are predominant in the Andean region (INCODER & IGAC 2015) which contains higher carbon content than the warm, lowland soils of Colombia dominated by Oxisols, Ultisols, and Entisol. The impact of pasture management practices on carbon assimilation rates in farms remains unstudied. As a result, it is unclear whether livestock systems in the Sibundoy Valley have increased or decreased accumulation rates over the past 20 years, as well as what their medium- and long-term projections might be. Additionally, the impact on soil carbon sequestration at specific silvopastoral system sites is unknown, highlighting the need for more detailed or additional studies to identify the most suitable management practices. On the

Fig. 5 Area and numbers of trees needed to offset the total CO₂e emissions at the farm level using carbon annual average carbon increment (AACI) in the scenarios of C capture in soil of pastures, in living biomass of wood lots and live fences in the Sibundoy Valley, and using the AACI determined by the National Appropriate Mitigation Actions (NAMA) for cattle in the southwest region of Colombia (CIPAV et al. 2021)



other hand, if only soil is considered as a carbon sink, in the characteristics of the systems studied, the area required to mitigate 100% of emissions exceeds the average farm area, making this a critical aspect for the environmental sustainability of livestock systems and biodiversity conservation due to the reduction of tree cover in the livestock landscape.

One the other hand, we acknowledge the methodological limitation of this study regarding the temporal mismatch between GHG emissions and soil carbon sequestration determinations. Indeed, and while GHG emissions are quantified using a 100-year global warming potential (GWP100) metrics (IPCC 2007), soil carbon sequestration was estimated as an annual average (0.7 ± 0.01 Mg C ha⁻¹ yr⁻¹), without assessing the long-term duration of such carbon. Nonetheless, a significant fraction of sequestered carbon in soil, especially labile organic carbon, can be rapidly decomposed and returned to the atmosphere in years or decades depending on land use, management practices, and environmental conditions (Silva-Olaya et al. 2022; Suárez et al. 2024). Such temporal inconsistency may lead to an overestimation of the mitigation

potential when comparing annual soil C gains to GWP100 emissions. Therefore, results should be interpreted with caution, particularly for mitigation scenarios based solely on soil carbon accumulation.

Future studies should aim to characterize the stability of soil carbon pools by integrating methods that estimate the mean organic matter permanence time (Cotrufo et al. 2013). Furthermore, they should distinguish labile versus recalcitrant fractions (Barré et al. 2017), or simulate turnover dynamics using process-based in integrated models such as the Introductory Carbon Balance Model (ICBM). Such approaches would enable more robust long-term mitigation potential assessments on and improve alignment with GWP timeframes (Menichetti et al. 2020; Shi et al. 2018).

Although our study focuses on GHG mitigation through carbon capture in forest biomass, simplifying livestock farms to a single system with a single species must be carefully pondered. This is due to the environmental service of carbon capture also interact with other benefits such as animal welfare, increased availability of pasture and forage, cultural

services, food security, nutrient cycling, and biodiversity conservation. It has been demonstrated that 22–35% silvopastoral coverage has a positive effect on productivity and animal welfare in tropical dairy farms, in addition to contributing to ecological connectivity at the landscape scale (Mancera et al. 2018). Our results suggest a broad potential for diversification between exotic and native species, particularly in live fences. With 10% silvopastoral coverage using *A. melanoxylum* and *E. globulus* live fences, a positive carbon balance could be achieved, allowing the inclusion of other species on the farm, such as high-nutritional-value shrubs like *Acacia decurrens*, *Baccharis latifolia*, and *Sambucus peruviana* in lower strata. It has been demonstrated that supplementing 10% of the daily intake with cut-and-carry of these shrubs and 90% *Cenchrus clandestinus* grass in small-scale dairy systems with *Bos taurus* in the Andean Region of Colombia has the potential to increase milk yield by up to 37% and reduce the enteric methane emission factor by up to 1.6%.

Furthermore, such practices would increase milk yield between 19–37%, as these plants have higher protein content while having low amounts of fiber, providing palatability and digestibility benefits (González-Quintero et al. 2024). In the case of timber lots, there are also advantages as they are concentrated in a specific farm area and do not directly compete for light with pastures. In this case, silvopastoral coverage could also be expanded by dividing pastures with forage shrubs. From the NAMA perspective, there is also a significant potential to mitigate emissions with large differences in the area required between dispersed trees and intensive silvopastoral systems. Intensive silvopastoral systems have mainly been evaluated in warm regions of Colombia, showing improvements in animal welfare, forage availability, carrying capacity, and milk productivity (Chará et al. 2020), but specific studies are needed for the Andean region, not only in Colombia but also in other areas of the mountain chain.

Conclusions

For the first time, and to the best of our knowledge, an analysis on carbon balance was conducted in a dairy-producing sub region of Colombia, combining carbon footprint and annual average carbon increase

in silvopastoral systems. This study is, therefore, a reference for tropical Andean regions and small-scale dairy production systems that are predominant in various tropical and subtropical areas of the world.

Sixty-three percent of farms had a carbon footprint below the overall average of 1.2 ± 0.2 MgCO₂-eq MgFPCM⁻¹, and carbon footprint per area below 3.3 ± 0.3 MgCO₂-eq·yr⁻¹ ha⁻¹, with no significant differences between high, medium, and low silvopastoral coverage levels. Additionally, farms with high silvopastoral coverage showed a carbon uptake potential of 4.43 ± 0.96 Mg·C·ha⁻¹·yr⁻¹, allowing them to offset up to 63% of the total farm emissions. Transitioning farms from low-productivity cows (1,600 kg-FPCM·y⁻¹) to medium productivity (3,190.9 kg-FPCM·y⁻¹) resulted in a 200% reduction in the carbon footprint, mainly due to better practices during lactation, shorter weaning times, and improved feeding practices. Such improvements are applicable across all silvopastoral coverage levels.

Although a larger tree basal area can contribute to GHG emissions mitigation, it does not guarantee a positive carbon balance on farms. Biomass accumulation alone is not sufficient to fully offset emissions, especially on farms with both high biomass and high emissions. Additionally, silvopastoral coverage has limited predictive capacity for carbon balance, indicating that isolated tree-based metrics must be complemented with farm-level variables. The mitigation scenario relying solely on carbon soil without silvopastoral systems is the most critical, as it exceeds the average farm size and reduces the availability of environmental services.

Finally, our findings can assist policymakers in rural agricultural planning by integrating productive and environmental aspects at the farm level to increase production while adhering to carbon-neutral principles in the tropical Andean region. This approach supports achieving low-carbon livestock commitments in the medium and long term.

Competing Interests

The authors declare no competing interests.

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Data Availability No datasets were generated or analysed during the current study.

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