



OPEN ACCESS

EDITED BY

Pradeep Mishra,
Jawaharlal Nehru Agricultural University, India

REVIEWED BY

José Muñoz-Rojas,
University of Evora, Portugal
María Elena Tavera Cortés,
Instituto Politécnico Nacional-UPIICSA,
Mexico

*CORRESPONDENCE

Carol Tatiana Chamorro-Vargas
✉ tatiana.chamorro@ubc.ca

RECEIVED 25 March 2025

ACCEPTED 01 October 2025

PUBLISHED 03 November 2025

CITATION

Chamorro-Vargas CT, Morgan S, Pantevz H,
Gomez M, Kennedy CM and Kremen C (2025)
Enablers and barriers to adoption of
sustainable silvopastoral practices for
livestock production in Colombia.
Front. Sustain. Food Syst. 9:1600091.
doi: 10.3389/fsufs.2025.1600091

COPYRIGHT

© 2025 Chamorro-Vargas, Morgan, Pantevz,
Gomez, Kennedy and Kremen. This is an
open-access article distributed under the
terms of the [Creative Commons Attribution
License \(CC BY\)](#). The use, distribution or
reproduction in other forums is permitted,
provided the original author(s) and the
copyright owner(s) are credited and that the
original publication in this journal is cited, in
accordance with accepted academic
practice. No use, distribution or reproduction
is permitted which does not comply with
these terms.

Enablers and barriers to adoption of sustainable silvopastoral practices for livestock production in Colombia

Carol Tatiana Chamorro-Vargas^{1*}, Seth Morgan²,
Heiber Pantevz³, Manuel Gomez³, Christina Marie Kennedy⁴
and Claire Kremen¹

¹WorRCs Lab, Institute for Resources Environment and Sustainability, The University of British Columbia, Vancouver, BC, Canada, ²Monitoring, Evaluations and Learning, The Nature Conservancy, Durham, NC, United States, ³Ganadería Colombiana Sostenible, Federación Colombia de Ganaderos (FEDEGAN), Bogota, Colombia, ⁴Global Science, The Nature Conservancy, Fort Collins, CO, United States

In Latin America, the expansion of land for Extensive Cattle Ranching (ECR) is the leading driver of deforestation causing unsustainable levels of environmental degradation and social vulnerability to climate change extremes of drought or flood. Silvopastoral Systems (SPS) are a promising agroecological alternative to ECR. SPS combines trees and shrubs with forage grasses to enhance cattle production and landscape heterogeneity in this region. Despite strong evidence of SPS benefits (e.g., soil protection and recovery, increased cattle productivity and benefits to biodiversity), its adoption remains low. Previous work on how to scale out this practice has considered adoption as a binary option, without examining levels of adoption based on the amount (area) of SPS and types of practices adopted. This research aimed to assess how SPS can be scaled out by exploring the factors that influenced the number of hectares and component practices of SPS adopted by individual farmers to understand enablers and barriers. We used mixed effects linear models to analyze socio-economic survey data from 2,900 farms in Colombia collected over 9 years under the Sustainable Cattle Ranching (SCR) project (organized by The Nature Conservancy, CIPAV, FEDEGAN and Fondo Acción) combined with open access environmental information (8 spatial layers). The factors that had a positive significant effect on adoption were Payments for Ecosystem Services (PES), distance to closest SCR farm, presence of forest or watershed on the farm, and high levels of soil erosion. Water demand and hydric vulnerability (i.e., susceptibility to drought and flood) had a negative effect on adoption. These findings enhance knowledge of enablers and barriers for SPS adoption, including environmental constraints, thereby improving our understanding of pathways for scaling out agricultural transformation and shifting ECR to more sustainable alternatives.

KEYWORDS

enablers, barriers, adoption, silvopastoral systems, sustainable cattle ranching, Colombia, diversified farming system

Introduction

The earth is facing a huge environmental crisis at a critical rate due to human activities, such as the expansion of the agricultural frontier (Vitousek et al., 1997; Ceballos et al., 2015; Tollefson, 2019). For instance, in Latin America the expansion of land used for Extensive Cattle Ranching (ECR) has and continues to be the leading cause of deforestation threatening biodiversity, ecosystem services, and human resilience (Geist and Lambin, 2002; Adams, 2009; Harrison et al., 2014; Keenan et al., 2015). ECR is characterized by large extensions of pasture monoculture with low cattle density (Adams, 2009; Mahecha and Angulo, 2012), causing unsustainable levels of environmental degradation (Vitousek et al., 1997; Rivera et al., 2013; Aryal et al., 2018; Ballesteros-Correa and Pérez-Torres, 2022), including soil erosion and loss of soil fertility that results in pasture abandonment and further deforestation. Additionally, it is known to have low productivity per land area (Lamela et al., 2005; Houriet et al., 2009; Lopera et al., 2015; Zuluaga et al., 2021), be susceptible to climate change effects (Montagnini et al., 2013; FEDEGAN, 2018; Loboguerrero et al., 2019; Becking et al., 2021; Zuluaga et al., 2021; Schmitt Filho et al., 2023), and contribute to poverty and inequality (Murgueitio et al., 2011; Morales, 2017; Becking et al., 2021).

Silvopastoral systems (SPS), which combine trees and shrubs with forage grasses to enhance cattle production and landscape heterogeneity (Murgueitio et al., 2011), are a promising alternative to extensive cattle production in Latin America (Calle et al., 2011; Murgueitio et al., 2011; Mauricio et al., 2019; Freitas et al., 2020). These systems are associated with benefits to the environment (e.g., improving biodiversity, ecological resilience, water quality, recovering soil and other ecosystem services) and people (e.g., increasing income, cattle production, and adapting to climate change and mitigating its impacts) (Chará and Murgueitio, 2005; Murgueitio et al., 2011; Montagnini et al., 2013; Rivera et al., 2013; Mauricio et al., 2019; Carrera et al., 2021; Silva-Olaya et al., 2022; Simioni et al., 2022; Kinneen et al., 2023). For example, SPS favors ecological processes that improve soil health by increasing on-farm invertebrate diversity (e.g., dung beetles and worms) that provide key ecosystem functions such as decomposition and bioturbation (Nair, 1993; Calle et al., 2011; Silva-Olaya et al., 2022). SPS also helps to decrease soil degradation by creating physical barriers to prevent soil erosion, such as fodder banks and deep-rooted trees that hold the soil (Chará and Murgueitio, 2005; Murgueitio et al., 2011; Polanía-Hincapié et al., 2021; Shah et al., 2022; Silva-Olaya et al., 2022). Additionally, the trees and shrubs (which can include nitrogen-fixing legumes) increase the availability of soil nutrients and enhance the stock of soil organic carbon, which ultimately increases forage production, nutrient density and cattle productivity (Dubeux et al., 2017; Muir et al., 2017; Freitas et al., 2020; Lira Junior et al., 2020; Almeida et al., 2021).

Despite strong evidence for SPS benefits, its adoption remains low across many suitable regions of the world, creating an opportunity and a need to scale out these practices (Calle et al., 2013; Rudel et al., 2015; Solymosi et al., 2016; Haddad et al., 2022). For instance, in Colombia, pastures using ECR occupy 34% of the national territory (33.89 million ha), of which 12% (4.16 million ha) have the potential to be converted to SPS (Chará and Murgueitio, 2005; Mahecha and Angulo, 2012; DANE, 2016; FEDEGAN, 2018). Scaling out SPS, which we define as promoting and achieving the adoption of SPS by a significantly larger number of farms in Colombia, could benefit farmers by increasing

their productivity and income and decreasing their environmental and climatic vulnerability (Montagnini et al., 2013; Moore et al., 2015; Valencia et al., 2022; Schmitt Filho et al., 2023). Furthermore, it could benefit biodiversity conservation by creating heterogeneous landscapes suitable for multiple species, and potentially providing connections between protected areas (Estrada-Carmona et al., 2019) and preventing further deforestation in megadiverse countries (Kremen and Merenlender, 2018; Clerici et al., 2019). Altogether, scaling out SPS can create resilience in the production system and long-term holistic sustainability (Calle et al., 2011; Kremen and Miles, 2012; Lerner et al., 2017; Kremen and Merenlender, 2018).

To determine how best to encourage scaling out of SPS, it is necessary to have a thorough understanding of the factors influencing its adoption (Liu et al., 2018; Begho et al., 2022; Priya and Singh, 2024). Although some research has examined factors that influence the scaling out of SPS in Latin America, most studies have been based on expert reviews and lack quantitative, cross-regional data to assess the effect of factors on adoption of SPS (Dagang and Nair, 2003; Clavero and Suárez, 2006; Calle et al., 2011; Calle et al., 2013; Fuentes et al., 2022; Chamorro-Vargas et al., 2025). Other efforts have considered adoption as a binary option or as part of multiple technologies adopted by farmers (Nkamleu and Manyong, 2005; Cuevas Reyes et al., 2013; Gil et al., 2015; Cedamon et al., 2018; Jara-Rojas et al., 2020). To our knowledge, previous work in Latin America has not studied the adoption of SPS as a continuous variable (i.e., hectares of SPS adopted on farms), which can offer different insights into the adoption process. This paper aims to assess the social, economic, and environmental factors influencing the amount of SPS adoption by individual farmers, in order to improve understanding of how these systems can be scaled out, using an extensive data set collected during the Sustainable Cattle Ranching (SCR) project in Colombia over 9 years. We have included a list of the abbreviations used throughout this paper in Table 1.

TABLE 1 List of abbreviations used in the text and their explanations.

Abbreviation	Explanation
ECR	Extensive Cattle Ranching
SPS	Silvopastoral Systems
TA	Technical Assistance
PES	Payments for Environmental Services
SCR	Sustainable Cattle Ranching
FEDEGAN	Cattle Ranching Federation of Colombia
GDP	Gross Domestic Product
DANE	National census data
SIAC	Environmental information system
IGAC	Geographic Institute Agustín Codazzi
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies
IQR	Interquartile range
AIC	Akaike Information Criterion
LASSO	Least Absolute Shrinkage and Selection Operator
BART	Bayesian Additive Regression Trees
BMPs	Best Management Practices

Materials and methods

The sustainable cattle ranching project

The SCR project was a collaborative effort among multiple organizations [i.e., The Nature Conservancy (TNC), The Cattle Ranching Federation of Colombia (FEDEGAN), Centre for Research on Sustainable Agricultural Production Systems (CIPAV), and Fondo Acción], which promoted the conversion of the commonly used extensive cattle ranching systems (ECR) into Silvopastoral Systems (SPS) (Chará et al., 2011). During the SCR project, around 4,000 farms across five contrasting regions of Colombia (Figure 1; Supplementary Table S1) adopted SPS practices (Table 2), which can include planting intensive silvopastoral systems (iSPS) [i.e., a type of SPS that combine fodder shrubs planted at high densities ($>5,000$ plants ha^{-1} for areas between 0 and 2,000 m.a.s.l and $>2,000$ for areas higher than 2,000 m.a.s.l; Ayala et al., 2017], or any combination of dispersed trees, fodder banks, live fences, and fodder hedges, along with other sustainable practices, such as water-stream protection, forest protection and natural regeneration, use of electric fences, rotation of cattle, soil management and reduced use of synthetic chemicals

(fertilizers, herbicides, pesticides) (Chará et al., 2011). The organizations collaborating in the SCR collected farm-level data regarding social, economic, and environmental variables on the farms that participated in the project.

Cattle farmers joined the project through four open calls between 2011 and 2018 (Table 2), according to the reference terms of the project (Chará et al., 2011). To encourage farmers to participate, the project offered three main incentives: technical assistance (TA), provisioning of supplies (i.e., nursery trees), and payments for ecosystem services (PES). TA was given to all the farms that participated in the project while PES was given to some of the farms that participated in the project according to the selection criteria of the project (Table 3; Chará et al., 2011). The amount of PES received by farms depended on the land use changes made on the farm which included SPS practices and forest conservation (Chará et al., 2011). The PES was expected to cover the cost of SPS implementation (mainly related to seed and tree acquisition and labor for tree planting and management) and to increase farmers' income. The first round of payments (PES1) was given to the farmers in cash, while the second round (PES2) was given as in-kind support (i.e., trees, seeds, fences...) (Chará et al., 2011). Building on this project design, our research

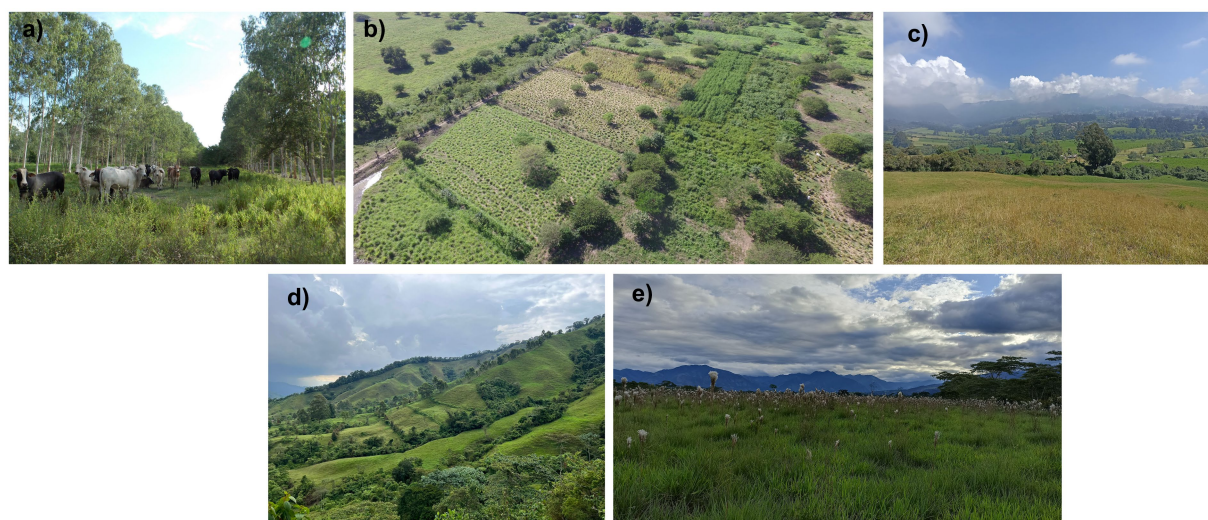


FIGURE 1

Landscape pictures show an example of a farm in each region of the Sustainable Cattle Project. (a) Valle del Rio Cesar, (b) Bajo Magdalena, (c) Boyacá y Santander, (d) Ecoregion cafetera, (e) Piedemonte Orinocense. Picture (b) is an image of demonstration farms from the Sustainable Cattle Ranching project from Galindo Ospina et al. (2019).

TABLE 2 Number of farms that joined the project in each call per region.

Regional	I—2011	II—2012	III—2015	IV—2018	Total
Bajo Magdalena	124	307		177	608
Valle del Río Cesar	208	217	322	187	934
Boyacá y Santander	150	343		212	705
Ecorregión Cafetera	326	464	89	290	1,169
Piedemonte Orinocense	170	179	89	246	684
Total	978	1,510	500	1,112	4,100

Some farms participated in it from the beginning till the end, while others joined later or retired from the project before it finished.

TABLE 3 The SCR project calls description including year, incentives provided to the treatment and control groups, the purpose of the incentive and type of farms targeted by the intervention.

Call	Year	Incentive to all farmers (control group)	Incentive to some farmers (treatment group)	Purpose	Farms targeted
I	2011	TA	PES1, or PES1 + PES2	Biodiversity conservation	Larger farms in regions where biodiversity corridors were chosen for expansion
II	2012	TA	PES1 or PES1 + PES2	Biodiversity conservation	Larger farms in regions where biodiversity corridors were chosen for expansion
III	2015	TA	PES2	Carbon sequestration and poverty alleviation	Smaller, less wealthy farms with potential for carbon sequestration
IV	2018	TA	PES2	Carbon sequestration and poverty alleviation	Smaller, less wealthy farms with potential for carbon sequestration

Farms that joined early could obtain both rounds of PES.

followed several methodological stages, which are illustrated in [Figure 2](#) and explained in detail in the following sections.

Data collection

Socio economic survey data and variables

Farm-level socio-economic data was collected through comprehensive surveys by FEDEGAN from 2011 to 2019 ($N = 3,644$). The survey comprised 10 main modules including farm characteristics (e.g., size, type of production), management practices (e.g., use of technology, rotation), productivity (e.g., liters of milk or kgs of meat), environmental information (e.g., presence of springs or forest patches), social information about the farmer/manager (e.g., demographics of the farmer, region), financial information about the farmer/manager (e.g., income, assets) ([Supplementary Figure S1](#)). We selected the socio-economic explanatory variables for this study from these variables based on factors influencing adoption of SPS in Latin America identified through a systematic literature review ([Supplementary Figures S1, S2](#); [Supplementary Table S2](#); [Chamorro-Vargas, 2024](#); [Chamorro-Vargas et al., 2025](#), submitted manuscript). To reduce dimensionality of the data, some variables were combined based on the themes identified in the systematic literature review. For example, we summed binary survey data (yes/no responses) within themes (e.g., number of sources of information for the project, number of best management practices) (see [Supplementary Table S3](#) for full list). We excluded variables that had many missing values for the surveyed farms ([Supplementary Table S4](#)). We obtained additional variables of interest from secondary sources, such as the gross domestic product (GDP) of the departments where the farms were located (national census data, [DANE, 2023](#); [Supplementary Table S5](#)). We calculated some variables using the distance matrix algorithm in QGIS ([QGIS Development Team, 2022](#)), including distance of farms to the closest demonstration farm and distance to the nearest SCR neighbor. We included department size to validate if the barriers to the adoption of SPS changed with the inclusion of this variable.

Environmental data and variables

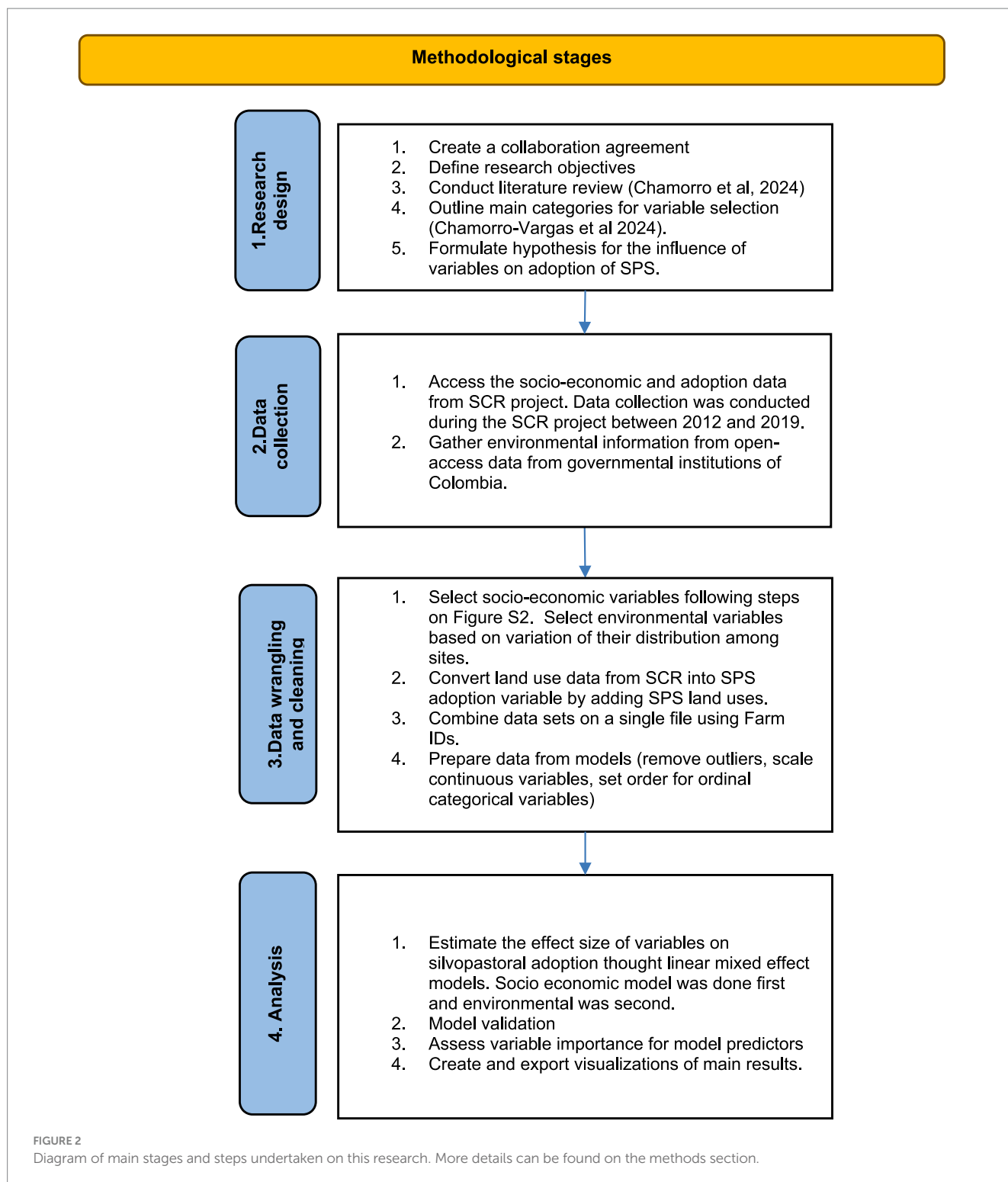
Informed by the systematic literature review of factors influencing adoption of SPS in Latin America ([Chamorro-Vargas, 2024](#); [Chamorro-Vargas et al., 2025](#), submitted manuscript), we gathered environmental information on climate change (e.g., expected changes

in temperature and precipitation in the upcoming years, environmental vulnerability), forest cover, soil conditions (e.g., soil erosion) and water variables (e.g., water demand, humidity) from open-access data provided by governmental institutions of Colombia such as the environmental information system (SIAC), Geographic Institute Agustin Codazzi (IGAC *Datos Abiertos*), and Institute of Hydrology, Meteorology and Environmental Studies (*Geoportal IDEAM*). Data were downloaded from the relevant websites ([Supplementary Table S5](#)), set to the same projection (EPSG: 3116 MAGNA-SIRGAS/Colombia Bogotá zone) and cropped to the extent of the SCR area ([Figure 1](#)). We extracted the target variables of interest ([Supplementary Table S5](#)) associated with each farm coordinate from the vector shapefiles using the function *st_join* in the R sf package ([Pebesma and Bivand, 2023](#)). We explored visualizations of the distributions of each variable of interest and only included variables in the models that showed some variation among sites. Finally, farm level environmental information on presence of forest or water springs collected in the surveys by FEDEGAN was extracted for the environmental data frame to complement the environmental analysis with finer scale data. The final data frame containing farm environmental information included 31 variables for a total of 2,945 farm centroids.

Adoption variable

During the SCR project land use information was collected quantifying the area of each SPS land use type on the farm (i.e., of iSPS, dispersed trees, fodder banks, live fences, and fodder hedges). Although forest protection and natural regeneration were practices targeted under the SCR project, they were not considered in our analysis of adoption of SPS. For the majority of the farms, this data collection was done at the beginning of the project. Some farms were also re-surveyed in a second round of data collection at the end of the project; in total 3,188 farms had land use data from both the beginning and end of the project.

We calculated the SPS adoption variable as the total area on which an SPS practice was implemented for each farm. Here we aimed to understand the process of adoption of all types of SPS together rather than the adoption of each specific feature of SPS ([Jara-Rojas et al., 2020](#)), thus, adoption was measured as the sum of hectares of all types of SPS present in the farms at the end of the SCR project (SPS_{end}). For live fences and fodder hedges measured as linear features in meters, data were transformed to reflect the



area these SPS features occupy in the farm. To calculate area, live fences were assumed to be 3.5 m wide and fodder hedges 1 m wide (Heiber Pantevez, personal observations). iSPS, dispersed trees and fodder banks were measured in hectares. We chose SPS_{end} as the adoption variable instead of the difference of SPS hectares from the beginning of the project to the end (SPS_{change}) because the goal of the study was to understand the total adoption or maintenance of SPS on farms. Further, we deemed this measure more interpretable.

Nevertheless, we explored the SPS_{change} and found that most farms increased their SPS coverage through the project ($N = 2,843$), while a smaller number did not change it ($N = 270$) or decreased ($N = 75$) (Supplementary Table S6).

Data wrangling and cleaning

We merged the adoption dataset ($N = 3,188$ farms) with the socio-economic survey ($N = 3,644$ farms) and environmental

($N = 2,945$ farms) data with the *merge* function in R using the farm ID, which resulted in a sample of 2,986 unique farms with adoption, socio-economic, and environmental data. We identified and removed outliers for the SPS adoption variable using a custom outlier removal function implemented in R. This function uses an interquartile range criterion where data points outside the set bounds were considered outliers. The upper and lower bounds for outliers were defined with the equations $[Q1 - \text{multiplier} * IQR \text{ and } (Q3 + \text{multiplier} * IQR)]$, and a multiplier of 6 was used as default, where $Q1$ = quartile 1, $Q3$ = quartile 3 and IQR = interquartile range ($Q1 - Q3$). This process removed 60 farm sites leading to a final data set of 2,926 farms for the analysis.

Data analysis

Estimating the effect size of variables on the outcome

We used linear mixed effects models fitted by maximum likelihood using *lmer* function in *lmer4* R package version 4.4.2 (Bates et al., 2015) to study the effect size of socio-economic (Model 1) and environmental (Model 2) variables on adoption of SPS (fixed effects Table 4). Both models included region (Figure 3; Supplementary Table S1) and call year (i.e., the year when the farm joined the project, Tables 2, 3) as random effects, since values within each group were expected to be more similar than values between groups due to similarities within regions and within calls. Covariates were also included to account for their effects on the model, such as the amount of SPS coverage in the farm in the baseline (initial) measure of the project (SPS_{baseline}). The response variable for the models (hectares of SPS adopted at the end of the project) were log-transformed, due to their right-skewed distribution (Speekenbrink, 2023). To avoid multicollinearity, correlation matrixes, correlation tests, and principal component analyses were done on the original selection of variables of each model using the R package *factoextra* (Kassambara and Mundt, 2020). For correlated variables, we selected the subset that permitted a complete set of variables based on the systematic literature review of factors influencing the adoption of SPS in Latin America, prioritizing inclusion of variables with highest response rate (Supplementary Table S4; Chamorro-Vargas, 2024; Chamorro-Vargas et al., 2025, submitted manuscript). Our final models included 18 and 11 variables respectively, which falls far below the maximum number of variables that could be estimated in theory, based on the rule of thumb of >10 observations per estimated parameter (Harrison et al., 2018). The assumptions of linear regressions were validated visually using the distribution of residuals (Harrison et al., 2018; Speekenbrink, 2023). We also conducted several additional analyses on data subsets, including analysis of (1) each region separately (Table 2), and (2) each of the specific SPS practices (Dispersed trees, Live fences, iSPS) adopted during the project, to determine if the socio-economic and environmental factors affecting adoption changed.

Linear Mixed Effects Model equation including dependent variable, fixed effects, and random effects. To make the variables comparable all the numeric variables in the dataset were scaled using the *scale* function in R.

$$\log(Y_{ijt}) = \beta_{0jt} + \sum_{k=1}^K \beta_k X_i + \epsilon_{ijt} \quad (1)$$

$$\beta_0 = \gamma_{00} + u_{0j} + v_{0t}$$

Where $\log(Y_{ijt})$ represents the log-transformed SPS adoption in hectares for the i th farm in the j th region and t th call year. $\beta_1, \dots, \beta_K$ are fixed-effect coefficients for the individual-level socioeconomic or environmental predictors (see Table 4 for variables used for each model). β_0 is the intercept, which is made up of a mean component γ_{00} , a random intercept for each region u_{0j} and a random intercept for each call year of the survey v_{0t} . ϵ_{ijt} is the residual error term for each observation.

Assessing variable importance

To assess the importance of the factors influencing adoption we used a model selection algorithm with the *dredge* function in R package MuMIn (Bartoń, 2023) for Model 1 and Model 2. This function uses the Akaike Information Criterion (AIC) metric which balances model fit and complexity. The AIC aids in identifying the variables to include in the most parsimonious model, which are expected to be the most important ones to explain the outcome variable (Bartoń, 2023). Then, we utilized the *glmnet* function (Friedman et al., 2010) to run the Least Absolute Shrinkage and Selection Operator (LASSO) implementation technique, a regularization method widely employed for variable selection and regularization in high-dimensional data settings (Tibshirani, 1996). LASSO penalizes unimportant variables by shrinking their coefficients to zero and keeps the coefficients of the important variables (Tibshirani, 1996). Additionally, using the *bartMachine* R package (Kapelner and Bleich, 2016), we conducted Bayesian Additive Regression Trees (BART), a Bayesian ensemble approach for modeling the unknown relationship between a vector of observed responses y (SPS adoption in this case) and a set of predictor variables, without assuming any parametric functional form for the relationship. For BART, the *var_selection_by_permute* function was used to identify the variables that split the branches of the decision trees more often as they were expected to be important predictors of the adoption of SPS (Bleich et al., 2014). By using three different methods to assess variable importance, and exploring similarities and differences, we increase the robustness of our analysis since each technique has different strengths and limitations.

Results

Farm sample characteristics

The farms in the sample used for the analysis were located across 5 regions of Colombia: Bajo Magdalena (18.3%), Valle del Rio Cesar (22%), Boyacá Santander (16.7%), Ecorregión Cafetera (27%) and Piedemonte Orinocense (15%) (Supplementary Table S1; Chará et al., 2011). The sample showed a relatively high adoption rate of silvopasture overall, with average hectares under any silvopastoral land use of 18.5 hectares by the end of the SCR project, up from 9.5 at baseline (Table 4). Farm areas in the sample are highly variable, with a mean of 34 hectares, and a standard deviation of 84 hectares.

TABLE 4 Dependent variable, fixed effects, and covariates of the socio-economic and environmental model.

Variable	Description	EE	Mean	Std. Dev.
Dependent variable				
Adoption of SPS	Number of hectares of SPS at the end of the SCR in each farm (ha). Source: FEDEGAN survey, Scale: farm scale survey data.	NA	18.530	21.403
Independent socio-economic variables				
Information sources about SCR	Number of sources from where the farmer got information about the SCR project (e.g., television, ruffles, radio, socialization meetings, internet, other people...) *. Source: FEDEGAN survey, Scale: farm scale survey data.	+	1.350	1.093
Distance to closest SCR farm	Distance of the farm to the closest SCR farm measured from a centroid coordinate in the farm to the central coordinate of the closest farm (km). Source: FEDEGAN survey, Scale: farm scale survey data.	+	1.041	1.183
Distance to closest demonstration farm	Distance to the closest demonstration farm (from SCR farm centroid coordinate to demonstration centroid coordinate). There were in total 45 farms exemplar across the country that were intended to show farmers how their farms could look like if they adopted SPS as well as the real-life examples of farm productivity improvements, hence the name demonstration farm. (km). Source: FEDEGAN survey, Scale: farm scale survey data.	–	12.280	9.500
Additional Technical Assistance (TA)	The farmer is receiving additional technical assistance to the one granted by the SCR. 1 = yes, 0 = no. Source: FEDEGAN survey, Scale: farm scale survey data.	+	0.398	0.490
Payments for Ecosystem Services (PES)	Amount of US dollars paid to the farmer in total as PES during the SCR project (\$). Source: FEDEGAN survey, Scale: farm scale survey data.	+	873.97	1397.31
Access to credit	Farmers applied for credit in the past 5 years. 1 = yes, 0 = no. Source: FEDEGAN survey, Scale: farm scale survey data.	+	0.623	0.485
Farm machinery	Number of tools, machines and facilities owned by the farmers for their production (e.g., back pump, electric fence, drinkers, chainsaw, scythe, tractor-pump, cooling tank, stall, storage) *. Source: FEDEGAN survey, Scale: farm scale survey data.	+	5.763	3.271
Use of inputs	Number of inputs reported being used by the farmers includes fertilizers, pesticides, salts, concentrate, hay, chicken manure *. Source: FEDEGAN survey, Scale: farm scale survey data.	–	2.887	1.946
Number of best management practices (BMPs)	Number of BMPs used by the farmers includes capacity, rotation, paddock division, weed control, vaccination, water treatments *. Source: FEDEGAN survey, Scale: farm scale survey data.	+	4.133	1.311
Farm crop diversity	Number of crops grown in the farm (e.g. rice, plantain, yucca, beans...) *. Source: FEDEGAN survey, Scale: farm scale survey data.	+	1.279	1.641
Age	Age of the farmer (years). Source: FEDEGAN survey, Scale: farm scale survey data.	–	54.15	13.45
Gender	Gender of the farmer. 1 = Male, 0 = Female. Source: FEDEGAN survey, Scale: farm scale survey data.	Null	0.684	0.465
Education	Highest level of education obtained by the farmer. 1 = Elementary school, 2 = High School, 3 = Technical degree, 4 = University. Source: FEDEGAN survey, Scale: farm scale survey data.	+	2.343	1.236
Farm area	Area of the farm (ha). Source: FEDEGAN survey, Scale: farm scale survey data.	+	34.17	80.952
Vegetation diversity	Tree and shrub species in pasture per hectare in the farm. 1 = 1–5, 2 = 6–10, 3 = 11–15, 4 = 16–20, 5 = > 20. Source: FEDEGAN survey, Scale: farm scale survey data.	+	2.828	1.719
Gross Domestic Product (GDP)	Total GDP of the department where the farm is located (millions of Colombian pesos (COP)). Source: DANE (2023) , Scale: Department.	+	32.556	21.048
Independent environmental variables				
Forest	Presence of forest on the farm 0 = no, 1 = yes. Source: FEDEGAN survey, Scale: farm scale survey data.	+	0.6275	0.483
Water spring	Presence of spring on the farm 0 = no, 1 = yes. Source: FEDEGAN survey, Scale: farm scale survey data.	+	0.514	0.499
High precipitation anomaly	Abnormally high precipitation measured as standard deviations from historical data (30 years) in 2014, high values indicate abnormally higher levels of rain (which can be related to floods) (mm) Source: IDEAM, 2014, Scale: 1:100,000.	–	1.131	0.587
Hydric vulnerability	Index of hydric vulnerability. 1 = Low, 2 = Medium, 3 = High. Source: IDEAM, 2014, Scale: 1:100,000.	+	2.552	0.619
Water demand	Total water demand of the livestock sector (Millions of m3/years) Source: IDEAM, 2014, Scale: 1:100,000.	+	190,952	126,016
Humidity	Humidity levels according to the lang climate classification (Thornthwaite, 1948). It indicates how dry or humid an area is 1 = Arid, 2 = Semi-arid, 3 = Semi-humid, 4 = Humid, 5 = Superhumid. Source: IDEAM, 2014, Scale: 1:100,000.	+	2.941	0.954

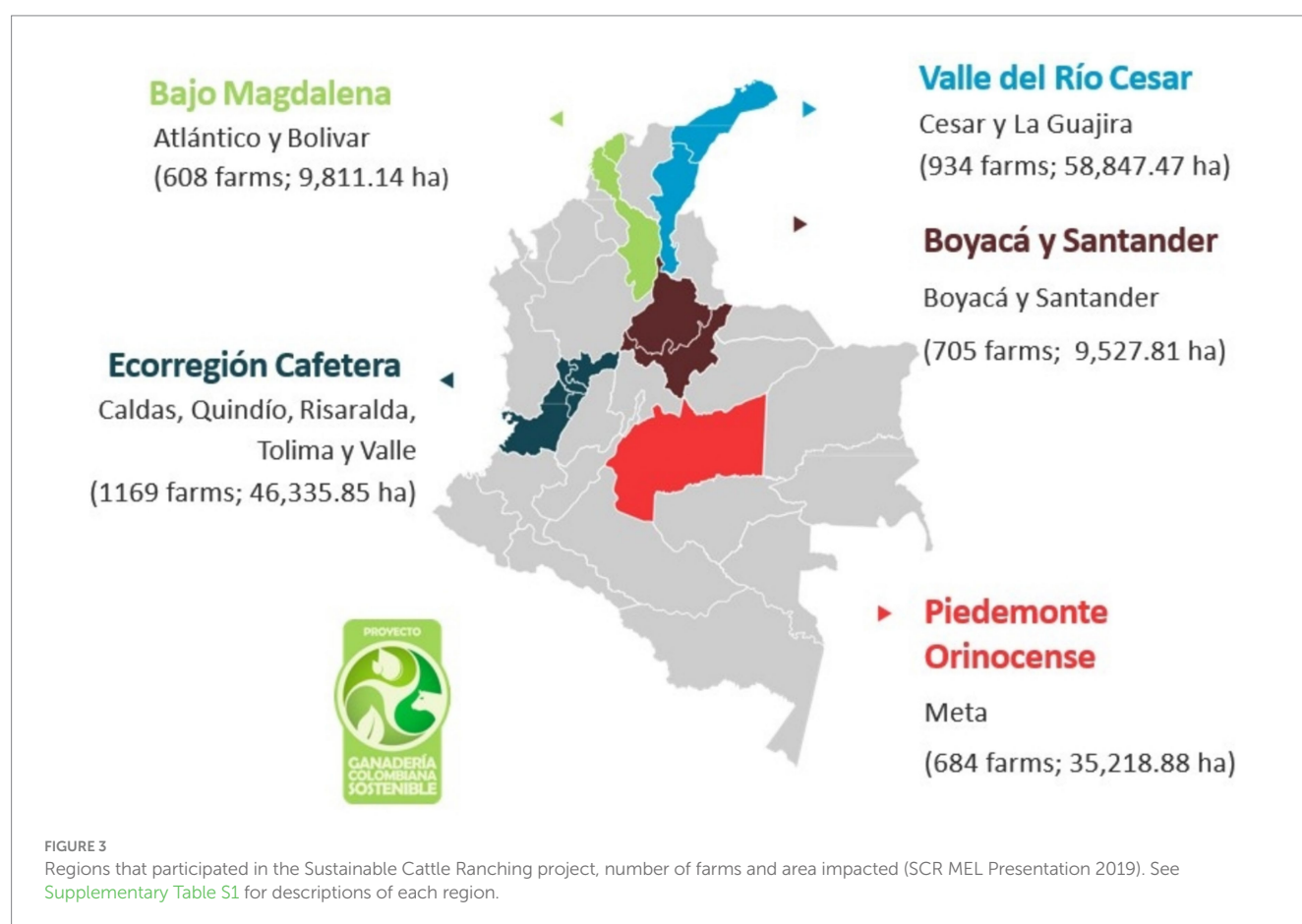
(Continued)

TABLE 4 (Continued)

Variable	Description	EE	Mean	Std. Dev.
Environmental vulnerability	Environmental vulnerability considers climate change vulnerability, human population sensitivity and adaptation capacity for 2011–2040. 1 = Low, 2 = Medium, 3 = High, 4 = Very high. Source: IDEAM, 2023, Scale: 1:100,000.	–	2.795	0.519
Soil erosion level	Zoning of soil degradation by erosion, baseline 2010–2011. 1 = No erosion evidence, 2 = Light erosion, 3 = Moderate erosion, 4 = Severe erosion. Source: IGAC, 2014, Scale: 1:100,000.	–	1.523	0.765
Precipitation_change_2040	Calculated precipitation changes for Colombia (%) for 2011–2040 vs. 1976–2005. Source: IDEAM, 2014, Scale: 1:100,000.	–	3.714	1.211
Change_temperature_2070	Calculated maximum temperature difference between the climate of 2071 to 2100 vs. 1971 to 2000. 1 = (1–2), 2 = (2–3), 3 = (3–4), 4 = (4–5), 5 = (5–6). (°C). Source: IDEAM, 2014, Scale: 1:100,000.	–	3.051	0.679
Covariates for both models				
SSP _{baseline}	Total SPS area at the beginning of the project (ha). Source: FEDEGAN survey, Scale: farm scale survey data.	+	9.573	16.324
Call year	Year when the farm joined the project. 1 = 2011, 2 = 2012, 3 = 2015, 4 = 2018. Source: FEDEGAN survey, Scale: farm scale survey data.	+	2.393	0.485

The full equations for both models are found in [Equations S1, S2](#). Summarized variables are indicated with a *.

EE, Expected effect on adoption; Std Dev, standard deviations of the variable. More detailed descriptions of secondary environmental variables can be found on [Supplementary Table S5](#).



The main type of cattle production in all the regions was dual purpose (i.e., meat and milk production) (66.5%), meat only (13.6%), breeding (11.7%) and milk only (8.2%). Most of the farmers in the sample were male (67.7%). Regarding education, most farmers had completed primary school (32.3%) and secondary education (25.6%), which is in accordance with national census data, and the second largest group of the sample (28.6%) had achieved university education (DANE, 2016). Farmers in this sample received a relatively high but varying

amount of financial support in order to encourage silvopasture adoption. The average number of dollars received was 874 USD. 40% of the sample also reported receiving technical assistance in addition to the assistance provided by the SCR project, and 62% reported applying for credit. The mean number of mechanical implements owned by the farms was 5.7, and mean number of inputs such as fertilizer and pesticides was 2.9. See [Table 4](#) for full summary statistics on all variables used in our analysis.

Socio-economic analysis

Socio-economic model

For the socio-economic model (Model 1), PES had the largest significant positive effect on the number of hectares adopted by farmers during the project, whereas access to credit and farm area did not significantly affect adoption (Figure 4). Farm characteristics including farm machinery and GDP of the region where the farm was located had a positive significant effect on adoption. Various farm management aspects were also influential on the adoption of SPS. Farms that used more inputs like fertilizers and pesticides adopted fewer hectares of SPS than farms that used less inputs (Figure 4). In contrast, farms that already used best management practices (BMPs) such as water and forest protection, paddock rotation and division, and crop diversification, had more adoption. In contrast, vegetation diversity (i.e., the number of tree and shrub species in pasture per hectare on the farm) did not significantly affect adoption of SPS. Most of the information transfer variables had a null effect on adoption, except for distance to the closest SCR farm, which had a significant positive effect on adoption, meaning that farms adopted more hectares of SPS when they were further from other SCR farms. Farmers' characteristics such as gender, age and education did not have a significant effect on adoption. As expected, the covariate hectares of SPS_{baseline} had a large positive effect on the amount of SPS at the end of the project. We found similar results when including department size in our model, except that while department size is a significant predictor (driven largely by a single, large department with significant adoption), local GDP becomes insignificant (Supplementary Figure S3).

We found differences compared to the full dataset when separately analyzing adoption in each region (Supplementary Figure S4) and for each SPS practice (Supplementary Figure S5). For instance, economic incentives such as PES were only positively significant in three of the studied regions: Magdalena, Cesar and Orinoco (Supplementary Figure S4) and for two of the SPS adoption practices: dispersed trees and live fences (Supplementary Figure S5). Farm characteristics, such as farm area, had a positive significant effect on adoption of SPS in most of the regions (Supplementary Figure S4) and for most practices (Supplementary Figure S5). While the specific variables for management, information transfer and farmers' characteristics varied slightly, the regional and practice level models resembled the general model trend of good management practices being positive for adoption, and that most information sources and farmers characteristics were not significant.

Socio-economic variable importance

The most important classes of variables from Model 1 were economic incentives and farm characteristics (Table 5). PES was ranked as important in all three variable selection procedures (i.e., AIC, LASSO, BART), followed by farm machinery and GDP, which appeared in two of the methods (Table 5). Farm area was another important variable in the farm characteristics category, although it only appeared in the BART result (Table 5). Management variables are important in at least one of the variable selection methods were number of BMPs and crop diversity (Table 5). Information transfer and farmer characteristics variables were not ranked as important by any of the selected methods, confirming their lack of significance. As expected, the covariate SPS_{baseline} had the largest fixed effect, coefficient, and variable inclusion proportion. The variable selection results are in accordance with the results of the model (Figure 4).

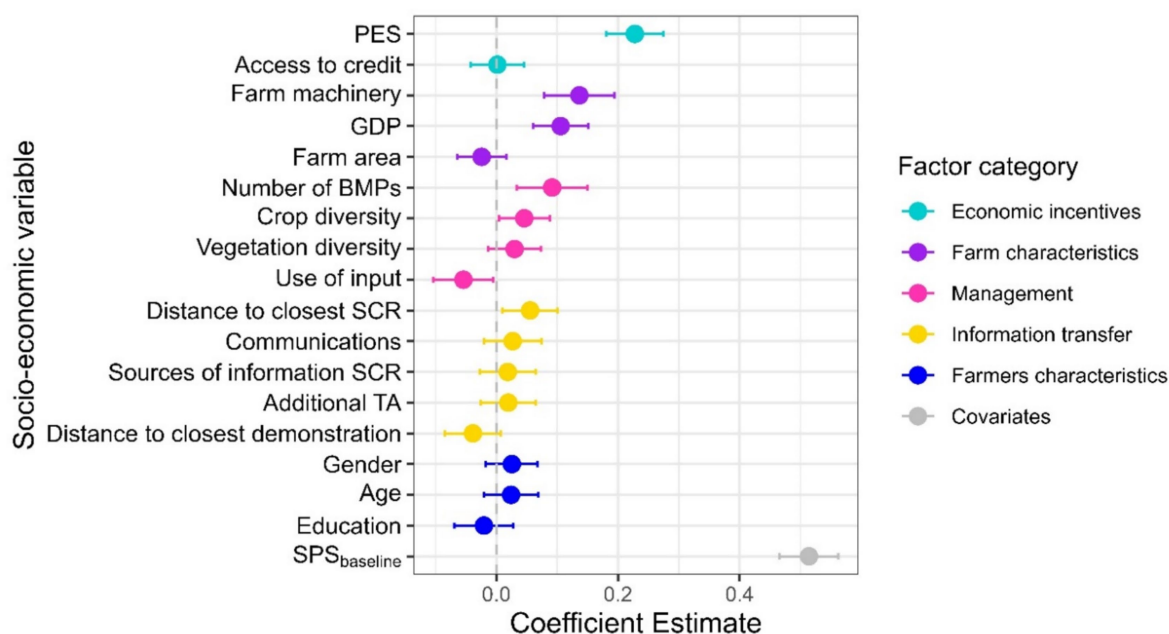


FIGURE 4
Results of Socio-Economic mixed effect model (Model 1). Effect sizes, confidence intervals. Additional details of the models are in Supplementary Table S7 and Equation 1.

TABLE 5 Results of variable importance assessment methods for socio-economic variables.

Variable	Dredge (AIC)	LASSO	BART
PES	FE = 0.2222	C = 0.1994	VIP = 0.1083
Farm machinery	FE = 0.1241	C = 0.0189	
GDP	FE = 0.1094		VIP = 0.1440
Number of BMPs	FE = 0.0885		
Crop diversity		C = 0.0170	
Farm area			VIP = 0.1168
SPS _{baseline}	FE = 0.5,165	C = 0.5408	VIP = 0.1604

FE, Fixed effect; C, coefficient; VPI, Variable inclusion proportion. The variables omitted in this table did not appear as important variables in any of the methods used.

Environmental analysis

Environmental model

For the environmental model (Model 2), farm characteristics such as soil conditions, forest presence, water conditions and vulnerability to climate change had a significant effect on adoption of SPS (Figure 5). For example, soil erosion was found to have a positive significant effect on adoption in Model 2. The presence of forests and springs on the farm also had a positive influence on adoption. In contrast, humidity, water demand and environmental vulnerability to climate change negatively affected the number of SPS hectares adopted by farmers during the SCR project (Figure 5). Hydric precipitation anomaly, precipitation changes by 2040, temperature change by 2070 and hydric vulnerability did not significantly affect adoption, although the trend of their effect was negative (Figure 5). Similarly to Model 1, we found that the results of this model varied across regions (Supplementary Figure S6) and practices (Supplementary Figure S7). For instance, the vulnerability variables that had a significant negative effect on adoption in the full dataset changed across regions and constrained adoption (Supplementary Figure S6). Hydric vulnerability had a negative significant effect in Cesar and Orinoco, whereas precipitation anomalies affected Boyacá & Santander, and environmental vulnerability to climate change affected Magdalena and the Coffee region (Supplementary Figure S6). The presence of forest and arid conditions had a negative significant effect on the adoption of dispersed trees, while precipitation change by 2040 had a positive significant effect on the adoption of iSPS (Supplementary Figure S7).

Environmental variable importance

The most important variables from Model 2 were water conditions and vulnerability to climate change (Table 6). Water demand was the most important variable being ranked in all the methods used, followed by humidity and high precipitation anomaly, which appeared in two of the methods (Table 6). Water spring presence was another important variable, although it only appeared in the AIC methodology (Table 6). As expected, the covariate SPS_{baseline} had the largest fixed effect, coefficient, and variable inclusion proportion. Although the model found soil erosion and presence of forest on farm as significant predictors of adoption (Figure 5), these variables were not selected with the methodologies used to rank variable importance. Further, precipitation anomalies experienced by the farms were not significant in the model (Figure 5) but were ranked by variable selection methods (Table 6).

Discussion

Enablers and barriers to adoption SPS in Colombia

Economic incentives

Studies on adoption of agriculture technology around the world show how economic incentives are an effective way of overcoming initial reluctance from farmers to adopt new practices (Liu et al., 2018; Begho et al., 2022; Priya and Singh, 2024). Furthermore, studies on scaling out SPS in Colombia have found that lack of capital for investment is one of the main barriers for adoption in the country (Calle et al., 2013; Lerner et al., 2017; Jara-Rojas et al., 2020). We found that PES was the strongest positive socioeconomic predictor for adoption of SPS, and that it was consistently ranked as an important predictor of SPS adoption. Our study thus concurs with other works showing that economic incentives are an important mechanism for promoting adoption of SPS, by helping farmers overcome initial economic barriers, such as the costs associated with planting (Cerrud Santos, 2004; Casasola Coto et al., 2007; Pagiola et al., 2007; Calle et al., 2013; Lerner et al., 2017; Calle, 2020; Jara-Rojas et al., 2020). Furthermore, PES can be seen by farmers as a support for their stewardship values, encouraging them to continue their ongoing care for their land and forest (Chapman et al., 2020). In contrast, we did not find that access to credit influenced SPS adoption. A possible reason for the lack of importance of access to credit was that other economic variables such as PES, farm machinery and farm area overshadowed any effect access to credit had on adoption. Further, the variable access to credit used in this study was based on whether a farmer applied for a credit but did not indicate whether they obtained credit. There were multiple steps for credit approval, and many SCR farmers were subsequently denied credit. Thus, the variable that we had access to from the survey did not fully capture actual access to credit. Our work suggests that future SPS promotion projects can use economic incentives such as PES to increase the probability of adoption of SPS, potentially including both initial uptakes, as well as increase in amount (hectares) of adoption. Access to credit should be further investigated for its potential to increase adoption.

Farm characteristics

Previous studies on agriculture adoption have also found that lack of capital for investment affects farmers differently (Holguín et al., 2003; Cerrud Santos, 2004; López et al., 2007; Zabala et al., 2022). For instance, studies have found that wealthier farmers who own larger farms and more machinery tend to have more capital for investing in SPS and can afford to devote a larger area of their lands to SPS (Frey et al., 2012; Cárdenas Gutiérrez, 2014; Bussoni et al., 2015; Gosling et al., 2020; Babi, 2021; Apan-Salcedo et al., 2022). In accordance with this expectation, we found that farms with more machinery adopted more SPS, and that farm area had a significant effect on adoption for most regions and SPS practices. Machinery can help farmers with the management of SPS, making tasks such as preparing soil for planting, pruning trees, mowing grass and watering plants more efficient and less labor-intensive. Furthermore, we observed that farms located in departments with higher GDP had higher adoption of SPS, which was expected according to the literature on adoption of agriculture innovation which finds that wealthier regions have higher capacity for investment (Feder et al., 1985; Mwangi and Kariuki, 2015). Both farm

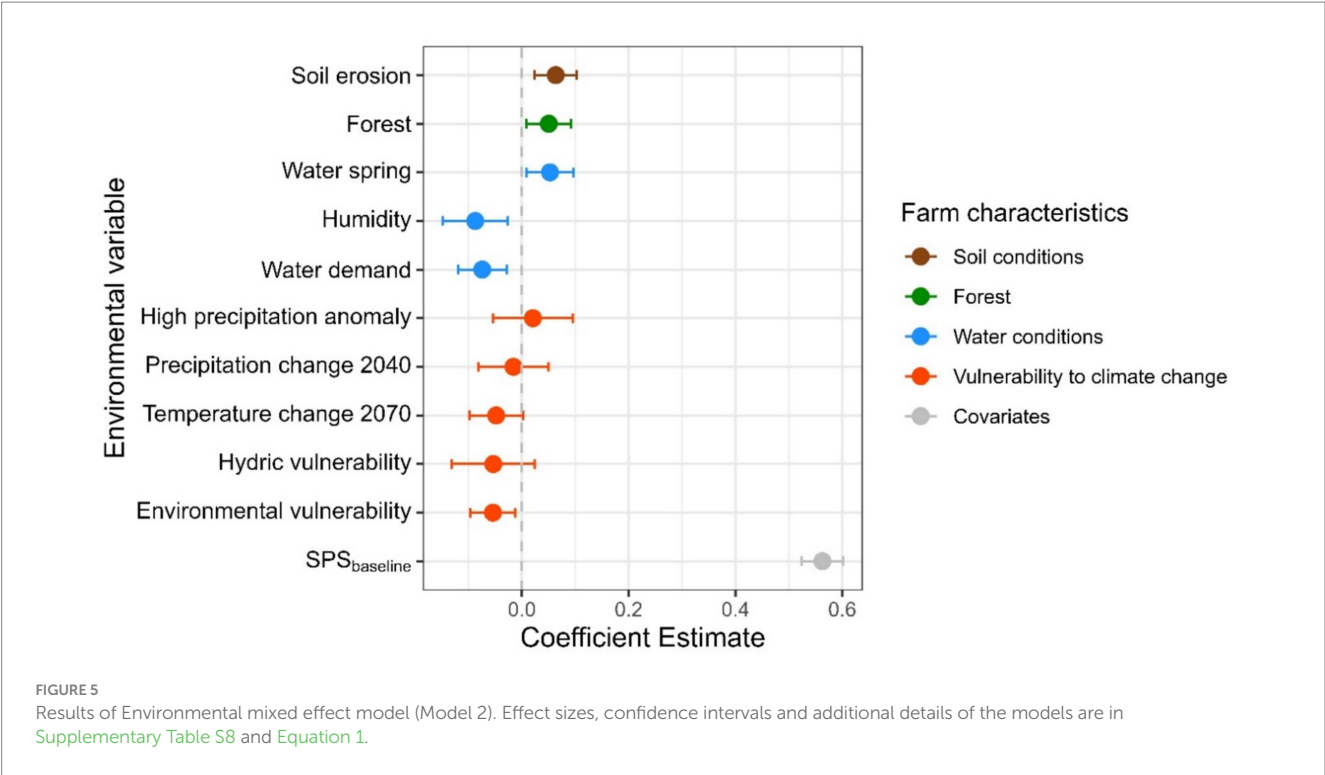


TABLE 6 Results of variable importance assessment methods for environmental variables.

Variable	Dredge (AIC)	LASSO	BART
Water demand	FE = −0.0671	C = −0.0933	VIP = 0.1367
Humidity	FE = −0.0791	C = −0.0607	
High precipitation anomaly		C = 0.0557	VIP = 0.1365
Water spring	FE = 0.0678		
SPS _{baseline}	FE = 0. 5,735	C = 0.5482	VIP = 0.2836

FE, Fixed effect; C, coefficient; VPI, Variable inclusion proportion. The variables omitted in this table did not appear as important variables in any of the methods used.

machinery and GDP were ranked as important variables in at least two of the variable selection methods used, demonstrating their importance for the adoption of SPS. These results highlight that the implementation cost of SPS is likely an important barrier to adoption for farms with less wealth and capital for investment (Calle et al., 2013; Lerner et al., 2017; Jara-Rojas et al., 2020). Future projects and research should create initiatives and interventions that consider the heterogeneity of farmer populations in each region and develop appropriate programs to reach socially and economically vulnerable groups for which adopting SPS is more challenging.

Given the constraints climate change imposes on agricultural production, environmental factors, such as poor soil and water conditions and less predictable climates leading to higher vulnerability to climate change, were expected to have a negative effect on adoption. For instance, some authors have found that the fear of investing in trees that might not survive intense climatic events keeps farmers from adopting silvopasture (Calle et al., 2009; Calle, 2020; Lee et al., 2020; Apan-Salcedo et al., 2022). We found that most environmental factors did constrain adoption of SPS, except for presence of forest and water springs on farms and high levels of soil erosion, each of which promoted adoption. The

presence of forest and water springs on the farm can be related to the environmental values of farmers that are in close contact with nature which could motivate them to adopt more hectares of SPS. For instance, the protection of water sources, biodiversity and forests is frequently mentioned as a motivation to adopt SPS by farmers in literature of Latin America (Calle, 2020; Rizo-Chavarría et al., 2022; Timoteo et al., 2023; Chamorro-Vargas, 2024; Chamorro-Vargas et al., 2025, submitted manuscript), and may also help farmers adapt to climate extremes of drought or flood. Additionally, the expectation of soil recovery is another strong motivator for adoption of SPS in Latin America (Oliva et al., 2018; Olival et al., 2022; Rizo-Chavarría et al., 2022). Thus, farmers experiencing high levels of soil erosion could be motivated to adopt SPS.

Farmer characteristics and management

Farmer characteristics, management practices and preferences are some of the most studied factors in the literature on adoption of SPS in Latin America (Chamorro-Vargas, 2024; Chamorro-Vargas et al., 2025, submitted manuscript). In general, no conclusive trends exist regarding the influence of age, gender or

education on the adoption of sustainable practices (López et al., 2007; Garbach et al., 2012; Cancino et al., 2016; Torres, 2016; Rasch et al., 2021). However, farmers' preferences and management practices were found to be important to the adoption of SPS (Torres, 2016; Sibelet et al., 2017; Stefano et al., 2020). The results of this analysis are in accordance with previous studies that found a null effect of age, gender and education on adoption of SPS (Patiño et al., 2012; Apan-Salcedo et al., 2022). Furthermore, we found that management variables had significant effects on adoption, where farmers who use more sustainable management practices (less external inputs, more crop diversity, and more use of BMPs) adopted more SPS than farmers that use less environmentally friendly practices, with crop selection and use of BMPs ranked as important variables. Management decisions taken by farmers can be influenced by farmers' preferences, stewardship and environmental values which lead them to have strong personal motivations to improve their farms and pass them to the next generations demonstrating long-term motivations (Calle, 2008, 2020; Smith et al., 2022). Furthermore, SPS_{baseline} had a large positive significant effect on the amount of SPS adopted, which means that farms with SPS have great potential for further adoption. Promotion projects can target farmers who already have strong environmental values and that already have adopted SPS regardless of their age, education, or sex to achieve a greater area of adoption of SPS.

Information transfer

Communication among farmers, sources of information and short distances between farms were expected to have a positive influence on adoption because communication facilitates information transfer about implementation of new systems and can increase the likelihood of neighbors to adopt (Anfinnsen et al., 2009; Frey et al., 2012; Apan-Salcedo et al., 2022). However, in this study, most of the variables related to information transfer did not have a significant effect on adoption, except for distance to closest SCR farm, which had the opposite effect than expected, where farms that were more separated from each other adopted more SPS area. A possible reason for this result is that larger farms are expected to be farther apart from each other, since the distance between farms was measured from a central coordinate of each farm. While economic factors had greater explanatory power on SPS adoption than social factors in our study, it is nonetheless well documented in the literature that social networks are important for creating synergies and communication, impacting collaboration, promoting social acceptance, and acting as a main driver of adoption (Liu et al., 2018; Tapasco et al., 2019; Blesh et al., 2023).

Furthermore, studies on factors influencing adoption of agroforestry practices consistently found technical assistance (TA) to be a crucial factor promoting adoption (Cerrud Santos, 2004; Nascimento et al., 2014; Lerner et al., 2017; Tapasco et al., 2019; Babi, 2021; Smith et al., 2022). TA helps farmers overcome one of the main barriers for adoption, which is lack of knowledge (Calle et al., 2013). In this study we found a null effect of additional TA obtained by farmers on adoption, which may be because TA was provided by the SCR project to all of the farmers. While the TA provided by the project most likely had a significant positive effect on adoption, its influence could not be assessed because it was

provided to all farms in the sample. In spite of our finding, based on other literature, future studies and projects can use TA and extension programs to promote SPS adoption, given that lack of knowledge and awareness of SPS is one of the main current barriers to adoption (Cancino et al., 2016; Castillo Ruíz, 2019; Tapasco et al., 2019; Calle, 2020; Tarbox et al., 2020), and that SPS implementation is a complex process requiring substantial learning and experimentation by each practitioner (personal observations). Furthermore, future studies could explore in detail how the amount and quality of TA and farmer participation in TA workshops influences SPS adoption.

Limitations and future steps

Our study contributes to the literature on the factors that influence the adoption of an agroecological diversification technique, SPS, thereby revealing pathways to help scale out agricultural transformation. However, several limitations affected our study. The survey data had better quality and completeness in some variables than others. Regarding environmental data, as the model was created from open access data collected at national scale, it is constrained by the coarse scale of many of the variables (1:100,000), leading to limitations on the conclusions that can be made from this data as some of the intra-regional variability is lost due to the coarse resolution of the data. Further, many variables were not possible to assess despite their expected relevance to adoption of SPS according to the literature, such as membership in local organizations, farmers' wealth, and macro-scale factors. Membership in local organizations and farmers' wealth were included in the survey but had a low response rate leading to a large proportion of missing answers. However, all of the mentioned variables should be studied in future work to better understand their influence in the adoption of SPS. While this project studies the factors influencing adoption of SPS, future projects should also assess how long-term adoption in turn affects farmers' socio-economic conditions, climatic risk, biodiversity conservation and carbon sequestration. We recommend that future projects follow some of the steps undertaken by the SCR to promote replicability of the results. For example, the SCR defined a minimum baseline information set, comprising: (i) georeferenced delimitation of farms; (ii) census of the interventions by participant cohort; (iii) standardized instruments and protocols, with pilot projects and training for interviewers; (iv) digital traceability with unique IDs (farm), georeferencing, and timestamps for survey completion; (v) registration of indicators with operational definitions; (vi) core sets of comparable social, economic, and productive variables; (vii) quality assurance (variable dictionary, validation rules, and version control); and (viii) ethical guidelines, informed consent, and data anonymization. Future research should also focus on assessing the causal evidence for different interventions related to promoting SPS, which would require either experimental or quasi-experimental variation in interventions such as PES, technical assistance, credit provision, or in-kind transfers. We also recommend exploring in further detail the relationship between adoption and departmental size.

Conclusion

The results of this study strongly suggest that farmers are willing to adopt more sustainable production practices despite the current challenges they face if appropriate incentives, such as PES, are given. In addition to economic variables (PES, GDP), social (Distance to the closest farm and environmentally friendly management practices) and environmental factors (soil erosion, presence of forest, presence of water spring on farm, farm humidity, water demand, and environmental vulnerability) modified the extent to which farmers adopted SPS; therefore, it is important to recognize and use the existing enablers to leverage the effects of future efforts promoting SPS. Promoters of SPS should work to find solutions to overcome barriers to adoption by smaller, less capitalized, and more environmentally vulnerable farms. It is urgent to transform the current agriculture systems to achieve sustainability on food production and face the global environmental crisis.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the datasets presented in this article are not readily available because of ethical, legal and privacy issues. Requests to access these datasets should be directed to mgomez@fedegan.org.co.

Ethics statement

The studies involving humans were approved by Behavioral Research Ethics Board of the University of British Columbia with the code H23-00804. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

C-VC: Writing – review & editing, Formal analysis, Project administration, Data curation, Writing – original draft, Methodology, Visualization, Conceptualization. MS: Supervision, Writing – review & editing, Methodology, Conceptualization. PH: Writing – review & editing, Data curation. GM: Data curation, Writing – review & editing, Resources. KeC: Methodology, Conceptualization, Writing – review & editing, Funding acquisition. KrC: Methodology, Conceptualization, Writing – review & editing, Funding acquisition, Supervision.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The authors acknowledge the support of The Nature Conservancy via the Colombia Sustainable Cattle Ranching Monitoring and Evaluation Project grant number F23-02060 and TNC's Global Science program. Philip A. Jones Fellowship funded by University of British Columbia awards (Grant number 6700).

Acknowledgments

We would like to thank all the farmers that participated in the Sustainable Cattle Ranching project (Ganadería Colombiana Sostenible) and made this research possible. We also want to acknowledge all the people that were part of the Sustainable Cattle Ranching project such as member of the Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria (CIPAV), The Nature Conservancy (TNC) and the Cattle Ranching Federation of Colombia (FEDEGAN) and Fondo Acción. Thanks to Hannah Wittman and Terre Satterfield for their invaluable suggestions on the original draft. This research paper was submitted as part of the master thesis of Carol Tatiana Chamorro Vargas at the University of British Columbia, named *Revealing the pathways to scale out agricultural transformation: factors influencing adoption of silvopastoral systems*.

Conflict of interest

GM and PH were employed by The Cattle Ranching Federation of Colombia (FEDEGAN) during the development of this study.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1600091/full#supplementary-material>

References

- Adams, M. L. (2009). Pasture extensification in the southern Ecuadorian Andes: appraisal and recommendations. *J. Sustain. For.* 28, 866–887. doi: 10.1080/10549810902936649
- Almeida, L. L. S., Frazão, L. A., Lessa, T. A. M., Fernandes, L. A., de Carvalho Veloso, A. L., Lana, A. M. Q., et al. (2021). Soil carbon and nitrogen stocks and the quality of soil organic matter under silvopastoral systems in the Brazilian Cerrado. *Soil Tillage Res.* 205:104785. doi: 10.1016/j.still.2020.104785
- Anfinnsen, B., Aguilar-Stoen, M., and Vatn, A. (2009). Cattle farmers' attitudes toward the implementation of silvopastoral systems in Peten, Guatemala. *Agroforestería en las Américas* 47, 20–26.
- Apan-Salcedo, G. W., Nahed-Toral, J., Pérez-Luna, E., Piñeiro-Vázquez, Á., and Jiménez-Ferrer, G. (2022). Level of adoption of silvopastoral techniques in the Sierra Madre de Chiapas, Mexico. *Trop. Subtrop. Agroecosyst.* 25, 1–15. doi: 10.56369/tsaes.4001
- Aryal, D. R., Morales Ruiz, D. E., Tondopó Marroquín, C. N., Pinto Ruiz, R., Guevara Hernández, F., Venegas Venegas, J. A., et al. (2018). Soil organic carbon depletion from forests to grasslands conversion in Mexico: a review. *Agriculture* 8:181. doi: 10.3390/agriculture8110181
- Ayala, K., Melo, A., Zuluaga, A. F., Chica, D., Gómez, J. C., and Uribe, F. (2017). Manual de usos de la tierra. Marcela Chaves. (ed.) Colombia: Proyecto Ganadería Colombiana Sostenible.
- Babi, H. A. (2021). Factores que inciden en la adopción de tecnología en pequeños productores de sistemas silvopastoriles del Municipio de Itacaruaré, Misiones, Tesis de Maestría: Universidad de Buenos Aires. Facultad de Agronomía. Escuela para Graduados.
- Ballesteros-Correa, J., and Pérez-Torres, J. (2022). Silvopastoral and conventional management of extensive livestock and the diversity of bats in fragments of tropical dry forest in Córdoba, Colombia. *Agrofor. Syst.* 96, 589–601. doi: 10.1007/s10457-021-00698-4
- Bartoñ, K. (2023). MuMin: multi-model inference. Available online at: <https://cran.r-project.org/web/packages/MuMin/index.html> (Accessed March 6, 2024).
- Bates, D., Mächler, M., Bolker, B., and Walker, S. (2015). Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67, 1–48. doi: 10.18637/jss.v067.i01
- Becking, J. B. T., Ramirez, M., and Bernia, L. (2021) Building pathways to sustainable cattle ranching in Colombia: why and how private sector should engage and support the sustainable transformation of cattle production in Colombia. World Bank. Available online at: <http://documents.worldbank.org/curated/en/653941623047310683/Building-Pathways-to-Sustainable-Cattle-Ranching-in-Colombia-Why-and-How-Private-Sector-Should-Engage-and-Support-the-Sustainable-Transformation-of-Cattle-Production-in-Colombia> (Accessed February 8, 2023).
- Begho, T., Glenk, K., Anik, A. R., and Eory, V. (2022). A systematic review of factors that influence farmers' adoption of sustainable crop farming practices: lessons for sustainable nitrogen management in South Asia. *J. Sustain. Agric. Environ.* 1, 149–160. doi: 10.1002/sae2.12016
- Bleich, J., Kapelner, A., George, E. I., and Jensen, S. T. (2014). Variable selection for BART: an application to gene regulation. *Ann. Appl. Stat.* 8, 1750–1781. doi: 10.1214/14-AOS755
- Blesh, J., Mehrabi, Z., Wittman, H., Kerr, R. B., James, D., and Madsen, S. (2023). Against the odds: network and institutional pathways enabling agricultural diversification. *One Earth* 6, 479–491. doi: 10.1016/j.oneear.2023.03.004
- Bussoni, A., Juan, C., Fernández, E., Boscana, M., Cubbage, F., and Bentancur, O. (2015). Integrated beef and wood production in Uruguay: potential and limitations. *Agrofor. Syst.* 89, 1107–1118. doi: 10.1007/s10457-015-9839-1
- Calle, A. (2008). What makes an early adopter? Transforming landscapes one farmer at a time. *Trop. Resour. Res.* 27, 7–14.
- Calle, A. (2020). Can short-term payments for ecosystem services deliver long-term tree cover change? *Ecosyst. Serv.* 42:101084. doi: 10.1016/j.ecoser.2020.101084
- Calle, A., Montagnini, F., and Zuluaga, A. F. (2009). Farmer's perceptions of silvopastoral system promotion in Quindío, Colombia. *Bois et Forêts des Tropiques* 300, 79–94.
- Calle, Z., Murgueitio, E., and Chará, J. (2011). Integrating forestry, sustainable cattle-ranching and landscape restoration. *Unasylva (English ed.)* 63, 31–40.
- Calle, Z., Murgueitio, E., Chará, J., Molina, C. H., Zuluaga, A. F., and Calle, A. (2013). A strategy for scaling-up intensive Silvopastoral systems in Colombia. *J. Sustain. For.* 32, 677–693. doi: 10.1080/10549811.2013.817338
- Cancino, R. M. Z., Zebadúa, M. E. V., Toral, J. N., Garay, A. H., and Martínez Tinajero, J. J. (2016). Adoption of silvopastoral systems and the sociocultural context of producers: support and limitations [Adopción de sistemas silvopastoriles y contexto sociocultural de los productores: Apoyos y limitantes]. *Revista Mexicana De Ciencias Pecuarias* 7, 471–488. doi: 10.22319/rmcp.v7i4.4282
- Cárdenas Gutiérrez, J. M. (2014). Balance de gases de efecto invernadero y efectividad del pago por servicios ambientales en fincas ganaderas, península de Nicoya, Costa Rica. Available online at: <https://repositorio.catie.ac.cr/handle/11554/7092> (Accessed August 2, 2023).
- Carrera, R., Fierro, N., Jiménez, L., and Capa Mora, D. (2021). Good practices of sustainable livestock in the ecosystem of Páramo and Bosque alto Andino, an alternative of resilience to climate change. *REVISTA FAVE - Sección Ciencias Agrarias* 20, 7–19.
- Casasola Coto, F., Ibrahim, M. A., Ramírez, E., Villanueva, C., Sepúlveda López, C. J., and Araya, J. L. (2007). Pago por servicios ambientales y cambios en los usos de la tierra en paisajes dominados por la ganadería en el trópico subhúmedo de Nicaragua y Costa Rica. Available online at: <https://repositorio.catie.ac.cr/handle/11554/7947> (Accessed October 2, 2023).
- Castillo Ruiz, C. P. (2019). Factores que limitan la adopción de los sistemas agroforestales pecuarios por parte de ganaderos en la microcuenca agua negra, abastecedora del acueducto municipal de Puerto Asis- Putumayo. Available online at: <https://ridum.umanizales.edu.co/handle/20.500.12746/3443> (Accessed March 29, 2023).
- Ceballos, G., Ehrlich, P. R., Barnosky, A. D., García, A., Pringle, R. M., and Palmer, T. M. (2015). Accelerated modern human-induced species losses: entering the sixth mass extinction. *Sci. Adv.* 1:e1400253. doi: 10.1126/sciadv.1400253
- Cedamon, E., Nuberg, I., Pandit, B. H., and Shrestha, K. K. (2018). Adaptation factors and futures of agroforestry systems in Nepal. *Agrofor. Syst.* 92, 1437–1453. doi: 10.1007/s10457-017-0090-9
- Cerrud Santos, H. N. (2004). Efecto del pago por servicios ambientales y otras variables socioeconómicas en la adopción de usos del suelo amigables con el ambiente en zonas ganaderas de Esparza, Costa Rica y Matiguás, Nicaragua. [Internet]. [Turrialba, Costa Rica]: Centro Agronómico Tropical De Investigación Y Enseñanza Programa De Enseñanza Para El Desarrollo Y La Conservación Escuela De Posgrado; 2004 [cited 2025 Oct 9]. Available online at: <https://repositorio.catie.ac.cr/handle/11554/4923>. (Accessed Oct 9, 2025)
- Chamorro-Vargas, C. T. (2024). Revealing the pathways to scale out agricultural transformation: factors influencing adoption of silvopastoral systems. Vancouver, B.C, Canada: University of British Columbia.
- Chamorro-Vargas, C. T., Cudney-Valenzuela, S., Morgan, S., and Kremen, C. (2025). Review of factors influencing the adoption of Silvopastoral systems in Latin America: Discover Agriculture.
- Chapman, M., Satterfield, T., Wittman, H., and Chan, K. M. A. (2020). A payment by any other name: is Costa Rica's PES a payment for services or a support for stewards? *World Dev.* 129:104900. doi: 10.1016/j.worlddev.2020.104900
- Chará, J., and Murgueitio, E. (2005). The role of silvopastoral systems in the rehabilitation of Andean stream habitats. *Livest. Res. Rural. Dev.* 2, 1–11.
- Chará, J., Murgueitio, E., Zuluaga, A., and Giraldo, C. (2011). Ganadería Colombiana Sostenible. 2da Edición Edn. Cali, Colombia: Fundación CIPAV.
- Clavero, T., and Suárez, J. (2006). Limitaciones en la adopción de los sistemas silvopastoriles en Latinoamérica. *Pastos y Forrajes* 29, 1–6.
- Clerici, N., Salazar, C., Pardo-Díaz, C., Jiggins, C. D., Richardson, J. E., and Linares, M. (2019). Peace in Colombia is a critical moment for Neotropical connectivity and conservation: save the northern Andes-Amazon biodiversity bridge. *Conserv. Lett.* 12:e12594. doi: 10.1111/connl.12594
- Cuevas Reyes, V., Baca del Moral, J., Cervantes Escoto, F., Espinosa García, J. A., Aguilar Ávila, J., and Loaiza Meza, A. (2013). Factores que determinan el uso de innovaciones tecnológicas en la ganadería de doble propósito en Sinaloa, México. *Revista mexicana de ciencias pecuarias* 4, 31–46.
- Dagang, A. B. K., and Nair, P. K. R. (2003). Silvopastoral research and adoption in Central America: recent findings and recommendations for future directions. *Agrofor. Syst.* 59, 149–155. doi: 10.1023/A:1026394019808
- DANE (2016). Tercer Censo Nacional Agropecuario: Resultados Tomo II. 1st Edn. Bogota: Departamento Administrativo Nacional de Estadística.
- DANE (2023). Geoportal del DANE - Geovisor PIB Departamental Base 2015. Available online at: <https://geoportal.dane.gov.co/geovisores/economia/pib-departamental/> (Accessed March 7, 2024).
- Dubeux, J. C. B., Jaramillo, D., Santos, E. R. S., Garcia, L., and Queiroz, L. D. (2017). Tree legumes: an underexploited resource in warm-climate silvopastures. *Rev. Bras. Zootec.* 46, 689–703. doi: 10.1590/S1806-92902017000800010
- Estrada-Carmona, N., Martínez-Salinas, A., DeClerck, F. A. J., Vilchez-Mendoza, S., and Garbach, K. (2019). Managing the farmscape for connectivity increases conservation value for tropical bird species with different forest-dependencies. *J. Environ. Manag.* 250:109504. doi: 10.1016/j.jenvman.2019.109504
- FEDEGAN (2018). Ganadería Colombiana. Hoja de ruta 2018-2022. Bogotá, Colombia. Available online at: https://estadisticas.fedegan.org.co/DOC/download.jsp?pRealName=Hoja_de_ruta_Fedegan.pdf&idFiles=682 (Accessed April 26, 2023).
- Feder, G., Just, R. E., and Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: a survey. *Econ. Dev. Cult. Chang.* 33, 255–298. doi: 10.1086/451461
- Freitas, I. C., Ribeiro, J. M., Araújo, N. C. A., Santos, M. V., Sampaio, R. A., and Fernandes, L. A. (2020). Agrosilvopastoral systems and well-managed pastures increase soil carbon stocks in the Brazilian Cerrado. *Special Sect. Weed-Suppressive Bacteria* 73, 776–785. doi: 10.1016/j.rama.2020.08.001
- Frey, G. E., Fassola, H. E., Pachas, A. N., Colcombet, L., Lacorte, S. M., Pérez, O., et al. (2012). Perceptions of silvopasture systems among adopters in Northeast Argentina. *Agric. Syst.* 105, 21–32. doi: 10.1016/j.agsy.2011.09.001
- Friedman, J., Hastie, T., and Tibshirani, R. (2010). Regularization paths for generalized linear models via coordinate descent. *J. Stat. Softw.* 33, 1–22. doi: 10.18637/jss.v033.i01

- Fuentes, H., Gómez, E., Pizarro, C., Alegre, D., Castillo, J., Vela, M., et al. (2022). A review of silvopastoral systems in the Peruvian Amazon region. *Tropical Grasslands-Forrajes Tropicales* 10, 78–88. doi: 10.17138/tgft(10)78-88
- Galindo Ospina, A., Uribe Trujillo, F., and Murgueitio Restrepo, E. (2019). Fincas demostrativas Proyecto Ganadería Colombiana Sostenible. 1st Edn. Cali, Colombia: Editorial CIPAV.
- Garbach, K., Lubell, M., and DeClerck, F. A. (2012). Payment for ecosystem services: the roles of positive incentives and information sharing in stimulating adoption of silvopastoral conservation practices. *Agric. Ecosyst. Environ.* 156, 27–36. doi: 10.1016/j.agee.2012.04.017
- Geist, H. J., and Lambin, E. F. (2002). Proximate causes and underlying driving forces of tropical deforestation: tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *Bioscience* 52, 143–150. doi: 10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2
- Gil, J., Siebold, M., and Berger, T. (2015). Adoption and development of integrated crop–livestock–forestry systems in Mato Grosso, Brazil. *Agric. Ecosyst. Environ.* 199, 394–406. doi: 10.1016/j.agee.2014.10.008
- Gosling, E., Reith, E., Knoke, T., and Paul, C. (2020). A goal programming approach to evaluate agroforestry systems in eastern Panama. *J. Environ. Manag.* 261:110248. doi: 10.1016/j.jenvman.2020.110248
- Haddad, F. F., Herrera, P. M., and Besbes, B. (2022). Grazing with trees: a silvopastoral approach to managing and restoring drylands, FAO forestry paper. Rome, Italy: Food and Agriculture Organization of the United Nations, 1–153, 155–160.
- Harrison, P. A., Berry, P. M., Simpson, G., Haslett, J. R., Blicharska, M., Bucur, M., et al. (2014). Linkages between biodiversity attributes and ecosystem services: a systematic review. *Ecosyst. Serv.* 9, 191–203. doi: 10.1016/j.ecoser.2014.05.006
- Harrison, X. A., Donaldson, L., Correa-Cano, M. E., Evans, J., Fisher, D. N., Goodwin, C. E. D., et al. (2018). A brief introduction to mixed effects modelling and multi-model inference in ecology. *PeerJ* 6:e4794. doi: 10.7717/peerj.4794
- Holguín, A. V., Ibrahim, M., Mora, J., and Rojas, A. (2003). Characteristics of the feeding systems in livestock farms of the Central Pacific area of Costa Rica. *Agroforestería en las Américas* 10, 40–46.
- Houriet, J. L., Rossner, M. B., and Colcombet, L. (2009). Implementación de sistemas silvopastoriles en establecimientos de pequeños productores de Misiones, Argentina. Available online at: https://www.produccion-animal.com.ar/produccion_y_manejo_pasturas/manejo%20silvopastoril/135-INTA-silvopastoriles_pequenos.pdf (Accessed June 9, 2023).
- IDEAM. (2023). *Vulnerabilidad [Dataset]*. Available online at: https://bart.ideam.gov.co/cneideam/Capasgeo/Vulnerabilidad_Ambiental_2011_2040.zip, <http://www.ideam.gov.co/web/siac/climaticovulnerabilidad>.
- IGAC. (2014). *Zonificación de los Suelos por Grado de Erosión [Dataset]*. Available online at: https://bart.ideam.gov.co/cneideam/Capasgeo/Zonificacion_degradacion_suelos_erosion_Linea_base_2010_2011.zip, <http://www.siac.gov.co/catalogo-de-mapas>.
- Jara-Rojas, R., Russy, S., Roco, L., Fleming-Muñoz, D., and Engler, A. (2020). Factors affecting the adoption of agroforestry practices: insights from silvopastoral systems of Colombia. *Forests* 11:648. doi: 10.3390/f11060648
- Kapeller, A., and Bleich, J. (2016). bartMachine: machine learning with Bayesian additive regression trees. *J. Stat. Softw.* 70, 1–40. doi: 10.18637/jss.v070.i04
- Kassambara, A., and Mundt, F. (2020) Factoextra: extract and visualize the results of multivariate data analyses. Available online at: <https://cran.r-project.org/web/packages/factoextra/index.html> (Accessed March 7, 2024).
- Keenan, R. J., Reams, G. A., Achard, F., de Freitas, J. V., Grainger, A., and Lindquist, E. (2015). Dynamics of global forest area: results from the FAO global forest resources assessment 2015. *For. Ecol. Manag.* 352, 9–20. doi: 10.1016/j.foreco.2015.06.014
- Kinneen, L., Escobar, M. P., Hernandez, L. M., Thompson, J., Ramos-Pastrana, Y., Córdoba-Suarez, E., et al. (2023). “Silvopastoral systems benefit invertebrate biodiversity on tropical livestock farms in Caquetá, Colombia” in *Agricultural and forest entomology*, vol. 26 (Hoboken, NJ: Wiley), 126–134.
- Kremen, C., and Merenlender, A. M. (2018). Landscapes that work for biodiversity and people. *Science* 362:eaau6020. doi: 10.1126/science.aau6020
- Kremen, C., and Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.* 17:art40. doi: 10.5751/ES-05035-170440
- Lamela, L., Castillo, E., Iglesias, J., and Pérez, A. (2005). Main advances of the introduction of silvopastoral systems under production conditions in Cuba. *Pastos y Forrajes* 28, 47–58.
- Lee, S., Bonatti, M., Löhr, K., Palacios, V., Lana, M. A., and Sieber, S. (2020). Adoption potentials and barriers of silvopastoral system in Colombia: case of Cundinamarca region. *Cogent Environ. Sci.* 6:1823632. doi: 10.1080/23311843.2020.1823632
- Lerner, A. M., Zuluaga, A. F., Chará, J., Etter, A., and Searchinger, T. (2017). Sustainable cattle ranching in practice: moving from theory to planning in Colombia's livestock sector. *Environ. Manag.* 60, 176–184. doi: 10.1007/s00267-017-0902-8
- Lira Junior, M. A., Fracetto, F. J. C., Ferreira, J. S., Silva, M. B., and Fracetto, G. G. M. (2020). Legume silvopastoral systems enhance soil organic matter quality in a subhumid tropical environment. *Soil Sci. Soc. Am. J.* 84, 1209–1218. doi: 10.1002/saj2.20106
- Liu, T., Bruins, R. J. F., and Heberling, M. T. (2018). Factors influencing farmers' adoption of best management practices: a review and synthesis. *Sustainability* 10:432. doi: 10.3390/su10020432
- Loboguerrero, A. M., Campbell, B. M., Cooper, P. J. M., Hansen, J. W., Rosenstock, T., and Wollenberg, E. (2019). Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems. *Sustainability* 11:1372. doi: 10.3390/su11051372
- Lopera, J. J., Márquez, S. M., Ochoa, D. E., Calle, Z., Sossa, C. P., and Murgueitio, E. (2015). Producción Agroecológica De Leche En El Trópico De Altura: Sinergia Entre Restauración Ecológica Y Sistemas Silvopastoriles. *Agroecología* 10, 79–85.
- López, C., Pezo, D., Mora, J., and Prins, M. (2007). The decision-making process in the adoption of *Gliricidia sepium* protein banks by double purpose producers in Rivas, Nicaragua. *Pastos y Forrajes* 30, 177–185.
- Mahecha, L., and Angulo, J. (2012). “Nutrient management in silvopastoral systems for economically and environmentally sustainable cattle production: a case study from Colombia” in *Soil fertility improvement and integrated nutrient management - a global perspective*. ed. J. Whalen (InTech).
- Mauricio, R. M., Ribeiro, R. S., Paciullo, D. S. C., Cangussú, M. A., Murgueitio, E., Chará, J., et al. (2019). “Silvopastoral systems in Latin America for biodiversity, environmental, and socioeconomic improvements” in *Agroecosystem diversity* (Elsevier), 287–297.
- Montagnini, F., Ibrahim, M., and Restrepo, E. M. (2013). Silvopastoral systems and climate change mitigation in Latin America. *Bois et Forêts des Tropiques* 316, 3–16.
- Moore, M.-L., Riddell, D., and Vocisano, D. (2015). Scaling out, scaling up, scaling deep strategies of non-profits in advancing systemic social innovation. *J. Corp. Citizsh.* 2015, 67–84. doi: 10.9774/GLEAF.4700.2015.ju.00009
- Morales, L. (2017). Peace and environmental protection in Colombia. [Internet]. Bogotá: Universidad de los Andes; 2017 p. 1–32. Available online at: https://thedialogue.org/wp-content/uploads/2017/01/Colombia-report_Eng_Web-Res_Final-for-web.pdf. (Accessed Jan 18, 2022)
- Muir, J. P., Tedeschi, L. O., Dubeux, J. C. B., Peters, M., and Burkart, S. (2017). Enhancing food security in Latin America with forage legumes. *Arch. Latinoam. Prod. Anim.* 25, 1–19.
- Murgueitio, E., Calle, Z., Uribe, F., Calle, A., and Solorio, B. (2011). Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *For. Ecol. Manag.* 261, 1654–1663. doi: 10.1016/j.foreco.2010.09.027
- Mwangi, M., and Kariuki, S. (2015). Factors determining adoption of new agricultural technology by smallholder farmers in developing countries. *J. Econ. Sustain. Dev.* 6:208.
- Nair, P. K. R. (1993). An introduction to agroforestry. 1st Edn. Dordrecht: Springer.
- Nascimento, L. E. S., Rocha, J. A., Magalhães, J. A., de Costa, N. L., da Nascimento, T. S., and Townsend, C. R. (2014). Technical support for environmental management in silvopastoral systems. *PUBVET* 8:1686.
- Nkamleu, G. B., and Manyong, V. M. (2005). Factors affecting the adoption of agroforestry practices by farmers in Cameroon. *Small Scale For. Econ. Manag. Policy* 4, 135–148. doi: 10.1007/s11842-005-0009-6
- Oliva, M., Santos, L., Collazos, R., Mestanza, C. N., and Maicelo, J. L. (2018). Factors that influence the adoption of silvopastoral technologies with native species *Alnus acuminata* (aliso). *Agrociencia (Uruguay)* 22, 113–121.
- Olival, A. D. A., de Oliveira, R. E., Sais, A. C., and Xavier Franco de Souza, S. E. (2022). Family farmers' local knowledge about native trees on pastures in portal da Amazonia, MT - Brazil. *Desenvolvimento E Meio Ambiente*. doi: 10.5380/dma.v59i0.76867
- Pagiola, S., Ramírez, E., Gobbi, J., de Haan, C., Ibrahim, M., Murgueitio, E., et al. (2007). Paying for the environmental services of silvopastoral practices in Nicaragua. *Spec. Sect. Ecosyst. Serv. Agric.* 64, 374–385. doi: 10.1016/j.ecolecon.2007.04.014
- Patiño, M., Moreira, V., Echeverría, R., and Nahuelhual, L. (2012). Factores que determinan la adopción de prácticas de conservación del agua en sistemas ganaderos de la cuenca alta del río Guarínó (Caldas, Colombia). *Revista Colombiana de Ciencias Pecuarias* 25, 46–55. doi: 10.17533/udea.rcpc.324732
- Pebesma, E., and Bivand, R. (2023). Spatial data science: with applications in R. 1st Edn. New York: Chapman and Hall/CRC.
- Polanía-Hincapié, K. L., Olaya-Montes, A., Cherubin, M. R., Herrera-Valencia, W., Ortiz-Moreno, F. A., and Silva-Olaya, A. M. (2021). Soil physical quality responses to silvopastoral implementation in Colombian Amazon. *Geoderma* 386:114900. doi: 10.1016/j.geoderma.2020.114900
- Priya, and Singh, S. P. (2024). Factors influencing the adoption of sustainable agricultural practices: a systematic literature review and lesson learned for India. *Forum Soc. Econ.* 53, 1–17. doi: 10.1080/07360932.2022.2057566
- QGIS Development Team (2022). QGIS geographic information system: QGIS Association.
- Rasch, S., Wünscher, T., Casasola, F., Ibrahim, M., and Storm, H. (2021). Permanence of PES and the role of social context in the regional integrated Silvo-pastoral ecosystem management project in Costa Rica. *Ecol. Econ.* 185:107027. doi: 10.1016/j.ecolecon.2021.107027
- Rivera, L. F., Armbricht, I., and Calle, Z. (2013). Silvopastoral systems and ant diversity conservation in a cattle-dominated landscape of the Colombian Andes. *Agric. Ecosyst. Environ.* 181, 188–194. doi: 10.1016/j.agee.2013.09.011

- Rizo-Chavarría, C., Cascante-Carvajal, C., Imbach-Hermida, A., and Tobar- López, D. (2022). Perception of livestock farmers on ecosystem services provision in the livestock production activity, Esparza, Costa Rica. *Revista Forestal Mesoamerica Kuru-Rfmk*. doi: 10.18845/rfmk.v19i45.6324
- Rudel, T. K., Paul, B., White, D., Rao, I. M., van der Hoek, R., Castro, A., et al. (2015). LivestockPlus: forages, sustainable intensification, and food security in the tropics. *Ambio* 44, 685–693. doi: 10.1007/s13280-015-0676-2
- Schmitt Filho, A. L., Kretzer, S. G., Farley, J., Kazama, D. C., Sinisgalli, P. A., and Deniz, M. (2023). Applied nucleation under high biodiversity silvopastoral system as an adaptive strategy against microclimate extremes in pasture areas. *Int. J. Biometeorol.* 67, 1199–1212. doi: 10.1007/s00484-023-02488-2
- Shah, F., Chavan, S. B., Chichaghare, A. R., Uthappa, A. R., Kumar, M., and Kakade, V. (2022). Agroforestry systems for soil health improvement and maintenance. *Sustainability* 14:14877. doi: 10.3390/su142214877
- Sibele, N., Chamayou, L., Newing, H., and Montes, I. G. (2017). Perceptions of trees outside forests in cattle pastures: land sharing within the central volcanic Talamanca biological corridor, Costa Rica. *Hum. Ecol.* 45, 499–511. doi: 10.1007/s10745-017-9924-3
- Silva-Olaya, A. M., Olaya-Montes, A., Polanía-Hincapié, K. L., Cherubin, M. R., Duran-Bautista, E. H., and Ortiz-Moreno, F. A. (2022). Silvopastoral systems enhance soil health in the Amazon region. *Sustainability* 14, 1–18. doi: 10.3390/su14010320
- Simioni, G. F., Schmitt Filho, A. L., Jones, F., Farley, J., Fantini, A. C., and Moreira, A. P. T. (2022). Response of birds to high biodiversity silvopastoral systems: integrating food production and biodiversity conservation through applied nucleation in southern Brazil. *Agric. Ecosyst. Environ.* 324:107709. doi: 10.1016/j.agee.2021.107709
- Smith, M. M., Bentrup, G., Kellerman, T., MacFarland, K., Straight, R., Ameyaw, L., et al. (2022). Silvopasture in the USA: a systematic review of natural resource professional and producer-reported benefits, challenges, and management activities. *Agric. Ecosyst. Environ.* 326:107818. doi: 10.1016/j.agee.2021.107818
- Solymosi, K., Braun, A., Dijk, S., and Grulke, M. (2016). Upscaling silvopastoral systems in South America. IDB Publications [Preprint]. Available online at: <https://publications.iadb.org/en/upscaling-silvopastoral-systems-south-america> (Accessed March 6, 2024).
- Speekenbrink, M. (2023). Chapter 9 linear mixed-effects models | an R companion to statistics: data analysis and modelling. Available online at: <https://mspeekenbrink.github.io/sdam-r-companion/linear-mixed-effects-models.html#formulating-and-estimating-linear-mixed-effects-models-with-lme4> (Accessed February 15, 2024).
- Stefano, P., Jordi, H.-R., and Jaume, F.-G. (2020). Assessing the permanence of land-use change induced by payments for environmental services: evidence from Nicaragua. *Trop. Conserv. Sci.* 13, 1–15. doi: 10.1177/1940082920922676
- Tapasco, J., LeCoq, J. F., Ruden, A., Rivas, J. S., and Ortiz, J. (2019). The livestock sector in Colombia: toward a program to facilitate large-scale adoption of mitigation and adaptation practices. *Front. Sustain. Food Syst.* 3:61. doi: 10.3389/fsufs.2019.00061
- Tarbox, B. C., Swisher, M., Calle, Z., Wilson, C. H., and Flory, S. L. (2020). Decline in local ecological knowledge in the Colombian Andes may constrain silvopastoral tree diversity. *Restor. Ecol.* 28, 892–901. doi: 10.1111/rec.13153
- Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geogr. Rev.* 38, 55–94. doi: 10.2307/210739
- Tibshirani, R. (1996). Regression shrinkage and selection via the Lasso. *J. Roy. Stat. Soc. Ser. B (Methodological)* 58, 267–288.
- Timoteo, J., Kainer, K. A., Luna Cavazos, M., García Moya, E., Sánchez Sánchez, O., and Vibrans, H. (2023). Trees in pastures: Local knowledge, management, and motives in tropical Veracruz, Mexico. *Agroforest. Syst.* doi: 10.1007/s10457-023-00819-1
- Tollefson, J. (2019). Humans are driving one million species to extinction. *Nature* 569:171. doi: 10.1038/d41586-019-01448-4
- Torres, S. (2016). The effects on values, beliefs and norms of payments for environmental services: evidence from a PES program in Colombia. M.S. Available online at: <https://www.proquest.com/docview/1797424009/abstract/42648A87DA8B450APQ/72> (Accessed June 15, 2023).
- Valencia, V., Bennett, E. M., Altieri, M., Nicholls, C., Pas Schrijver, A., and Schulte, R. P. O. (2022). Learning from the future: mainstreaming disruptive solutions for the transition to sustainable food systems. *Environ. Res. Lett.* 17:051002. doi: 10.1088/1748-9326/ac6ad9
- Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. (1997). Human domination of earth's ecosystems. *Science* 277, 494–499. doi: 10.1126/science.277.5325.494
- Zabala, A., Barrios, L. E. G., and Pascual, U. (2022). From participation to commitment in silvopastoral programmes: insights from Chiapas, Mexico. *Ecol. Econ.* 200:107544. doi: 10.1016/j.ecolecon.2022.107544
- Zuluaga, A., Etter, A., Nepstad, D., Chará, J., Stickler, C., and Warren, M. (2021). Colombia's pathway to a more sustainable cattle sector: a spatial multi-criteria analysis. *Land Use Policy* 109:105596. doi: 10.1016/j.landusepol.2021.105596