ADOPTION OF SUSTAINABLE LIVESTOCK INNOVATIONS

EVIDENCE FROM LATIN AMERICA

Edited by:

Allen Blackman
Gonzalo Muñoz
Lina Salazar
Paul Winters

IDB

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Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library

Adoption of sustainable livestock innovations: evidence from Latin America / Edited by Allen Blackman, Gonzalo Muñoz, Lina Salazar, Paul Winters.

p. cm. — (IDB Monograph ; 1324)

Includes bibliographical references.

1. Agriculture and state-Latin America. 2. Agricultural innovations-Latin America. 3. Sustainable agriculture-Latin America. I. Blackman, Allen, editor. II. Muñoz, Gonzalo, editor. III. Salazar, Lina, editor. IV. Winters, Paul, editor. V. Inter-American Development Bank. Agriculture and Rural Development Division. VI. Inter-American Development Bank. Climate Change and Sustainable Development Sector. VII. Series.

IDB-MG-1324

JEL Codes: D22, D24, D81, L21, O33, Q1, Q2, Q5, Q12, Q15, Q16, Q18, Q40, Q55, Q56, Q57 and Z13.

Keywords: Adoption barriers, adoption decisions, agricultural policy, cattle farming, choice experiment, climate change, Colombian-Orinoquia, environmental sustainability, gender-responsive extension, impact evaluation, institutional support, land tenure, livestock, livestock management, pasture management, pasture-based cattle systems, risk aversion, stocking rate, sustainability, sustainable grazing, sustainable livestock, technology adoption, rural development

Inter-American Development Bank
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Washington, DC 20577

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1
OVERVIEW

Allen Blackman, Gonzalo Muñoz,
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1.1 Motivation

In Latin America, the livestock sector generates critical economic benefits. It contributes just under one half of agricultural GDP and helps alleviate poverty and food insecurity (Williams and Anderson 2019; Otte et al. 2012). Because global demand for livestock products is growing quickly—for example, meat demand is projected to increase by 80 percent over the next 25 years—these economic benefits will likely become even more important over time (Nadathur et al. 2017).

But livestock also has significant environmental costs. It accounts for 14 percent of Latin America's greenhouse gas emissions, is the proximate cause of the vast majority of deforestation in the region and is a leading source of water pollution (Arango et al. 2020; Pendril et al. 2022; Li et al. 2022).

To maintain the vital economic benefits of Latin America's livestock sector while minimizing its environmental footprint, producers must adopt clean and climate-friendly 'sustainable' technologies. These include improved feed and grazing systems, silvopastoral systems and improved reproductive and herd management practices.

Emerging evidence suggests that such technologies hold particular promise for climate change mitigation efforts. For example, using global data, Chang et al. (2021) find that from 2000-2018, technology driven increases in protein-production efficiency reduced the emissions intensity of methane, a potent greenhouse gas, for most livestock categories. In addition, they find that this supply-side phenomenon has much greater mitigating effects than demand-side efforts to shift consumer diets away from animal products. And Herrero et al. (2016) find that globally, livestock accounts for up to half of the technical mitigation potential of the agriculture, forestry, and other land-use (AFOLU) sector.

Hence, it is important to understand the barriers to and opportunities for the adoption of sustainable livestock technologies in Latin America and, based on that understanding, to distill lessons for policy. Yet we have limited evidence on the adoption of sustainable livestock technologies, and even less on that topic in Latin America and other developing regions where socioeconomic and geophysical conditions often differ from those in the developed countries. The product of more than half a century of study, a considerable literature examines agricultural technology adoption (see Rosário et al. 2022 for a recent review and Ruzzante et al. 2021 for a recent metanalysis). A much smaller subliterature focuses on sustainable agricultural technologies (see Lu et al. 2022 and Foguesatto et al. 2020 for recent reviews). However, almost all of this subliterature examines agronomic innovations, not livestock ones (Prokopy et al. 2008). For example, a recent systematic review of evidence on the adoption of sustainable agriculture practices in Africa found that only 2.5 percent examined livestock innovations (Arslan et al. 2022).

1.2 Research questions

The overall objective of this monograph is to build the evidence base on the barriers to and opportunities for the adoption of sustainable livestock technologies in Latin America. Specifically, all five papers address one or more of the following (related) research questions:

- **What are the determinants of the adoption of sustainable livestock technologies in Latin America?**
- **What are producers' preferences regarding them?**
- **What policies and programs can speed adoption?**

1.3 Articles

The five articles that comprise the monograph (Table 1) are the products of a competitive, open call by the Inter-American Development Bank (IDB) to Latin American research institutions. The project entailed a two-stage proposal and selection process in late 2023 and early 2024; continuous feedback from a Scientific Committee; and two workshops in April 2024 and April 2025.

Table 1 Articles in the Monograph: Summary

Authors	Country	Technologies	Goal	Methods	Data
Aguirre et al.	**Uruguay**	Reproductive & herd management practices	Evaluate the impact of the Sustainable Family Production Program (PFIS) on beef production, technology adoption, and emissions intensity	Regression discontinuity	Various secondary producer-level data sets
Basurto et al.	**Mexico**	Six grazing practices aggregated to an Environmental Sustainability Index	Characterize the determinants of the adoption of sustainable livestock practices	Fractional panel regression	Municipality-level panel data from Census of Agriculture
Bravo-Peña et al.	**Chile**	Silvopastoral systems & regenerative livestock approaches	Characterize the determinants of the adoption of sustainable livestock practices	Logistic and bivariate probit regressio	Original producer-level survey data
Guerrero et al.	**Uruguay**	Improved grazing systems; sustainable intensification; silvopastoral approaches	Characterize and analyze farmers' preferences for the adoption of sustainable livestock practices	Discrete choice experiment	Original producer-level survey data
Flórez-Díaz et al.	**Colombia**	Improved pasture management practices	Characterize the determinants of the adoption of sustainable livestock practices	Logistic regression	Original producer-level survey data combined with GIS data

Of the articles in the monograph, three aim to identify the determinants of the adoption of sustainable livestock practices:

- **Basurto et al.** use municipality-level panel data drawn from two waves of the Census of Agriculture along with Fractional panel regression to assess the determinants of the adoption of sustainable grazing technologies in Mexico.

- **Bravo-Peña et al.** use original producer-level cross-sectional survey data along with logistic and bivariate probit regression to characterize the determinants of the adoption of silvopastoral systems and regenerative livestock technologies in Chile.

- **Flórez-Díaz et al.** use logistic regression along with original producer-level cross-sectional survey and geographic information system data to analyze the determinants of the adoption of improved pasture management technologies in Colombia.

As for the other two papers:

- **Aguirre et al.** presents a quasi-experimental impact evaluation. They use a regression discontinuity approach along with secondary producer-level data to identify the causal effect on beef production, technology adoption, and emissions intensity of a program aimed at promoting reproductive and heard management practices in Uruguay.

- **Guerrero et al.** use a discreet choice survey experiment along with behavioral measures of risk and time preferences to characterize producers' preference for improved grazing systems, sustainable intensification and silvopastoral approaches in Uruguay.

1.4 Findings

Several broad finding emerge from the set of five articles. First, generalizing about the drivers of the adoption of sustainable livestock technologies in Latin America is ill advised: they are both technology- and site-specific. For example, Bravo-Peña et al. find that in Chile, farm size is positively correlated with the adoption of silvopastoral systems, all other things equal, but negatively correlated with the adoption of regenerative livestock technologies. Similarly, Guerrero et al. find that financial incentives are needed to promote the adoption of silvopastoral systems but not sustainable intensification practices.

Relatedly, land tenure matters. For example, Flórez et al. find that in Colombia, owning land is correlated with adoption of improved pasture management and sustainable stocking rates and Basurto et al. find that in Mexico private (versus communal) land tenure is correlated with adoption of sustainable grazing practices.

Third, all good things do not necessarily go together: adopting one sustainable livestock technology does not necessarily increase the chances of adopting others. For example, Bravo-Peña et al. find that in Chile, the adoption of silvopastoral systems is not correlated with the adoption of regenerative livestock technologies, and Flórez et al. find that in Colombia, adoption of sustainable pasture management is not correlated with sustainable stocking decisions.

Fourth, the adoption of sustainable livestock innovations does not guarantee significant impacts on targeted outcomes. Aguirre et al. find that Uruguay, although a program aimed at speeding the adoption of sustainable livestock technologies spurred adoption of reproductive and herd management practices, it did not have a discernable effect on productivity or greenhouse gas emissions intensity.

Finally, all four studies that aim to econometrically explain adoption of sustainable livestock technologies (i.e., all except Guerrero et al. which focuses on producer preferences) find two of the most common policy interventions—enhancing access to credit and/or providing technical extension—are correlated with adoption, at least for some technologies and subgroups.

As detailed in the articles, these findings have a variety of implications for policy. Perhaps most important, as every one of the articles points out, one-size-fits-all policies aimed at promoting adoption are unlikely to be effective or efficient. Rather, policies must be carefully targeted and tailored to specific technologies and locations and/or must provide menus of technological and support options for diverse sets of farmers.

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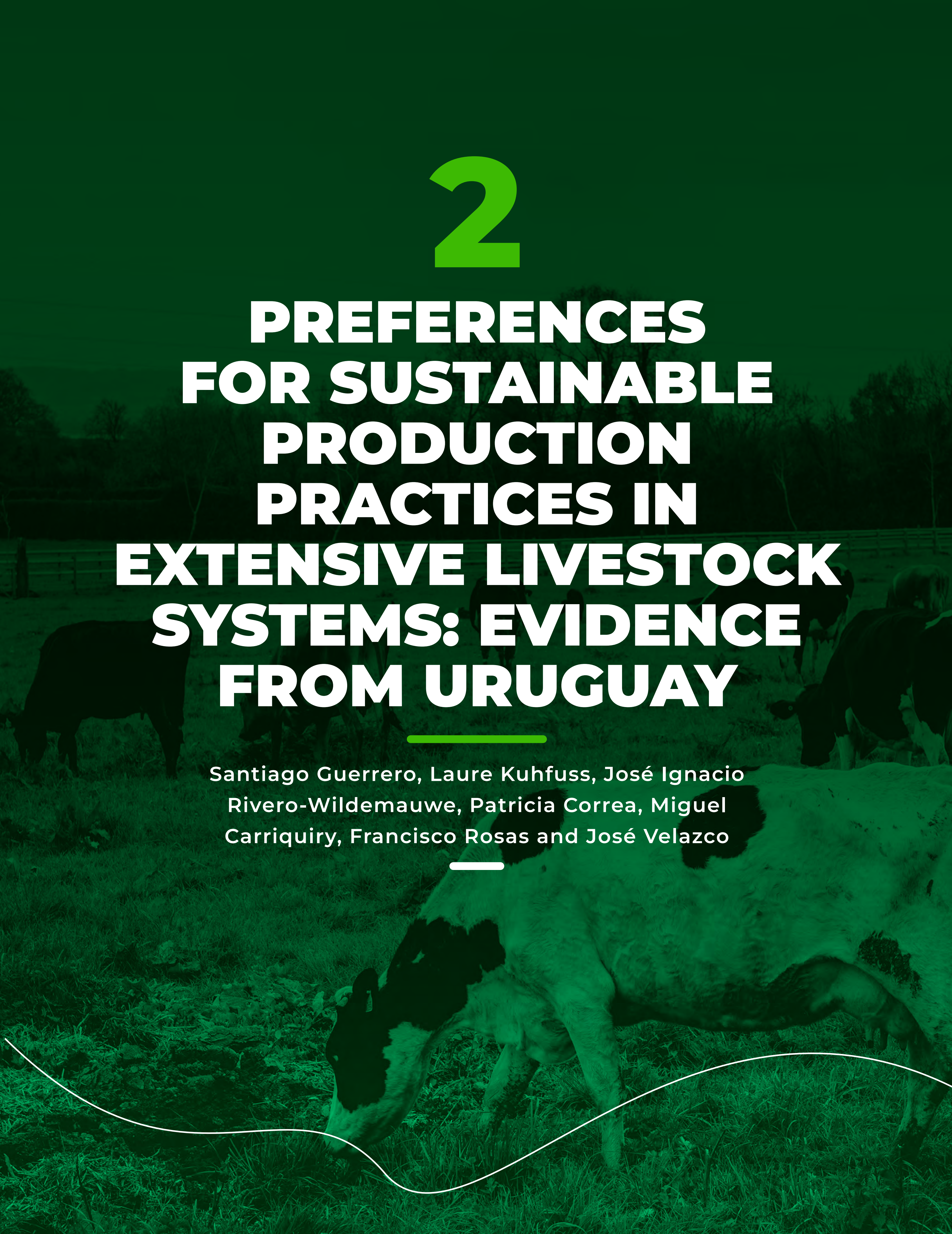

2

PREFERENCES FOR SUSTAINABLE PRODUCTION PRACTICES IN EXTENSIVE LIVESTOCK SYSTEMS: EVIDENCE FROM URUGUAY

Santiago Guerrero, Laure Kuhfuss, José Ignacio Rivero-Wildemauwe, Patricia Correa, Miguel Carriquiry, Francisco Rosas and José Velazco

Abstract

This research uses a discrete choice experiment along with behavioral measures of risk and time preferences to analyze the preferences of Uruguayan cattle producers for three types of sustainable livestock practices: improved grazing systems, sustainable intensification, and silvopastoral approaches. The results indicate that, on average, producers favor sustainable intensification, are indifferent to improved grazing practices, and require monetary compensation to adopt silvopastoral systems. A latent class model reveals significant preference heterogeneity, identifying two distinct producer profiles: one inclined to adopt the proposed practices and another that requires stronger incentives. These findings underscore the importance of designing differentiated policy instruments tailored to the characteristics and motivations of diverse producer types.

Introduction

The grazing sector is an important source of income and livelihoods and provides nourishment for more than 1.3 billion people globally, accounting for 17 percent of the total global energy intake (Nin-Prat et al., 2019). The sector also exerts substantial pressure on the environment. It generates 12% of global greenhouse gas (GHG) emissions, with cattle alone responsible for more than 60% of that total (FAO, 2023). It also contributes to deforestation, water pollution, and soil degradation (Steinfeld et al., 2006; Herrero et al., 2015; Thornton and Herrero, 2010). These effects are particularly pronounced in extensive grazing systems, which combine low productivity per hectare with high emissions intensity (Petermann and Buzhdygan, 2021; Arndt et al., 2022).

Although many sustainable livestock practices offer clear environmental and economic benefits, adoption rates remain low in much of the Global South (Knowler and Bradshaw, 2007; Kassie et al., 2015; Dessart et al., 2019). Structural and institutional barriers—such as land size, credit constraints, insecure tenure, low economic returns and limited extension services—are known to constrain uptake (Delaroche, 2020; Jara-Rojas et al., 2020; Xin et al., 2025).

This paper examines producers' preferences for a package of sustainable livestock practices relevant to regions with extensive livestock systems—improved grazing, sustainable intensification, and silvopastoral systems—using a discrete choice experiment (DCE) in Uruguay. DCEs have become a useful tool to study farmers' preferences and policy design, but relatively few focus on extensive livestock systems, and fewer still evaluate preferences for bundled climate-smart practices (Ruto and Garrod, 2009; Glenk and Colombo, 2011; Villanueva et al., 2015; Bougherara et al., 2021).

Beyond "classical" determinants, such as farm scale and farmers' sociodemographic characteristics, we also test whether behavioral traits—specifically, risk and time preferences—help explain willingness to adopt. Although lab-in-the-field methods have generated robust measures of these traits (Naranjo et al., 2019; Bonjean, 2023), few studies have embedded them into the preference structure of DCEs or used them to explain latent class heterogeneity (Fischer and Wollni, 2018; Ali et al. 2021; Hannus et al., 2020; Bougherara et al., 2021; Angioloni and Cerroni, 2025). This is the first study to elicit these behavioral traits for Uruguayan livestock farmers. Previous work studied the general population (Gandelman and Hernández-Murillo, 2015), and other studies in Latin America targeted row crop farmers (Gonzalez-Rodriguez et al. 2018).

Uruguay offers a strategically relevant setting for this study. Extensive cattle ranching dominates both land use and agricultural exports, and livestock is the primary source of the country's greenhouse gas emissions. At the same time, Uruguay has emerged as an innovator in climate policy, most notably by issuing a sovereign sustainability-linked bond tied to greenhouse gas emissions targets. This dual condition—a country with high emissions intensity in livestock that is also a frontrunner in results-based climate finance—makes Uruguay an instructive case for understanding how producers respond to bundled, performance-oriented mitigation incentives.

Our findings defy common assumptions in two ways. First, farmers show willingness to pay for sustainable intensification (USD 22–28/ha/year)—a surprising result given that participants in mitigation programs typically require compensation. Second, although behavioral traits like risk aversion and impatience are often thought to influence adoption, we find that most preference heterogeneity is explained by farm and demographic characteristics. Farmers are indifferent toward improved grazing and express strong aversion to silvopastoral practices—especially at high adoption levels (willingness to accept, WTA, of USD 12–21/ha/year). The latent class model reveals two producer types: class A (81%) broadly reflects the average response, and class B (19%) includes small-scale, older farmers less engaged in sustainable practices and less willing to adopt them. Including behavioral variables to explain class membership improves the precision of the farm and farmers' characteristics estimates and helps to distinguish more clearly the differences in preferences for sustainable practices. In the model that includes behavioral variables to explain class membership, class B farmers' coefficients on improved grazing techniques and a medium level of sustainable intensification practices are negative and statistically significant, revealing that these farmers require compensation to adopt these practices. Nevertheless, behavioral variables do not significantly predict class membership, since none of them are statistically significant in explaining class membership. We argue this may be consistent with the short-term, low-risk, and relatively familiar nature of the proposed practices—suggesting that behavioral traits may matter only in high-risk, long-horizon decisions.

This paper makes three main contributions to the literature. First, it adds evidence on DCEs in extensive livestock systems—an understudied setting, especially in Latin America. Second, it provides insight into farmers' preferences for bundled climate-smart interventions. Third, it shows that the relevance of behavioral traits in adoption models may depend on context, supporting their use in some, but not all, policy environments.

The rest of the paper is organized as follows.

Section 2.1 presents the geographical and institutional context of the survey

Section 2.2 describes the choice experiment design

Section 2.3 summarizes the responses to the behavioral questions

Sections 2.4 outlines the model specification

Section 2.5 describes the variables used in the models and the sample

Section 2.6 reports the results

Section 2.7 concludes

2.1 Geographical and Institutional Context

Uruguay is a prominent beef producer, located in La Pampa grasslands area. Animal production takes place in extensive farming systems that rely on natural grasslands. Beef production is a major component of Uruguay's agriculture sector and the primary land use (accounting for more than 80% of agricultural land). Historically, beef has been the main export product, with forestry products having gained share in recent years. It is also an important source of livelihoods, with almost 50,000 cattle production units and around 65,000 livestock producers.

Cattle production is responsible for 68% of GHG emissions in the country (Ministerio de Ambiente, 2022), mainly from enteric fermentation. Although Uruguay has recently invested in the promotion of sustainable practices to mitigate the sector's emissions, it does not offer subsidies to incentivize their adoption. Sustainable practices in livestock production are embedded in Uruguay's nationally determined contribution (NDC) under the Paris Agreement and in a sustainability-linked bond recently issued by the government, which ties interest rates to GHG emissions targets.

Public and private institutions have a long history in the country, with organizations that represent livestock producers dating to the 19th century. The country also has a robust animal health system, with the beef production chain monitored by the Ministry of Livestock, Agriculture, and Fisheries and related institutions. The ministry also manages an internationally recognized system that traces the movement and location of individual bovine animals from birth. In addition, several other public institutions, such as the National Meat Institute (abbreviated INAC, for its name in Spanish), the Department of Agronomy of the University of the Republic, and the National Institute of Agricultural Research (INIA), carry out research on beef production and animal science and provide technical advice to firms along the value chain. Instituto Plan Agropecuario is the main public organization that offers training and advisory services to more than 4,000 cattle producers across Uruguay.

2.2 Choice Experiment

2.2.1 Survey

The survey has three main sections: (1) questions on producer and farm characteristics, including adoption status of sustainable practices and perceptions regarding their benefits and costs; (2) the discrete choice experiment; and (3) behavioral questions. The DCE is presented before the behavioral section to avoid introducing potential biases into the choice tasks.

The DCE comprised a series of choice cards, each presenting producers with two hypothetical agri-environmental programs and the option to opt out of the offered programs. Administered by the government, these programs offered payments in exchange for the adoption of a set of sustainable practices.

The survey was distributed via a Qualtrics link shared through WhatsApp by the Instituto Plan Agropecuario to different producers' groups. The distribution method aligned with the organization's standard practice for administering surveys to its network of producers. Importantly, before we ran the final survey, we conducted semistructured interviews with nine producers and ran two pilots with 35 producers each, aimed at identifying and addressing potential design and methodology issues.

2.2.2 Attribute Selection

The attributes related to sustainable practices used in the choice experiment were selected based on a review of the literature, expert consultations, and the nine semistructured interviews with producers. The goal was to identify production practices that reduce GHG emissions from the cattle sector in Uruguay. A summary of the sustainable practices in extensive systems is provided in Appendix 1. The semistructured interviews and the pilots were used to determine the attribute levels and to refine the survey's vocabulary and language. Varying attribute levels allowed us to assess producers' preferences across a range of program designs.

The hypothetical agri-environmental programs in the survey had four attributes: (1) incorporating artificial pastures and/or forage crops in the grazing area, (2) sustainable intensification practices, (3) silvopastoral practices, and (4) payment. The first attribute has the objective of increasing overall pasture production and quality and reducing the stocking rate in the natural grasslands grazing area, especially in periods of forage shortages. It includes grass-leguminous fodder mixtures and annual crops (corn, sorghum, oats, barley) that can be used for animal feed. The levels of this attribute are the percentage increase of their share in the total farm area: increases of 0%, 1%, 5%, and 10%, relative to the existing level.

For the second attribute, we considered four sustainable intensification practices:

1. Seasonal adjustment of stocking rate: rotating cattle based on forage availability and herd requirements, monitoring weight and body condition, and adjusting accordingly.

2. Defining breeding periods and categorizing females: reproductive planning, health monitoring, and grouping cows for nutritional and reproductive management.

3. Prebreeding bull review and pregnancy diagnostics: semen quality checks, hormone testing, and recordkeeping.

4. First pregnancy at two years and postcalving nutrition: tracking weight, scoring body condition, providing supplementary diets, and using artificial insemination for heifers.

This second attribute has four levels: (1) no practices adopted, (2) first practice adopted, (3) practices 2, 3, and 4 adopted, and (4) all practices adopted.

The third attribute is the silvopastoral system, which integrates trees, natural grasslands, and livestock in the same area, where trees are planted at an optimized density such that they do not compete for resources with the natural grassland. The levels of the attribute refer to the increase in the area under silvopastoral management as a share of the total farm area: increases of 0%, 1%, 5%, and 10%, relative to existing levels.

The fourth attribute is the payment. Levels were inferred from Instituto Plan Agropecuario's reports (Carpetas Verdes), which include reports on cattle production costs and revenues, with six values: USD 10, 20, 30, 40, 50, and 60 per hectare of the total area, applied to the entire farm area.

Before participants were shown the choice cards, they were informed that the objective was to understand their preferences for program options to promote sustainable practices. Each card would display two hypothetical programs offering annual payments per hectare of the entire farm, conditional on implementing the listed measures. The text also mentioned that the practices would be monitored and that the reporting of the practices implemented would be performed via "sworn statement," which is a widely used, legally binding document in Uruguay by which an individual or entity declares information to be true under oath. The five-year contract duration reflects standard practices in agri-environmental schemes (Bougherara et al., 2021; Guerrero, 2021; OECD, 2022).

An example choice card is shown in Figure 1. Each participant was shown six such cards and asked to choose their preferred option on each.

Figure 1 Example of choice card

Prácticas	Programas 1	Programas 2
Incremento del área de pastoreo con praderas artificiales y/o cultivos forrajeros anuales	+5% respecto al área total	+10% respecto al área total
Prácticas de intensificación sostenible	1. Ajuste estacional de la carga en función del forraje	1. Delimitar el inicio y final del entore 2. Revisión de toros y diagnóstico actividad ovárica 3. Primera preñez de vaquillonas a los 2 años
Incremento del área bajo silvopastoreo: cobertura forestal plantada que da servicios a la producción ganadera	No incremento	**+10% respecto al área total**
Pago que recibirá que aplica para toda el área del establecimiento durante 5 años	$10 (USD/ha/año)	**$50 (USD/ha/año)**

Programa 1 ○ **Programa 2** ○ **No me interesaría participar en ninguno de los programas** ○

2.2.3 Experimental Design

The full factorial design of the choice experiment—that is, the number of unique choice cards that can be constructed from the selected attributes and levels—consists of 384 profiles. To reduce the number of evaluations while preserving statistical efficiency, a D0-efficient design was generated using Ngene. The final design was divided into six blocks of six choice cards each, resulting in a total of 36 unique cards.

2.3 Behavioral Factors

Although the empirical literature is mixed, behavioral traits such as risk aversion and impatience have been linked to the failure to adopt agricultural innovations in some settings (e.g., Liu, 2013; Yesuf and Bluffstone, 2009), while others report limited effects (Ward and Singh, 2015). Most of the evidence comes from observational studies or labin-the-field experiments. Only a few discrete choice experiments have incorporated such traits into the analysis (e.g., Fischer and Wollni, 2018; Bougherara et al., 2021). We include elicited measures of risk and time preferences to explore whether they help explain preference heterogeneity in our discrete choice setting.

2.3.1 Time Preferences

To capture producers' time preferences, we employed a multiple price list approach (Coller and Williams 1999, Harrison et al. 2002). More precisely, we asked respondents to make a series of eight choices. Each choice was between receiving a certain sum of money (USD 10,000) within a year or a larger amount within two years. Thus, each choice involved an implied annual interest rate in dollars,[2] which varied between 1% and 30%. Table 1 presents the choices along with the implied discount rate bounds, as well as the distribution of choices.

[2] We follow the approach of delaying both payments (e.g., one year vs. two years) to reduce the influence of present bias and other immediacy effects. This allows for a cleaner approximation to long-run time discounting (Harrison et al. 2002, Frederick et al. 2002). Brañas Garza et al. (2023) provide evidence that both hypothetical and fully incentivized multiple price lists yield equivalent estimates of time preferences.

Table 1 **Distribution of switching points and corresponding implied annual discount rate bounds**

Switch point	Respondents	Lower bound (%)	Upper bound (%)
1	24 (91%)	0.0	1.0
2	1 (0.4%)	1.0	2.5
3	13 (4.9%)	2.5	4.0
4	18 (6.8%)	4.0	5.5
5	23 (8.7%)	5.5	7.0
6	45 (17.1%)	7.0	10.0
7	42 (16.0%)	10.0	20.0
8	20 (7.6%)	20.0	30.0
Never switch	77 (29.3%)	30.0	—
Total	**263 (100%)**		

The structure of the questionnaire implies that we should expect subjects to pick Option 1 for the very first questions before switching to Option 2 for the subsequent ones, without switching back. Our data show that of the 274 individuals who completed the questions, only 11 (3.8%) made such unexpected switches.

Among the 263 respondents who provided consistent answers, the distribution of time preferences reveals marked polarization. On one end of the spectrum, 21% of individuals are willing to wait an additional year for relatively modest returns—5.5% or less—indicating low discount rates. On the other end, almost 70% require returns above 7% to postpone payment by one year, reflecting a relatively high degree of impatience. Notably, nearly 30% never switch to the larger-later option, suggesting that even a 30% annual return is not sufficient to justify waiting an extra year.

2.3.1 Risk Preferences

Participants also completed a risk preference task involving a series of seven binary lotteries, following the ordered lottery design introduced by Eckel and Grossman (2002, 2008). Each lottery offered a 50-50 chance between a low and a high monetary payoff. Choices were designed to reflect increasing levels of risk and expected return. Specifically, the first five lotteries offer both higher expected returns and higher standard deviations. The sixth and seventh options offer the same expected return (USD 20,000) but progressively greater risk, with the final option having the highest variance. Participants were asked to select the lottery in which they would most prefer to participate.

Table 2 presents the structure of each lottery, along with the distribution of participants' choices. The implied constant relative risk aversion (CRRA) intervals are also shown, following standard calibration assumptions. A substantial share of participants (36%) chose the safest option with no variance, consistent with a CRRA coefficient above 3.56—typically interpreted as highly risk averse. Another 20% selected the second lottery, consistent with moderate levels of risk aversion. As the risk-return trade-off increases, the proportion of participants choosing each subsequent option declines, with only about 4% each selecting lotteries 5 and 6. Interestingly, 11% of participants selected the riskiest option, which implies risk-seeking behavior under CRRA assumptions. These findings suggest that although most producers are risk averse to varying degrees, a nonnegligible minority are willing to accept substantial risk for the chance of higher returns.

Table 2 Summary of 50-50 lottery choices in risk preference task

Choice	Low payoff (USD)	High payoff (USD)	Expected return	Std. dev.	Respondents	CRRA interval
1	11	11	11	0	99 (36%)	> 3.56
2	9	17	13	5.6	56 (20%)	[1.20, 3.56]
3	7	23	15	11.3	39 (14%)	[0.74, 1.20]
4	5	29	17	16.9	29 (11%)	[0.52, 0.74]
5	3	35	19	22.6	11 (4%)	[0.40, 0.52]
6	2	38	20	25.4	11 (4%)	[0, 0.40]
7	0	40	20	28.2	29 (11%)	< 0
Total					**274 (100%)**	

2.4 Modeling Approach for Discrete Choices

In this study, we use standard modeling approaches for discrete choice experiment data, which build on Lancaster's (1966) theory of consumer choice and McFadden's (1973) random utility framework. Because this framework is well known, we sketch it only briefly here. The main assumption is that the utility a cattle producer derives from selecting a given alternative consists of two components: an observable, deterministic part and an unobservable, stochastic error term. The deterministic component reflects the effect of the alternative's attributes on utility, and the random component captures unobserved influences and idiosyncratic preferences.

The probability that producer i selects alternative j among J available options depends on the relative utilities of all alternatives. Formally, following Lancsar and Louviere (2008)

$$Pr(Y_i=j)=Pr(U_{ij}>U_{ik})\ \forall\ k\neq j,$$

where utility is specified as

$$U_{ij}=\beta X_{ij}+\varepsilon_{ij},$$

with X_{ij} representing a vector of attribute levels for alternative j and producer i, β denoting the vector of preference parameters for these attributes, and ε_{ij} the error term.

Applied to the choice experiment implemented in this paper, we define this utility function as

$$U_{ij}=\beta_0+\beta_1\, grazing_1+\beta_2\, grazing_2+\beta_3\, grazing_3+\beta_4\, intens_1+\beta_5\, intens_2+\beta_6\, intens_3+\beta_7\, silvopast_1+\beta_8\, silvopast_2+\beta_9\, silvopast_3+\beta_{10}\, payment+\varepsilon_{ij}$$

We estimate a multinomial logit and a mixed logit model, in which the β parameters are treated as random variables and the probability that producer i selects alternative j is

$$Pr(Y_i=j|\beta_i)=\frac{e^{\mu\beta_i X_{ij}}}{\sum_{k=1}^{j} e^{\mu\beta_i X_{ik}}}$$

where μ is a scale parameter (typically normalized to 1 in estimation). The vector of parameters of interest β is estimated using simulated maximum likelihood, using the Apollo R package (Hess and Palma, 2019, 2022). Variables grazing, intens, silvopast, and payment refer to the analyzed practices and their levels (described in the next section).

Finally, we estimate a latent class model to identify different types of farmers with similar preferences for the programs and individual and farm characteristics. This approach helps characterize the heterogeneity of preferences identified through the mixed logit model in a way that facilitates policy recommendations. Indeed, a latent class model allows for the identification of segments of the farming population that would require different policy interventions for the adoption of sustainable livestock farming practices. Conditioned on belonging to class c, the probability of individual i choosing alternative j is defined as

$$Pr(Y_i=j|\beta_c)=\frac{e^{\mu\beta_c X_{ij}}}{\sum_{k=1}^{j} e^{\mu\beta_c X_{ik}}},\ c: \{1...,S\}$$

The probability of choice of alternative j in a choice card, over S classes, is therefore defined as

$$Pr(Y_i=j|\beta_S)=\sum_{s=1}^{S} M_{i,s}\frac{e^{\mu\beta_s X_{ij}}}{\sum_{k=1}^{j} e^{\mu\beta_s X_{ik}}}$$

with $M_{i,s}$ denoting the probability that individual i belongs to class s, which depends on individuals' characteristics (vector Z_i) and an error term $\mu_{i,s}$:

$$M_{i,s}=\alpha s Z_i+\mu_{is}$$

with α_s the vector parameters representing the weights of individual characteristics Z_i in the probability of class membership. This probability itself is estimated using a multinomial logit model, as follows:

$$M_{i,c}=Pr(c\backslash Z_i)=\frac{e^{\alpha_c' Z_i}}{\sum_{s=1}^{S} e^{\alpha_s' Z_i}}$$

2.5 Variable Construction and Sample Description

This section describes the sample and the variables used in the econometric models. Table 3 reports the description and summary statistics for all variables used in the models. Of the farmers who completed the survey, 78% were male, with an average age of 50 years. Their production units varied substantially, averaging 898 hectares but ranging from very small holdings to operations exceeding 15,000 hectares. Appendix 2 provides a more detailed summary of land-use and socioeconomic variables.

In addition to sociodemographic and farm structure data, we collected information on management practices and constructed a set of behavioral and attitudinal variables (see Section 4 for impatience and risk aversion) for inclusion in the models that capture producers' heterogeneity. The sustainability index variable takes a value of 1 if the producer implements the practice of seasonal adjustment of stocking rate and 2 if the producer also implements at least one other intensification practice (Section 3.2).

To summarize the environmental preferences into a single metric, we constructed an environmental awareness index by assigning numerical values to responses from five statements capturing perceptions of environmental issues and the role of producers. Participants indicated their level of agreement with the following statements: (1) “Global warming is a serious threat,” (2) “Livestock practices negatively affect the environment,” (3) “Environmentally friendly livestock practices can improve the state of the environment,” (4) “I feel that my production activities contribute to local environmental problems,” and (5) “I feel that my production activities contribute to international or global environmental problems (e.g., global warming).” Responses were scored as 3 for “agree,” 2 for “neither agree nor disagree,” and 1 for “disagree.” The index was calculated as the sum of these scores. On average, respondents neither strongly agreed nor disagreed with the statements, suggesting a moderate level of environmental awareness.

To approximate producers’ perception of social norms, we defined a binary variable equal to 1 if the respondent agreed with the statement “Producers in my community are willing to adopt (or have already adopted) sustainable practices,” and 0 otherwise. Only 30% of respondents perceive that their peers are moving toward adoption of sustainable practices. We also measured altruistic behavior with this question: “How willing are you to make material sacrifices to contribute to good causes without expecting anything in return?” Possible responses ranged from 0 (not willing) to 10 (very willing). On average, producers report a moderate level of altruism (6).

Risk aversion was elicited through a set of lottery tasks and reverse-coded from 1 (“risk seeking”) to 7 (“extremely risk averse”), based on Table 1. The discount rate was derived from the intertemporal choice tasks, calculated as the midpoint between upper and lower switching points in Table 2, assigning 50% to respondents who never switched.

Finally, the bottom part of Table 3 provides a description of the attributes included in the models: grazing (grazing1, grazing2, grazing3), intensification (intens1, intens2, intens3), silvopastoral management (silvopast1, silvopast2, silvopast3), and payment.

Table 3 Variables reflecting sustainable practices

Variable	Description	n	Mean	SD	Min	Max
Gender	Dummy variable (1=Male)	274	0,78	0.41	0	1
Age	Age of respondent	274	50	14	20	83
Surface	Farm area (ha)	274	898	1.439	0.0	15821
Sustainability index	Categorical variable (1 = implemented seasonal adjustment of stocking rates; 2 = seasonal adjustment of stocking rates + one more sustainable intensification practice)	274	1	0.79	0	2
Environmental awareness	Index of environmental perceptions (1–3 scale per item; sum of 5 items)	274	2	0.39	1	3
Social norm	Dummy = 1 if agrees community adopts sustainable practices	274	0.30	0.46	0	1
Altruism	Willingness to sacrifice for good causes (0–10 scale)	274	6	3	0	10
Discount rate	Implied discount rate (%)	274	21	19	0.5	50
Risk aversion	Risk preference (1 = risk seeking; 7 = extremely risk averse)	274	5	2	1	7
grazing1	Increase area of artificial pastures and/or forage crops by 1%	—	—	—	—	—
grazing2	Increase area of artificial pastures and/or forage crops by 5%	—	—	—	—	—
grazing3	Increase area of artificial pastures and/or forage crops by 10%	—	—	—	—	—
intens1	Implementation of seasonal adjustment of stocking rate	—	—	—	—	—
intens2	Implementation of (1) defining breeding periods and categorizing females, (2) prebreeding bull review and pregnancy diagnostics, and (3) first pregnancy at two years and post-calving nutrition	—	—	—	—	—
intens3	Implementation of (1) seasonal adjustment of stocking rate, (2) defining breeding periods and categorizing females, (3) prebreeding bull review and pregnancy diagnostics, and (4) first pregnancy at two years and postcalving nutrition	—	—	—	—	—
silvopast1	Increase area of under silvopastoral management by 1%	—	—	—	—	—

A common critique of DCEs is their limited external validity, often due to nonrepresentative samples. This issue arises because accessing microdata to construct representative samples—and contacting farmers in particular—can be challenging. To check the representativeness of our sample to the population, Table 4 compares the distribution of selected characteristics of our survey respondents with data from the 2016 Nationally Representative Livestock Survey, which provides the most up-to-date information on livestock producers.

Despite some discrepancies, the sample aligns reasonably well with the population along most dimensions. Discrepancies are observed in the share of smallholders and the share of respondents whose household nonfarm income is higher than 50% of total income. Nevertheless, we address this issue by applying our preferred specification to resampled data that replicates the herd-size distribution reported in the 2016 National Livestock Survey. The results remain robust under this sample (see Section 7).

Table 4 Comparison of own survey and 2016 National Livestock Survey respondents

Variable	Own survey (%)	2016 National Livestock Survey (%)
Owners	0.72	0.64
Household off-farm income higher than 50%	0.32	0.11
≤ 299 head of cattle	0.45	0.66
300 to ≤ 999 head of cattle	0.32	0.24
≥ 1,000 head of cattle	0.21	0.10

2.6 Results

2.6.1 Mixed logit model

Table 5 reports the results of the mixed logit (MXL) model, which accounts for preference heterogeneity among respondents, run with Apollo (Hess and Palma, 2019). The main specification was selected after testing alternative specifications (see Appendix 3). Column 1 presents the estimates from our preferred specification, based on the full sample of 274 respondents and 1,644 observations. Following Bougherara et al. (2021), columns 2, 3, and 4 present robustness checks. In the second column, we exclude respondents who reported finding the exercise too complex, based on their answers to the follow-up questions. In the third column, we remove respondents whose survey completion times were either unusually short or long—specifically, those falling below the first quartile or above the third quartile of the response time distribution. Finally, the fourth column shows results from a resampled data set adjusted to match the producer composition of the 2016 National Livestock Survey, using bootstrapping techniques.

Focusing on results from column 1, the alternative-specific constant (ASC) is positive and statistically significant, implying that farmers tend to prefer the proposed program alternatives over the status quo (conditions without the program).

The coefficients for improvements in grazing area using artificial pastures and/or forage crops are positive but not statistically significant, indicating that producers are on average indifferent to this attribute. In contrast, coefficients for sustainable intensification practices are positive and statistically significant at the 1% level for all levels, suggesting that farmers are willing to receive a lower compensation when these practices are included in the choice set. Furthermore, preferences for this attribute increase with the number of practices (intensification) included in a program, reflecting the producers' perception that sustainable intensification can enhance profitability.

The coefficients associated with silvopastoral practices are negative and statistically significant at the 1% level for the highest level of adoption and at only the 10% level for the medium level, but not statistically significant for the lowest level of this practice. These findings suggest that producers generally perceive silvopastoral systems as restrictive and would require compensation to adopt such practices. The coefficient of the logarithm of the payment attribute is negative and statistically significant at the 1% level, indicating a clear preference for programs that offer higher per hectare payments.[4]

These estimates also highlight substantial heterogeneity in preferences, particularly for silvopastoral and sustainable intensification practices. This is reflected in the statistically significant standard deviations of the random coefficients (σ's) in the MXL model (the bottom 11 coefficients in the table) for sustainable intensification, silvopastoral, and payment attributes. Overall, the results from these subsamples are consistent with those obtained using the full sample. Producers generally prefer participating in the proposed programs over maintaining the status quo. They appear indifferent toward improved grazing area, value sustainable intensification practices positively, and tend to dislike silvopastoral practices, especially at higher levels of adoption. Preference heterogeneity is also evident, as shown by the statistically significant estimates of the standard deviation parameters (σ's) for the ASC, sustainable intensification, silvopastoral, and payment attributes. Additionally, when respondents with extreme completion times are excluded, significant heterogeneity emerges for grazing parameters as well.

To test the robustness of our results to sample composition and to enhance external validity, the final column of Table 5 presents estimates from the MXL model using a resampled data set. This resampling was performed via bootstrapping techniques to approximate the distribution of cattle herd sizes observed in the 2016 national survey (Table 4). The resulting preference estimates are largely consistent with those obtained from the full sample, offering evidence of the external validity of our estimates. Moreover, preference heterogeneity remains significant across most attributes, including grazing practices.

[4] We assume the payment attribute is distributed as lognormal, to ensure purely positive responses to this attribute. A negative coefficient in the log of payment therefore indicates a positive effect on utility.

Table 5 Mixed logit model estimates across subsamples

Variable	All	Excl. complex	Excl. extreme duration	Resampled
ASC	1.360*** (3.36)	1.363*** (3.23)	1.046* (1.91)	1.407*** (0.4220)
Grazing1	0.077 (0.50)	0.028 (0.17)	0.121 (0.49)	0.075 (0.149)
Grazing2	0.251 (1.49)	0.212 (1.23)	0.483 (1.60)	0.244 (0.159)
Grazing3	0.065 (0.39)	0.050 (0.31)	0.132 (0.47)	0.066 (0.152)
Intens1	0.604*** (3.64)	0.541*** (3.37)	0.741*** (2.72)	0.593*** (0.163)
Intens2	0.654*** (3.50)	0.787*** (3.89)	0.575* (1.72)	0.666*** (0.174)
Intens3	0.843*** (4.33)	0.919*** (4.26)	0.969*** (2.98)	0.837*** (0.175)
Silvopast1	-0.080 -0.45)	-0.065 (-0.35)	-0.109 (-0.41)	-0.075 (0.169)
Silvopast2	-0.298* (-1.66)	-0.257 (-1.37)	-0.480 (-1.52)	-0.301* (0.156)
Silvopast3	-0.649*** (-2.85)	-0.586** (-2.52)	-0.853** (-2.05)	-0.651*** (0.189)
Log(payment)	-1.600*** (7.86)	-1.520*** (-7.29)	-1.299*** (-4.79)	-1.608*** (0.206)
σASC	3.545*** (8.55)	2.959*** (6.88)	3.774*** (5.25)	3.584*** (0.401)
σGrazing1	-0.318 (-0.69)	-0.346 (-1.04)	0.170 (0.60)	0.298 (0.515)
σGrazing2	-0.113 (-0.35)	0.125 (1.04)	-0.927** (-2.01)	0.101 (0.537)
σGrazing3	0.715* (1.79)	0.237 (0.35)	1.407*** (2.67)	0.662* (0.356)
σIntens1	-0.013 (-0.15)	0.013 (0.22)	0.261 (0.87)	-0.029 (0.371)
σIntens2	-1.162*** (-3.05)	-0.955** (-2.11)	1.891*** (2.99)	-1.168*** (0.313)
σIntens3	-1.204*** (-4.08)	1.141*** (3.54)	-1.683*** (-3.57)	-1.206*** (0.259)
σSilvopast1	-1.155*** (-4.46)	1.155*** (4.07)	-1.270*** (-2.73)	-1.143*** (0.266)
σSilvopast2	-0.827** (-2.25)	-0.880** (-2.13)	-1.091* (-1.75)	-0.791** (0.317)
σSilvopast3	-1.356*** (-3.35)	1.320*** (2.91)	-2.236*** (-3.35)	-1.319*** (0.310)
σPayment	-1.153*** (-5.24)	1.144*** (3.76)	1.129*** (4.61)	-1.170*** (0.191)
Respondents	274	237	148	274
Observations	1,644	1,422	888	1,644

Notes: Robust t-statistics in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01. Column 1 reports the main specification. Column 2 excludes respondents who reported finding the choice tasks too complex. Column 3 excludes respondents whose completion times were unusually short or long. Column 4 presents estimates from a resampled data set adjusted to match the distribution of production unit sizes in the population.

2.6.2 Latent class model

Although the MXL model provides evidence of preference heterogeneity, it does not identify the underlying sources of this heterogeneity. To explore these sources, we estimate a latent class model. The latent class model assumes that the sample consists of a finite number of unobserved (latent) groups of producers, each with distinct preference structures. Within each class, preferences are assumed to be homogeneous, but they can differ substantially across classes.

The model is essentially a conditional logit framework in which class membership is probabilistic and determined jointly with the choice model. The number of classes is specified by the researcher, guided by statistical fit criteria and interpretability (Greene and Hensher, 2003). Class membership probabilities can be modeled as a function of producers' characteristics—such as farm size, management practices, or behavioral attributes—allowing us to relate heterogeneity in preferences to observable differences among producers.

We estimated two latent class models with two classes each (the data did not support the estimation of a three-class specification because of nonconvergence of the model). The first model includes farm and producers' characteristics as explanatory variables in the class membership function. Specifically, we included the total area of the production unit, the producer's age, and the sustainability index.

The second model extends the membership function by incorporating behavioral variables: a continuous measure of impatience, proxied by the implied discount rate (see Table 1); the risk aversion variable (see Table 2); the altruism indicator; and the binary social norm variable.

The latent class model that uses farm and farmers' characteristics to define producer types is presented in the first two columns of Table 6 (Model 1). The top part of the table includes the coefficient estimates of the choice attributes and their levels. The bottom part displays how farm and producers' characteristics affect the likelihood of belonging to class B. The mean probability of membership in class A in this model is 81% and for class B, 19%. Small-scale producers who are older and have low levels of adoption of sustainable intensification practices are more likely to belong to class B than to class A.

All the explanatory variables for class membership are statistically significant at conventional levels. Class A producers dominate the sample and therefore their preferences toward the examined attributes are in line with those of the whole sample: they show an inclination for participating in the programs (ASC is positive and statistically significant), they do not exhibit strong preferences for grazing practices and tend to choose programs that include sustainable intensification practices, and they dislike high levels of silvopastoral practices. In contrast, class B farmers tend to dislike participating in the offered programs (ASC is negative and statistically significant), implying a fixed cost of changing from the status quo to the program. These producers would need to be compensated for adopting the grazing practices and seem to prefer low levels of sustainable intensification practices. In this class, silvopastoral coefficients are negative for high levels of this attribute but not statistically significant.

The last two columns of Table 6 display the results of the latent class model that includes behavioral traits for explaining class membership (Model 2). This model also includes two classes, with the same probabilities explaining class membership as Model 1. The probability of belonging to class B increases with age, smaller area, and low adoption of sustainable intensification practices. In this model, class B membership is positively associated with impatient, risk-averse, and less environmentally conscious producers, although none of these variables are statistically significant at conventional levels, indicating that class membership is mainly explained by more conventional variables. The precision of the farm and producers' characteristics estimates increases when we include behavioral characteristics. Additionally, including behavioral variables helps to distinguish more clearly the differences in preferences toward sustainable practices. In Model 2, all grazing attributes and the second level of sustainable intensification practices are negative and statistically significant for class B producers.

The lack of significance is consistent with the nature of most practices in the programs. Sustainable intensification measures—such as seasonal stocking adjustments and reproductive planning—are largely managerial changes that do not imply long delays in returns or significant increases in uncertainty. Previous studies show that such interventions often generate productivity gains within a single production cycle (Thornton and Herrero, 2010; de Haas et al., 2021a; de Haas et al., 2021b) and are generally classified as low-cost, high-return practices (FAO, 2014). Similarly, improved grazing through forage crops tends to be perceived as familiar and low risk (Fuglie et al., 2021; Modernel et al., 2016). Accordingly, it is reasonable that behavioral traits like risk and time preferences would not explain much variation in preferences for these options.

In contrast, silvopastoral practices—especially at higher levels of adoption—are associated with longer payback periods, higher upfront costs, and greater perceived risk (Jose et al., 2004; Nair, 2011). Yet these practices are generally disliked across classes, which may explain why behavioral traits also fail to predict their acceptance: producers may be uniformly averse to them, regardless of individual attitudes toward risk or time.

Alternative specifications splitting the sample by behavioral profiles (impatient vs. patient, risk averse vs. risk tolerant), using the full sample including an extended set of socioeconomic variables for class membership and only behavioral variables, are shown in Appendix 4. Results are largely consistent with those shown in Table 6.

Table 6 Latent class model estimates

Variable	Model 1		Model 2	
	Class A	Class B	Class A	Class B
ASC	1.315*** (6.09)	-1.567** (-2.25)	1.337*** (6.08)	-1.622** (2.92)
Grazing1	0.120 (1.04)	-0.696* (-1.81)	0.123 (1.1)	-0.72* (1.99)
Grazing2	0.189 (1.52)	-0.718 (-1.50)	0.172 (1.42)	-0.74* (1.98)
Grazing3	0.117 (1.04)	-0.797 (-1.64)	0.133 (1.23)	-0.939** (2.31)
Intens1	0.394*** (4.06)	0.630** (2.19)	0.419*** (3.59)	0.554 (1.9)
Intens2	0.516*** (3.79)	-1132 (-1.62)	0.563*** (4.94)	-1.221** (2.25)
Intens3	0.592*** (4.26)	0.098 (0.22)	0.642*** (5.85)	-0,002 (0.0)
Silvopast1	-0.066 (-0.55)	0.141 (0.31)	-0.056 (0.49)	0.256 (0.52)
Silvopast2	-0.188 (-1.52)	-0.166 (-0.31)	-0.202* (1.89)	0.161 (0.25)
Silvopast3	-0.400*** (-2.63)	-0.363 (-0.48)	-0.421*** (3.47)	0.051 (0.08)
Payment	0.204*** (8.94)	0.115* (1.84)	0.214*** (10.99)	0.14 (1.82)
Delta (intercept)		-3.798*** (-4.04)		-3.593** (2.7)
Surface		-0.00077** (-2.28)		-0.00079** (2.27)
Age		0.061*** (3.85)		0.058*** (3.15)
Sustainability index		-0.648* (-1.79)		-0.843** (2.2)
Discount rate				0.536 (1.37)
Risk aversion				0.307 (0.73)
Altruism				0.608 (1.32)
Environmental awareness				-0.064 (0.11)
Social norm				
Producers	274		263	-0.478 (1.04)
Observations	1,644		1,578	
BIC	2,924		2,800	
AIC	2,754		2,633	
Class membership probabilities	81%	19%	80%	20%

Notes: Robust t-statistics in parentheses. Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01.

2.6.3 Willingness-to-accept estimates

Table 7 presents the marginal willingness-to-accept (WTA) estimates obtained from the MXL model for average producers (column 1) and those from class A and class B obtained from the latent class Model 1 in Table 6 (columns 2 and 3, respectively). On average, producers' WTA is approximately USD –105 per hectare per year to participate in the proposed programs, which means they are willing to obtain a low payment for participating in the programs. Class A producers' WTA is USD –64, which also indicates that these producers are willing to obtain a low payment for participating in the programs. However, producers in class B display a negative preference for participation and would require compensation: their estimated WTA is USD 135 per hectare per year.

Results also suggest that producers' average WTA is negative and thus they are willing to accept a lower payment to adopt improved grazing practices, although the coefficients are only marginally significant for medium levels of adoption. In contrast, producers exhibit a negative and statistically significant willingness to accept for sustainable intensification practices, likely because of the perceived productivity benefits. The average WTA for these practices ranges from USD -22 to USD -28 per hectare per year, depending on the level of adoption, indicating a willingness to accept lower compensation when these practices are offered. In contrast, producers exhibit a strong and statistically significant willingness to pay for sustainable intensification practices, likely because of the perceived productivity benefits. The average WTP for these practices ranges from USD 22 to USD 28 per hectare per year, depending on the level of adoption. When accounting for heterogeneous preferences, class A producers exhibit similar preferences for sustainable intensification practices as those of average producers, whereas class B producers would need to be compensated to adopt medium levels of sustainable intensification practices; none of the coefficients for this attribute, however, are statistically significant.

On the other hand, on average, producers require compensation to adopt silvopastoral practices. The estimated WTA for medium and high levels of silvopastoral adoption is USD 12.3 and USD 21.4 per hectare per year, respectively, indicating these practices are perceived as burdensome or less beneficial in the short term. For class A producers, only high levels of adoption of this practice are statistically significant and indicate an average WTA of USD 19 per hectare per year. For class B farmers, none of the silvopastoral coefficients were statistically significant.

A fundamental question is why the adoption of sustainable intensification practices remains limited, despite producers' perceiving them as beneficial. To explore this, the survey included questions on perceived barriers to adoption. Seventy percent of respondents identified high upfront costs as an obstacle.

Overall, the findings highlight the importance of aligning policy instruments with producers' preferences. Whereas sustainable intensification practices may be promoted by addressing upfront investment barriers, silvopastoral techniques adoption may require direct financial incentives.

Table 7 Marginal willingness-to-accept estimates (USD/ha/year)

Attribute	Mixed logit model	Class A	Class B
ASC	−105.8*** (−6.36)	−64.3*** (−4.57)	135.8** (2.17)
Grazing1	−8.6 (−1.36)	−5.9 (−1.06)	60.3 (1.18)
Grazing2	−10.1* (−1.93)	−9.3 (−1.58)	62.2 (10.1)
Grazing3	−7.1 (−1.64)	−5.7 (−1.05)	69.1 (1.09)
Intens1	−21.9*** (−7.48)	−19.3*** (−3.80)	−54.6 (−1.34)
Intens2	−24.4*** (−5.76)	−25.2*** (3.70)	98.1 (1.11)
Intens3	−28.3*** (−6.63)	−29*** (−4.06)	−8.5 (−0.23)
Silvopast1	2.6 (0.86)	3.2 (0.55)	−12.3 (−0.31)
Silvopast2	12.3*** (3.55)	9.2 (1.54)	14.4 (0.30)
Silvopast3	21.4*** (4.45)	19.6*** (2.69)	31.5 (0.46)

Notes: Robust t-statistics in parentheses. Significance levels: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$. All values are expressed as marginal WTA (USD/ha/year). WTA estimates for MXL were derived from WTP-space coefficients. Class A and B refer to the two-class latent class model.

2.7 Conclusions

This study assesses cattle producers' preferences for adopting sustainable agricultural practices in Uruguay. Through a combination of discrete choice experiments and behavioral tasks eliciting and measuring risk and time preferences, we identify significant heterogeneity in producers' preferences for sustainable practices.

The results suggest that although sustainable intensification practices are generally liked and associated with productivity benefits, silvopastoral practices remain less appealing, likely because of perceived risks, costs, lack of familiarity, and less direct link with productivity. These findings highlight the need for tailored strategies to encourage sustainable practices in extensive livestock systems. Adoption of sustainable intensification practices involving herd management may not require large monetary incentives. In contrast, the adoption of silvopastoral practices may require additional resources.

Our latent class analysis uncovers two distinct farmer segments: a majority group inclined toward adoption and a minority who require stronger incentives to depart from the status quo. Although the elicitation of time and risk preferences showed an expected heterogeneity across producers, they were not statistically significant for explaining differences in attitudes toward sustainable practices. In contrast, conventional variables, such as age, farm area, and the level of adoption of sustainable practices, were statistically significant in explaining preference heterogeneity. Nevertheless, they appear to highlight differences in attitudes toward sustainable practices.

Designing agri-environmental schemes that address the behavioral and structural diversity of producers can improve both environmental outcomes and policy effectiveness. However, additional research is needed to reach a better understanding of livestock producers' behavioral characteristics, their decision-making processes, and how these factors affect preferences for sustainable practices.

An important aspect that could not be incorporated into the choice experiment is producers' relative preferences for different incentive mechanisms, such as tax deductions, subsidies, and cost-sharing arrangements. For instance, because of potential negative connotations, beef producers may favor tax deductions or government copayments over conditional payments. Exploring these preferences represents a promising direction for future research.

Acknowledgments

We are grateful to all participating producers. In particular to Esteban Carriquiry, whose help was critical for the successful distribution of the survey; to Ignacio Borba, who programmed the survey in Qualtrics; and to Allen Blackman, for his technical support. We are also grateful for the financial and technical support provided by the InterAmerican Development Bank.

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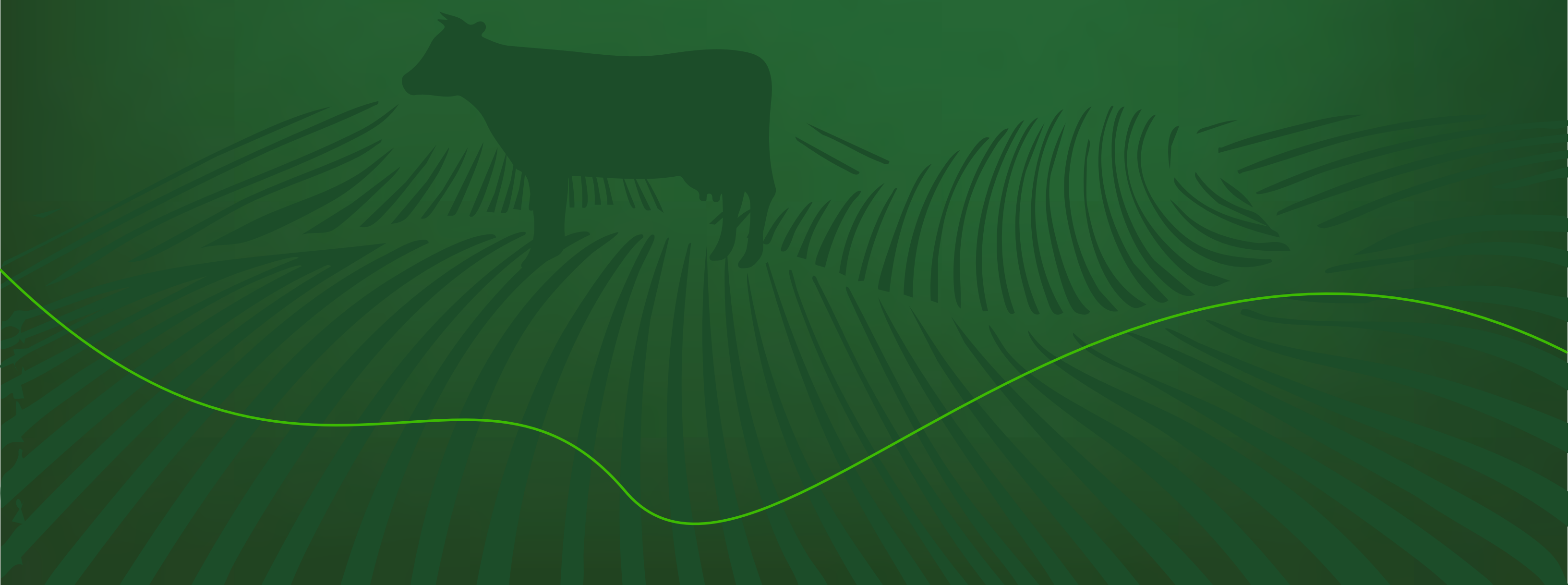
Appendix



Appendix 1. Sustainable Practices in Cattle Production

Sustainable practices to reduce emissions intensity and improve ecosystem services in livestock production include improved animal and feed management, diet formulation changes, and rumen interventions (Nabinger, 2011; Cubbage et al., 2012; Bussoni et al., 2015; Do Carmo et al., 2016; Jara-Rojas et al., 2020; Arndt et al., 2022; Caprarulo et al., 2022; Kelly, 2023). Examples of such techniques include feed processing, genetic selection, improved animal health, pasture management, increased feed levels, and enhanced forage quality. Other livestock practices, such as silvopastoral systems, also reduce net emissions by increasing carbon sinks through afforestation (Rivera et al., 2023). Our study focuses on three livestock techniques with the potential to reduce GHG emissions intensity (emissions per unit of output) and increase the provision of ecosystem services while maintaining and improving productivity: improved grazing area, sustainable intensification practices for herd management, and silvopastoral systems (Becoña et al., 2014; INIA, 2024; Eugène et al., 2021; Sancho et al., 2023).

In this study, improved grazing area involves establishing artificial pastures to increase forage availability and digestibility and reduce methane emissions (Eugène et al., 2021). Additionally, these pastures enhance adaptability to extreme weather events, reducing year-to-year output fluctuations (Becoña et al., 2014; Modernel et al., 2019). Sustainable intensification practices through herd management encompass multiple technologies and strategies. In rotational grazing, for example, farmers rotate the herd based on forage assessment instead of body condition. Research shows that this results in improved body condition, increased live weight, higher pregnancy rates, better milk yield, and heavier calves with earlier slaughter ages (Do Carmo et al., 2016; Claramunt et al., 2020). It also reduces emissions intensities by enhancing soil productivity, increasing carbon capture, boosting animal weight, and lowering the slaughter age (INIA, 2024). These techniques are consistent with Uruguay's NDC and other environmental goals, such as the National Adaptation Plan (República Oriental del Uruguay, 2022).

Many of these practices have the potential to improve profits because they improve productivity. A recent study conducted by Uruguay's National Institute of Agricultural Research (INIA) documents the economic and environmental gains of adopting improved grazing area and sustainable intensification practices in three production units in Uruguay (INIA, 2024).

Silvopastoral techniques, which integrate fodder plants, shrubs, and trees into livestock systems, also have the potential to enhance productivity (Lemes et al., 2021; Rivera et al., 2023) while providing valuable ecosystem services, including soil carbon sequestration (De Stefano and Jacobson, 2018; Rivera et al., 2023) and biodiversity habitat. Carbon sequestration in livestock systems is in line with mitigation objectives in the Uruguayan NDC. However, these practices remain relatively unfamiliar to many producers in the country and often require additional skills, such as knowledge of forest management, and investments, such as the

Table A.2.1. Detailed summary statistics

Variable	n	Mean	SD	Min	Max
Land use (ha)					
Permanent artificial pasture	125	202	555	0	5,000
Natural pasture	249	680	1.102	0	11,500
Improved natural pasture (cover crops)	150	177	237	0	1269
Annual forage crops	105	81	108	0	831
Orchard, fruit trees, vineyard	34	11	30	0	134
Artificial forest (dense, windbreak, shelter, shade)	99	65	130	0	750
Native forest	94	100	155	0	900
Production unit area	274	898	1.439	0	15,821
Head of cattle					
Bulls	218	15	23	0	220
Breeding cows, pregnant heifers	228	331	459	0	4,500
Cull cows or overwintering cows	166	70	78	0	350
Steers	172	182	390	0	3,400
Heifers	217	124	189	0	1,900
Calves	222	224	361	0	3,700
Labor force					
Family members	274	2	1	0	10
Employees	274	2	4	0	50

Appendix 3. Conditional Logit and Model Specification

Table A.3.1 presents estimates from three conditional logit models based on 274 respondents, totaling 1,644 observations. Column 1 reports results from a model that assumes linear effects for the grazing and silvopastoral attributes, each captured by a single dummy variable. Column 2 introduces a more flexible specification that accounts for nonlinear effects of the grazing and silvopastoral practices by including dummy variables for each level. The results largely confirm those in column 1: coefficients for grazing remain positive but statistically insignificant, while those for sustainable intensification remain positive, statistically significant, and increasing in magnitude. For silvopastoral practices, levels 2 and 3 yield negative and statistically significant coefficients (at the 10% and 1% levels, respectively), while level 1 remains insignificant. These findings provide evidence of nonlinear effects in both silvopastoral and sustainable intensification attributes.

Finally, column 3 presents a model in which the status quo alternative includes level 1 of sustainable intensification practices, consistent with the self-reported adoption of seasonal adjustment of stocking rate practice by 81% of respondents. The results mirror those from column 1: grazing practices remain statistically insignificant, sustainable intensification practices are positively valued, and higher levels are preferred. For silvopastoral practices, coefficients for levels 1 and 2 are negative but not statistically significant, while level 3 remains negative and statistically significant at the 1% level. Our preferred specification allows for nonlinear preferences across attribute levels, as reported in column 2.

Table A.3.1. Detailed summary statistics

Variable	(1)	(2)	(3)
asc	−0.057 (0.33)	−0.098 (0.53)	0.083 (0.47)
grazing1	—	0.033 (0.34)	−0.007 (0.07)
grazing2	—	0.061 (0.57)	0.039 (0.37)
grazing3	—	0.069 (0.71)	0.088 (0.93)
grazing	0.023 (0.70)	—	—
intens1	0.400*** (4.58)	0.401*** (4.59)	—
intens2	0.419*** (3.77)	0.423*** (3.77)	0.239** (2.45)
intens3	0.498*** (4.52)	0.513*** (4.51)	0.337*** (3.31)
silvopast1	—	−0.052 (0.48)	−0.047 (0.43)
silvopast2	—	−0.190* (1.76)	−0.176 (1.62)
silvopast3	—	−0.350*** (2.77)	−0.341*** (2.71)
silvopast	−0.118*** (2.91)	—	—
payment	0.196*** (9.74)	0.195*** (9.80)	0.198*** (9.86)

Notes: Robust t-statistics in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Appendix 4. Alternative Specifications

Table A.4.1. Mixed logit model estimates, by behavioral profile

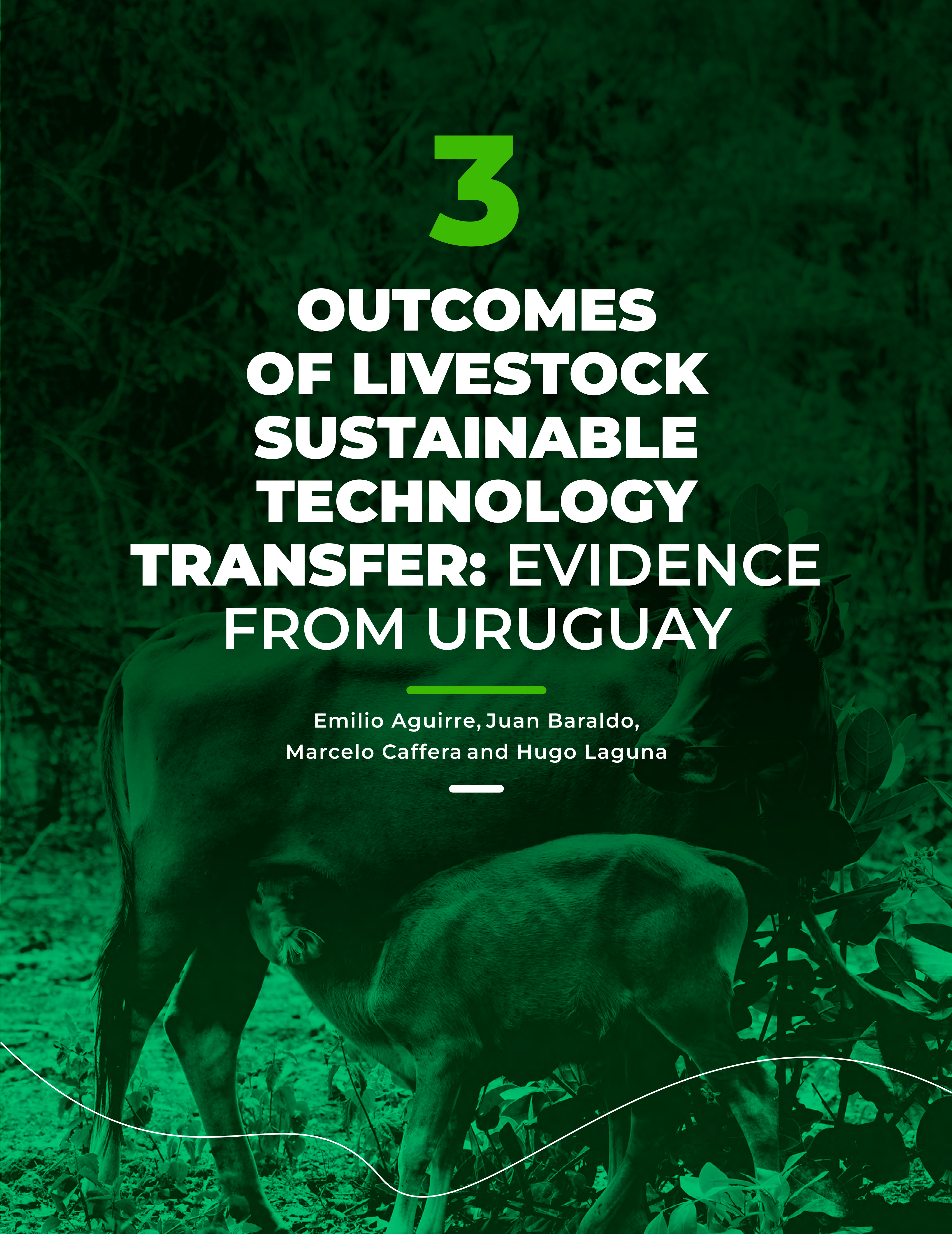
Variable	Risk seeking	Risk averse	Impatient	Patient
asc	1.033** (2.29)	1.926** (2.19)	0.762 (1.43)	1.713** (2.37)
grazing1	0.012 (0.06)	0.298 (1.03)	0.057 (0.19)	-0.069 (0.32)
grazing2	0.447** (2.14)	-0.228 (0.79)	0.114 (0.37)	0.135 (0.56)
grazing3	0.011 (0.05)	0.198 (0.67)	-0.004 (0.01)	0.007 (0.03)
intens1	0.538*** (2.84)	0.775*** (2.69)	0.768*** (2.79)	0.561** (2.53)
intens2	0.752*** (3.12)	0.517* (1.58)	0.775** (1.98)	0.758*** (3.02)
intens3	1.086*** (4.54)	0.295 (0.76)	0.925*** (2.69)	0.982*** (3.37)
silvopast1	0.093 (0.47)	-0.564 (1.18)	0.169 (0.46)	-0.152 (0.61)
silvopast2	-0.190 (0.91)	-0.621* (1.65)	0.029 (0.08)	-0.584* (1.93)
silvopast3	-0.676** (2.37)	-0.757* (1.71)	-0.462 (1.06)	-0.923** (2.43)
log(payment)	-1.598*** (6.73)	-1.567*** (3.74)	-1.428*** (3.94)	-1.487*** (6.12)
σasc	2.983*** (6.78)	-4.943*** (4.41)	3.446*** (6.38)	3.868*** (5.11)
σgrazing1	-0.219 (0.47)	-0.351 (0.54)	1.021 (1.55)	0.015 (0.33)
σgrazing2	-0.026 (0.25)	0.143 (0.23)	1.057* (1.78)	-0.050 (0.34)
σgrazing3	-0.778** (2.07)	0.048 (0.12)	-1.528** (2.06)	0.155 (0.56)
σintens1	-0.062 (0.65)	-0.008 (0.04)	-0.382 (1.11)	-0.319 (0.56)
σintens2	1.469*** (3.00)	0.700 (0.87)	-2.495*** (2.61)	-0.229 (0.27)
σintens3	-1.148*** (3.19)	-1.628** (2.22)	1.954*** (2.95)	-1.030** (2.91)
σsilvopast1	1.028*** (2.91)	-1.556** (2.00)	-1.816*** (3.09)	-1.019** (2.54)
σsilvopast2	-0.982** (2.29)	-0.400 (0.63)	1.079 (1.45)	1.088** (2.26)
σsilvopast3	1.570*** (3.30)	1.223* (1.78)	1.806** (2.39)	-1.584*** (2.66)
σpayment	-1.196*** (4.92)	-1.275*** (5.10)	-1.535*** (4.61)	-0.950*** (4.04)
Producers	194	80	139	124
Observations	1164	480	834	744
BIC	2063	868	1477	1329
AIC	1951	776	1373	1228

Table A.4.2. **Latent class model estimates with farm and producers' characteristics variables**

Variable	Class A	Class B
asc	1.305*** (5.99)	-1.569** (-2.08)
grazing1	0.121 (1.01)	-0.698* (-1.76)
grazing2	0.190 (1.44)	-0.723 (-1.50)
grazing3	0.118 (1.02)	-0.817 (-1.56)
intens1	0.394*** (4.04)	0.630** (2.15)
intens2	0.517*** (3.55)	-1.163 (-1.55)
intens3	0.593*** (4.01)	0.081 (0.17)
silvopast1	-0.066 (-0.54)	0.136 (0.30)
silvopast2	-0.191 (-1.53)	-0.133 (-0.22)
silvopast3	-0.401*** (-2.55)	-0.350 (-0.40)
payment	0.204*** (8.72)	0.116* (1.83)
delta (intercept)		-3.305*** (-3.31)
surface		-0.00074** (-2.13)
age		0.062*** (3.36)
male		-0.598 (-1.23)
income>50k		0.305 (0.71)
sustainability index		-0.406* (-1.90)
Producers	274	
Observations	1,644	
BIC	2,907.57	
AIC	2,756.23	
Class membership probability	81%	19%

Table A.4.3. Latent class model estimates with behavioral variables

Variable	Class A	Class B
asc	1.334*** (5.43)	-1.702** (-2.60)
grazing1	0.125 (1.08)	-0.745* (-1.82)
grazing2	0.164 (1.35)	-0.686 (-1.40)
grazing3	0.127 (1.13)	-0.900** (-2.01)
intens1	0.419*** (4.09)	0.557** (2.01)
intens2	0.560*** (4.01)	-1.218** (-2.16)
intens3	0.641*** (4.38)	-0.020 (-0.05)
silvopast1	-0.053 (-0.41)	0.163 (0.32)
silvopast2	-0.215 (-1.63)	0.260 (0.43)
silvopast3	-0.422*** (-2.63)	0.039 (0.06)
payment	0.214*** (8.95)	0.154** (2.18)
delta (intercept)		-1.474 (-1.35)
impatience		0.560 (1.52)
risk aversion		0.431 (1.22)
altruism		0.550 (1.31)
awareness		-0.155 (-0.31)
social norm		-0.485 (-1.15)
Producers	263	
Observations	1,578	
BIC	2,809.93	
AIC	2,659.74	
Class membership probability	80%	20%



3

OUTCOMES OF LIVESTOCK SUSTAINABLE TECHNOLOGY TRANSFER: EVIDENCE FROM URUGUAY

Emilio Aguirre, Juan Baraldo,
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Abstract

As global demand for beef increases, balancing livestock productivity with environmental sustainability has become a policy priority. In response, Uruguay implemented the Sustainable Family Production Program (PFIS). Between 2015 and 2017, this program provided support to small and medium-sized cattle farmers to invest in technologies and management practices aimed at enhancing both productivity and climate resilience. This study provides the first causal evaluation of a national program designed to promote these dual objectives in the cattle sector. We assess the effect of PFIS on three outcomes: (i) technology adoption, (ii) productivity, and (iii) greenhouse gas emissions intensity. To identify causal effects, we use a regression discontinuity design based on a strict eligibility threshold, using panel data from producers between 2015 and 2020. Although we found no statistically significant effects on beef productivity per hectare or greenhouse gas emissions intensity during the study period, the program significantly increased adoption of good reproductive and herd management practices, including early weaning, controlled mating, and ovarian activity diagnosis. These results highlight both the potential and the limitations of integrated technology transfer programs in promoting sustainable intensification of extensive livestock systems. They also suggest the need for longer-term evaluations to capture potential impacts on productivity and emissions that may emerge as these technologies, particularly reproductive ones, influence aggregate outcomes.

Introduction[5]

Global projections forecast a 10% increase in beef consumption by 2032 (OECD & FAO, 2023). Meeting this growing demand poses a significant challenge, especially as livestock grazing, the dominant land use worldwide (Nin et al., 2019), comes under increasing environmental scrutiny (Steinfeld, 2006; Gerber et al., 2013, MacLeod et al., 2018). Concerns are exacerbated by the accelerating effects of climate change and rising food prices.

The transition challenge is therefore to improve livestock productivity and climate resilience while simultaneously ensuring environmental and social sustainability. Enhancing productivity can support economic growth, reduce environmental pressures, strengthen farm competitiveness, and advance broader goals related to food security and climate change mitigation (Aguirre et. al, 2024). Achieving these interconnected objectives requires identifying and implementing effective livestock policies and programs, guided by robust empirical evidence.

The adoption of appropriate technologies can drive both productivity improvements and climate adaptation. However, in many developing countries, particularly among small-scale producers in low and middle-income regions, the uptake and effective use of new technologies remain limited (de Janvry et al., 2017; López et al., 2017). In the livestock sector, barriers to investment and adoption include producers' restricted access to financial markets and limited access to reliable information about available technologies and their potential economic benefits. These obstacles often

[5] The opinions expressed in this document are solely those of the authors and do not reflect or represent the official positions of the InterAmerican Development Bank (IDB) or the Ministry of Livestock, Agriculture, and Fisheries.

stem from broader structural issues, such as market failures, information asymmetries, and a misalignment between technological solutions and the actual needs and constraints faced by farmers.

In response, governments and development agencies have implemented technology transfer programs that combine financial incentives with technical assistance. Although these interventions primarily aim to increase productivity, they are increasingly expected to generate environmental co-benefits by improving resource efficiency and reducing emissions per unit of output. Nevertheless, in spite of the role of cattle farming in deforestation and methane emissions, rigorous evidence of their effectiveness remains limited. To our knowledge, no studies in livestock systems have simultaneously examined technology adoption, productivity, and environmental outcomes within a unified empirical framework using causal identification strategies.

Recent years have seen increasing interest in counterfactual-based methods to evaluate agricultural policies (Winters et al., 2010; de Janvry et al., 2017). Uruguay stands out, still uniquely so, for its rigorous application of these methods in the livestock sector. Previous studies on livestock interventions, particularly those focused on beef production units (BPUs), have used matching techniques combined with difference-in-differences estimators, producing mixed results (see Table S1 in the supplementary material). For example, Lopez & Maffioli (2008) found that the pilot Uruguayan Livestock Program, which subsidized up to 50% of extension service costs for small and medium-sized producers, encouraged technology adoption but had no effect on calf production. Conversely, Mullally & Maffioli (2016) reported that a revised version of the program led to increased output and net sales.

More recent evaluations have examined programs with explicit sustainability objectives. The Family Farmers and Climate Change Project (2013–2019), aimed at strengthening climate resilience among drought-prone producers, found no significant changes in most sustainable practices (Durán & Laguna, 2021).6 Similarly, Durán et al. (2018) analyzed four interventions in the Rural Productive Development Program (*Plan Ovino, Llamado Lechero,* and *Programa* Agroforestal, as well as PFIS) and reported mixed effects on the partial productivity of meat and milk production.

This study aims to fill the evidence gap by evaluating the effectiveness of the Sustainable Family Production Program (PFIS), a policy initiative of the Uruguayan government to enhance productivity and climate resilience among small and medium-sized livestock producers. PFIS provided targeted financial support for the adoption of a menu of technological and management innovations designed to improve both productivity and climate adaptation. To assess its effect, we estimate the causal effects of the program on (i) beef productivity per hectare, (ii) adoption of good management practices, and (iii) greenhouse gas (GHG) emissions intensity. Our approach employs a regression discontinuity design that leverages a natural experiment arising from the second phase of

PFIS, where program assignment followed a discontinuous rule based on a technical scoring system, providing robust estimates while mitigating self-selection bias.

To our knowledge, this is the first study to evaluate the effect of a livestock technology transfer program on GHG emissions intensity within a causal framework, using a regression discontinuity design approach. This research is timely, as many countries seek to align agricultural development efforts with their commitments under their Nationally Determined Contribution. Evidence from programs like PFIS can inform the design of integrated, multi-objective policies in similar agroecological and socioeconomic settings.

Our results indicate that although PFIS did not produce statistically significant changes in beef productivity or emissions intensity by 2020, it significantly increased the adoption of reproductive technologies: early weaning increased by 8.7 percentage points, controlled mating by 22.4 percentage points, and ovarian activity diagnosis by 16.3 percentage points. These findings suggest that, although immediate impacts on productivity and emissions were not observed, the adoption of reproductive technologies might set the stage for future improvements. Given that such technologies are tied to breeding and herd management cycles, their effects may manifest over a longer horizon, underscoring the importance of ongoing, long-term evaluations to capture the eventual benefits in productivity and environmental sustainability.

The paper is organized as follows.

Section 3.1 provides background on the Uruguayan livestock sector and PFIS

Section 3.2 describes the data sources and empirical strategy

Section 3.3 presents the main findings

Sections 3.4 concludes with a discussion of policy implications

3.1 Program context and description

3.1.1 The livestock sector in Uruguay

Uruguay has a significant share of global beef markets, ranking ninth among beef exporters in 2023 and contributing 4% of the global carcass weight equivalent. Domestically, the livestock sector (including meat, by-products, and dairy) accounts for about 10% of Uruguay's gross domestic product (GDP) and 19% of goods exports in 2023 (Uruguay XXI, 2024). The sector also provides around 6.5% of total employment nationwide. According to the 2011 General Agricultural Census, 74% of commercial farms specialize in meat and milk production, covering 12.6 million hectares, approximately 70% of the country's land area (DIEA-MGAP, 2014; Aguirre, 2018).

Uruguay's livestock production is predominantly extensive and pasture-based, relying on the *Río de la Plata* grasslands. These systems use minimal synthetic inputs and external energy, aligning well with sustainability principles (Álvarez, 2020; Lanfranco et al., 2022; Ruggia et al., 2021). However, sustainability challenges exist. In 2020, agriculture, forestry, and land-use activities accounted for 57% of Uruguay's total net GHG emissions, with non-dairy livestock contributing 30% of gross emissions (Ministerio de Ambiente, 2021). Improving productivity is therefore a critical strategy to attain the mitigation objectives included in the Uruguayan Nationally Determined Contribution, which are defined in terms of emissions intensity per unit of meat production.

Despite higher slaughter weights, shorter finishing periods, and the increased use of feedlots, overall beef production per hectare has experienced only modest growth over the past two decades (Peyrou, 2016; Nin et al., 2019; Aguirre, 2022c). There is notable variability across beef production units: the top decile can produce up to five times more beef per hectare than the bottom decile (Aguirre, 2018, 2019, 2022c, 2022b). This heterogeneity is driven by differences in land quality, production systems, infrastructure, and technology adoption. However, substantial productivity gains remain attainable through improved technical management, even within the existing technological frontier (Aguirre et al., 2024a, 2024b).

Nevertheless, the adoption of improved livestock practices in Uruguay remains limited (Peyrou, 2016; Paparamborda, 2017; Bervejillo et al., 2018; Aguirre, 2022; Jones et al., 2020; Polcaro, 2022) and empirical evidence on the effectiveness of technology transfer programs is scarce (Mullally & Maffioli, 2016).

3.1.2 The intervention and conceptual framework

The Sustainable Family Production Program (*Producción Familiar Integral y Sustentable*, PFIS) had two primary components (Aguirre et. al, 2018a).[7] The first aimed to enhance productivity by promoting technologies related to herd management, animal health, genetic improvement, and nutrition. The second focused on increasing the resilience of production systems to climatic variability by supporting sustainable natural resources management (improving water access, soil and vegetation conservation, sustainable pasture and forest management, tree planting for shade and shelter, and effluent management). The program's ultimate goal was to boost income and resilience among small and medium livestock producers while contributing to national objectives of low emission agriculture.

PFIS targeted multiple sectors, including beef and dairy, horticulture, beekeeping, poultry, pig farming, fruit production, viticulture, crop farming, and forestry (Gesto et al., 2019). It employed a demand driven approach. Instead of offering a fixed package of technologies, it provided a menu of eligible innovations from which producers could select, recognizing the heterogeneity of local conditions, production systems, and farmer types. This approach

[7] The program's guidelines can be accessed at Producción Familiar Integral y Sustentable | MGAP at: https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/comunicacion/convocatorias/produccion-familiar-integral-sustentable

aimed to improve both economic outcomes and environmental sustainability through tailored, integrated strategies. Its dual focus on productivity and sustainability, combined with a flexible and participatory design, sets PFIS apart from many previous rural development initiatives.

Eligibility for the livestock program was limited to family and small to medium-scale, those producers managing up to 1,250 hectares with average productivity (CONEAT index = 100).[8] In 2015, this segment constituted 81% of all producers, covered 43% of the total livestock area in the country, and represented 49% of total livestock units. Producers could participate individually or collectively.[9] The program was implemented at the national level and promoted through radio, television, and the ministry´s website.

Each participant could receive up to USD 16,000 in financial support, USD 8,000 per component, covering up to 80% of total project costs. Half of the funding was disbursed at the start of the project, with the remainder provided on successful completion and compliance with the proposed activities. Although participation in each component was voluntary, the program encouraged integrated proposals addressing both productivity and sustainability.[10] Projects were tailored based on a diagnostic assessment of farm-specific needs, with a maximum implementation period of 18 months. The total program budget was USD 13 million.

Figure 1 illustrates the program's procedures and its hypothesis that livestock producers who adopted the promoted technologies and received technical assistance would increase their productivity and income. These gains were expected to enhance economic sustainability, while reducing GHG emissions per unit of output. In addition to efficiency improvements, the adoption of more sustainable land and herd management practices offers a complementary pathway to strengthen climate resilience and environmental sustainability.

[7] The program's guidelines can be accessed at Producción Familiar integral y sustentable | MGAP.

[8] The CONEAT index, developed by the Uruguayan government, quantifies land productivity in terms of meat and wool output. It assigns values from 0 (unsuitable for cattle production) to 250, with a national average of 100. This index plays a crucial role in fiscal policies, because it determines soil productivity for taxation purposes and serves as a standard reference in land transactions.

[9] Applications were submitted online by an agronomy or veterinary technician accredited by MGAP, who had previously completed training in project formulation. Technicians received USD 409 for each approved proposal, and the program financed up to 10 technical monitoring visits per project at USD 130 each.

[10] Although the technological component was primarily aimed at improving productivity, many of its supported actions were closely linked to environmental sustainability, particularly through their effect on emission intensity. In practice, the classification of actions by component was not always clear cut: some interventions categorized under the technological component could have been equally considered as pasture or soil management, and vice versa.

Fugure 1. Conceptual framework of PFIS

Activities	Products	Results	Benefits
• Design of call guidelines • Registration and accreditation of technicians • Proposal assessment • Signing of contracts by producers • Project monitoring	**Beneficiaries** • Make investments • Receive technical assistance • Strengthen networks and producer groups	• ↑ Adoption of technologies • ↑ Sustainable practices • ↑ Network engagement	• ↑ livestock productivity • ↓ GHG intensity • ↑ Adaptive capacity to climate change

Source: Adapted from Durán & Hernández (2017)

PFIS held two competitive calls, in August and October 2014 (Durán & Hernández, 2017), and received 3,611 proposals across diverse sectors. This study focuses on its effect on beef cattle producers, who submitted 1,846 proposals, accounting for 51.1% of the total.

Applications were assessed through an online evaluation system and scored from 0 to 100, based on the strength of the justification, internal coherence, comprehensiveness, technical and financial feasibility, and quality of the proposed performance indicators across economic, environmental, and social dimensions (see Annex 1 for details). In the first call, all projects that scored 60 points or higher were funded. In the second call, because of financial constraints, the cutoff point was raised to 66 points. A total of 1,026 proposals from beef cattle producers received funding, representing 69.4% of their total submissions.

PFIS was implemented between 2015 and 2017 by the Rural Development Division of the Ministry of Livestock, Agriculture, and Fisheries (MGAP). Implementation began in early 2015, with the last beneficiaries entering by the end of 2016 (Table 1 outlines the program's activities). Baseline data were collected in 2015, before implementation, and follow-up data for the impact evaluation were gathered in 2020, three years after the program concluded.

Table 1. Gantt diagram for PFIS

Activity	2015	2016	2017	2018	2019	2020
Program start	✓	✓				
Program end		✓	✓			
Baseline	✓					
Result line						✓

Source: Authors.

Among livestock producers, the majority of PFIS investments were allocated to the purchase of breeding stock or semen for genetic improvement, infrastructure upgrades (e.g., roads, pens, squeeze chutes), nutrition, animal health, technical consulting, and subdivision of pastures (Durán et al., 2018). More than 90% of producers received technical assistance related to natural resources and productive management (see details in Annex 2). A significant portion of the total investment (42%) was directed toward technological and productive improvements, followed by water management (20%) and pasture management (16%).

3.2 Materials and methods

3.2.1 Data sources

Our evaluation of PFIS uses multiple data sources from the Uruguayan Ministry of Livestock, which implemented the program. These include administrative records, nationally representative surveys, and livestock traceability data. These databases are summarized in Table 2.

Table 2. Main database for PFIS evaluation

Database	Coverage	Year	Notes
PFIS application form	Applicants	2014	Technical and administrative project data
General Agricultural Census (CGA)	All agricultural producers	2011	Sampling frame for subsequent surveys
National Livestock Survey (EGN)	Applicants near threshold	2016	Baseline data on livestock farms (>7 LU), excluding dairy
Good Practices in Natural Grassland Management Survey (EBPMCN)	Applicants near threshold	2020	Land-use and grassland management data
National Livestock Information System (SNIG)	All livestock producers	2011–2020	Livestock transaction, movement, and traceability data

Source: Authors. Note: LU = livestock unit.

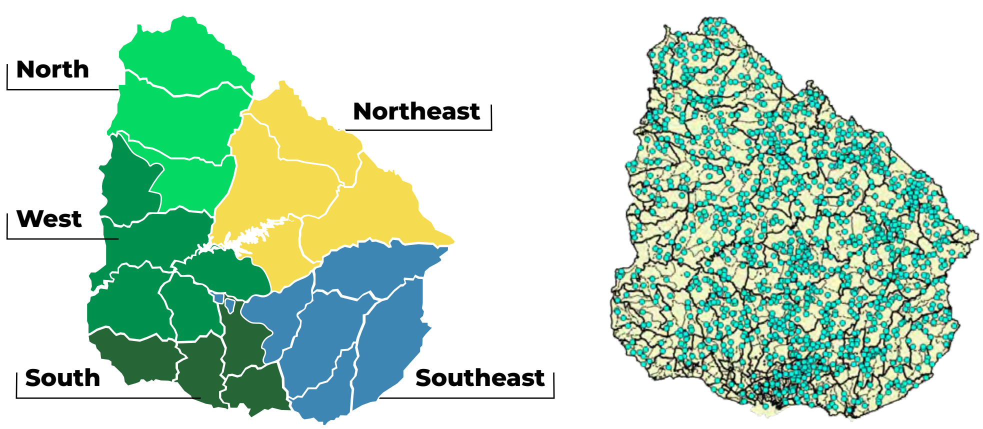
The PFIS application form collected technical and administrative data on proposed projects, allowing for the characterization of applicants and the construction of control variables for impact evaluation in the baseline.

Agricultural Censuses are part of Uruguay's statistical system, and served as the sampling frame for subsequent surveys. The latest available census is the 2011 CGA.

The 2016 National Livestock Survey (EGN) collected economic data on Uruguay's cattle and sheep sectors. It was specifically designed to establish a baseline for evaluating PFIS.[11] Covering the 2015–2016 agricultural year, the survey includes detailed information on production systems, technology adoption, services, labor, costs, and innovation practices (Bervejillo et al., 2018). The sample excluded dairy operations and included 1,428 commercial livestock farms with at least seven livestock units (LUs), selected from the CGA 2011.

A stratified random sampling strategy was applied based on farm size, region, and PFIS participation status. The national territory was divided into five regions (Figure 2) and farms, and farms were further classified into eight categories according to size, measured in LUs (Table 3). Within each category, farms were systematically selected based on LU size. Farms with more than 3,500 LUs or those included in the PFIS evaluation baseline, were automatically selected into the sample.

Figure 2. **Agroecological areas and location of sampled Beef Production Units in National Livestock Survey 2016**



Source: Bervejillo et al. (2018).

[11] The field survey was conducted by MGAP between spring 2016 and winter 2017, and collected data on the 2015/2016 agricultural season. Additional information necessary for evaluation was gathered for the two preceding seasons.

According to Bervejillo et al. (2018), Uruguay had 25,615 farms primarily dedicated to beef production (with at least seven LUs and no dairy activity), covering 12.4 million hectares. The average size was 487 hectares, with wide variation (from 61 to 6,332 ha).

Table 3. Distribution of beef production units, by size, in livestock units

Livestock Units	BPU	Land (miles ha)	% of BPU	% of Land	CDF BPU	CDF Land
<100	10.761	651	42,0%	5,2%	42,0%	5,2%
[100,150)	2.325	345	9,1%	2,8%	51,1%	8,0%
[150,300)	3.855	1.061	15,0%	8,5%	66,1%	16,5%
[300,600)	4.232	2.220	16,5%	17,8%	82,7%	34,4%
[600,1000)	1.949	1.934	7,6%	15,5%	90,3%	49,9%
[1000,2000)	1.539	2.519	6,0%	20,2%	96,3%	70,2%
[2000,3500)	709	2.160	2,8%	17,4%	99,0%	87,5%
>3500	245	1.551	1,0%	12,5%	100,0%	100,0%
Total	**25.615**	**12.441**	**100%**	**100%**		

Source: Adapted from Bervejillo et al. (2018).

Note: BPU: beef production unit; CDF: cumulative distribution function

The Good Practices in Natural Grassland Management Survey (EBPMCN), conducted by the Ministry of Agriculture in 2020, focused on farms that had livestock as the primary activity (excluding dairy), a minimum of seven LUs, at least 100 hectares in total area, and over 50% of land covered by native grasslands.[12] Participation was mandatory for selected producers in the PFIS evaluation sample. It quantified land and livestock managed under good practices (Jones et al., 2020; Polcaro, 2022), and served as the outcome line for evaluating PFIS.

Originally, the evaluation design aimed to include all applicants within two points of the selection threshold and a random sample of interviewed treated beneficiaries for a matched comparison group (Durán et al., 2018; Durán & Hernández, 2017). The baseline was collected, but budget constraints prevented follow-up data collection for the entire sample. As a result, our evaluation on technology adoption is limited to a Regression Discontinuity Design around the cutoff of the second PFIS call, comparing applicants who scored 66 points (treated) with those who scored 65 points (control).

[12] The sample frame was based on the 2016 EGN, updated with 2020 SNIG data. Stratification was done by farm size (above/below 500 ha) and region (center, north, northeast, east), yielding eight strata. A total of 500 farms were interviewed by phone, representing 11,362 producers managing 9.26 million hectares of native grasslands, roughly 83% of the total land used for livestock production in Uruguay.

The National Livestock Information System (SNIG) is a comprehensive administrative registry that ensures traceability of all major livestock species in Uruguay. It records the lifecycle of each animal, including movements and changes in ownership. By integrating data on slaughter weights and auctions, SNIG allows for estimating beef production at the farm (BPU) level, one of our outcome variables (Aguirre, 2022b).

3.2.2 Variable construction

We construct the variables for our RDD guided by existing literature and data availability. The definitions and data sources for major variables are outlined in Table 4 .

We have two outcome variables. The first one is $BEEF_i$, is defined as annual beef production per hectare in *farm i*[13]. This variable is derived from net cattle transactions (sales minus purchases), adjusted for inventory changes stemming from births, deaths, and reclassifications. It includes both slaughtered (fattened) and traded (lean) cattle. Expressing output per hectare facilitates meaningful comparisons across producers of different operational scales (see Annex A3 for details). Our second outcome variable is $GHGIntensity_i$, measures GHG emissions per kilogram of beef (kg CO2e/kg) produced at the farm level. These emissions, calculated using SNIG data and IPCC methods, encompass methane emissions from enteric fermentation and manure, as well as nitrous oxide from excreta. Emissions are expressed in CO_2 equivalents using GWP100 factors from IPCC AR5 and aggregated annually (Annex A4).

[13] We omitted sheep meat and wool production from our study for three reasons. First, 40.1% of BPUs that include sheep do not engage in production for commercial purposes (Bervejillo et al., 2018). Second, the contribution of ovine meat to the total combined bovine and ovine meat production is less than 7%. Third, accurate estimation of sheep meat production is significantly challenging (Aguirre, 2018).

Table 4. Table 4. Definitions and construction of variables

Variable	Definition
BEEF	Annual beef production (kg live weight per hectare)
GHGIntensity	GHG emissions per kg of beef produced (kg CO2e/kg)
Cow-calf technologies (from EBPCMN 2020)	
ControlledMating	1 if controlled mating practiced; 0 otherwise
RevisedBulls	1 if bulls evaluated before mating; 0 otherwise
ArtifInsemination	1 if artificial insemination used; 0 otherwise
OvActivityDiagnosis	1 if ovarian diagnosis performed; 0 otherwise
EarlyWeaning	1 if early weaning practiced; 0 otherwise
TemporaryWeaning	1 if temporary weaning practiced; 0 otherwise
Other outputs (from EBPCMN 2020)	
Cattle Health Problems	1 if reported cattle health problems; 0 otherwise
Producer Organization	1 if part of producer organization; 0 otherwise
AgronTA	1 if received TA from agronomist; 0 otherwise
Baseline control variables (from EGN 2016)	
BLU	Standarized Bovine Livestock Units
Land	Hectares under cattle production
Labor	Full-time-equivalent labor input
CONEAT	Soil productivity index for cattle production
GrazeAreaImprove	Share of improved grazing area
GrazeAreaImprove0	1 if no grazing improvements; 0 otherwise
RegionGroup	Regional indicator variable [categories: 1=North, Northeast and Southeast, 0= South and West]. See Figure 1.
ProductiveOrientation	1 if beef-only system (OBR<= 1)); 0 beef-sheep mixed (4>OBR>1).
BeefProductionSystem	1 if cow-calf (steers/cow-calf<=0.5); 0 full cycle or fattening (RSC>=0.5).

Source: Authors.

To evaluate the effects of PFIS, we focus on the adoption of specific cow-calf management practices and technologies, including: controlled mating, bull evaluation, artificial insemination, ovarian diagnostics, and various weaning practices.

Finally, we also assess the effect of the program on other outcomes: cattle health, participation in producer groups, and access to technical assistance.

3.2.3 Treatment selection mechanism

PFIS supported a total of 1,026 livestock producers through two calls for proposals. In both calls, applications were evaluated and scored on a 0–100 scale. However, approval rates differed substantially across calls: in the first call, 620 of 662 applicants were funded (93.7%), but in the second call, only 406 of 1,076 proposals received support (37.7%) because of budget constraints

In the first call, MGAP applied a strict eligibility rule: all proposals scoring 60 points or more were automatically approved. This rule was explicitly communicated to the evaluators. As shown in Table 5, this policy generated a sharp discontinuity in the probability of treatment at the 60-point threshold.

To assess the validity of using a regression discontinuity design (RDD), we tested the assumption of no manipulation around the cutoff—under the null hypothesis,the number of observations just above and just below the threshold should follow a smooth distribution. To do this, we conducted binomial tests within windows of ±1 and ±2 points around the cutoff (i.e., scores of 59–61 and 58–62), using Stata's bitest command. In both cases, the hypothesis of random assignment was rejected (p-value < 0.0001) in the case of the first call. Notably, in the first call, there were no proposals scored exactly at 59 points, suggesting upward manipulation of scores once the 60-point threshold became known. Given this strong indication of strategic behavior, data from the first call were excluded from the impact evaluation.

In contrast, for the second call, high demand and budget limitations led to an ex-post raising of the approval threshold to 66 points. Crucially, the adjustment occurred after all applications were scored and was not disclosed to evaluators during the scoring process. This minimizes the risk of strategic score manipulation and provides a more credible basis for a local randomization design.

We tested for potential manipulation at the 66-point threshold using the same binomial tests in the ±1-point window (scores of 65–66). As can be observed in Table 6, 78 applicants out of 174 obtained a 66 score, which is consistent with random assignment (p-value = 0.197). However, in the ±2-point window (scores of 64–67), the null of random assignment was rejected (p-value < 0.001), indicating potential selection at this bandwidth. Results in wider intervals (±3 and ±4) were mixed (p-value = 0.085 and p-value < 0.001, respectively), suggesting that local randomization is credible only within a very narrow range around the threshold.

Table 5. Frequency of proposal of PFIS, by score, first call

Score	Treated (N) No	Treated (N) Yes	Total	
[0,30]	1	0	1	
[31,50]	10	0	10	
[51,56]	16	0	16	Untreated: 42 (6.3%)
57	0	0	0	
58	15	0	15	
59	0	0	0	
60	**0**	**64**	**64**	
61	0	43	43	
62	0	26	26	
63	0	33	33	
64	0	51	51	Treated: 620 (93.7%)
65	0	33	33	
66	0	25	25	
67	0	28	28	
[68, 100]	0	317	317	
Total	**42**	**620**	**662**	**662**

Table 6. Frequency of proposal of PFIS, by score, second call

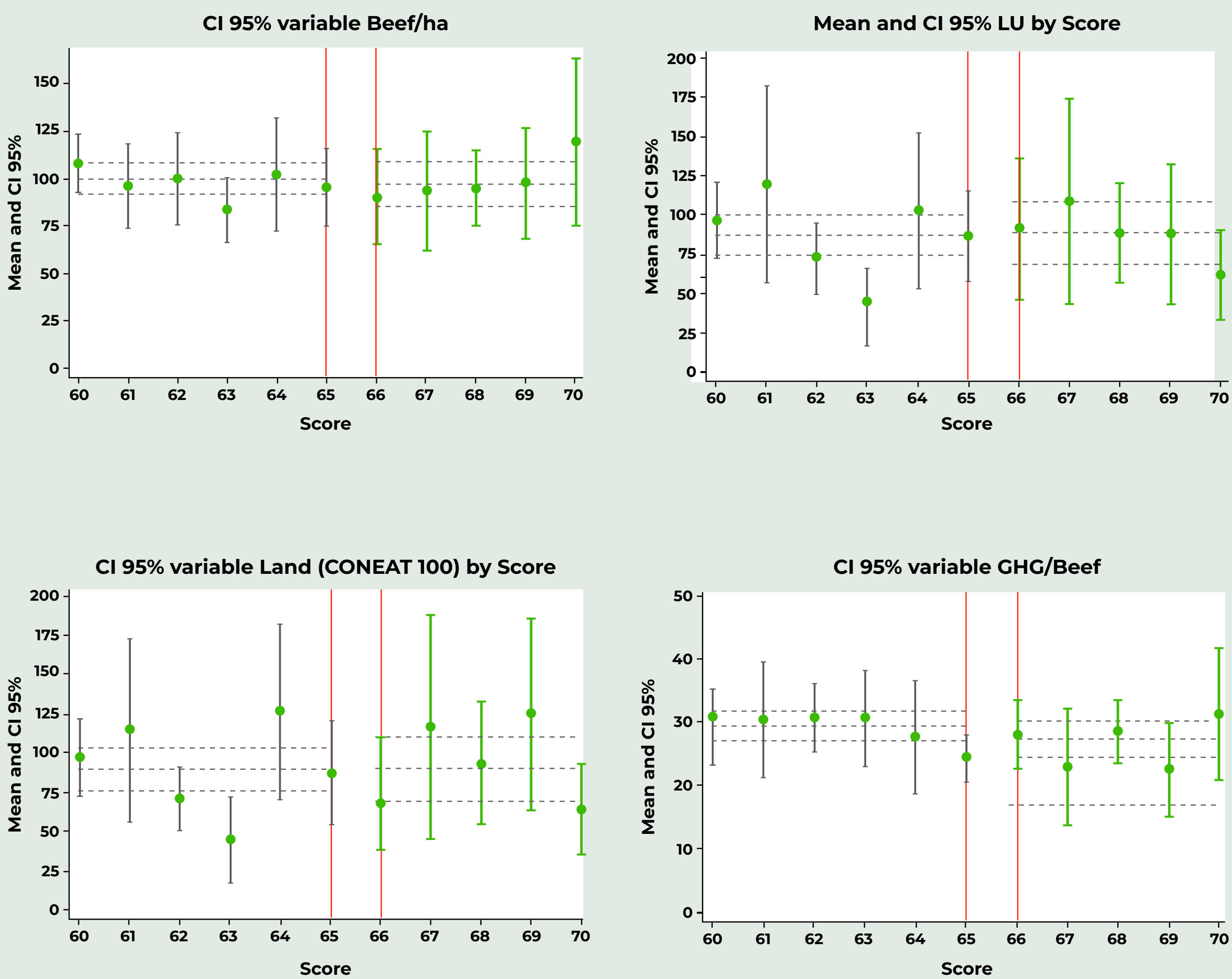
Score	Treated (N) No	Treated (N) Yes	Total	
[0,30]	61	0	61	
[31,58]	96	0	96	
59	4	0	4	Untreated: 670 (62.3%)
60	171	0	171	
61	50	0	50	
62	83	0	83	
63	49	0	49	
64	60	0	60	
65	96	0	96	
66	**0**	**78**	**78**	
67	0	22	22	Treated: 406 (37.7%)
68	0	77	77	
69	0	31	31	
70	0	49	49	
[71, 100]	0	149	149	
Total	**670**	**406**	**1076**	**1076**

Source: Authors.

To further assess the validity of the design, we examined covariate balance in pretreatment characteristics of applicants within symmetric bandwidths (±1 to ±5 points around the 66-point cutoff). As shown in Figure 3, we find no statistically significant differences between treated and control units in the baseline variables of livestock units, land area, beef production per hectare, and GHG emissions intensity. This balance holds consistently across all bandwidths tested (see details in table S8 in Annex 5).

Taken together, those results suggest that treatment assignment near the threshold is plausibly random with respect to observable covariates. Therefore, we adopt a local randomization framework and restrict the impact evaluation sample to applicants scoring 65 and 66 points. These observations were subsequently included in the resultline survey used for the evaluation.

Figure 3. **Falsification test on pre-treatment variables, under second call**



Note. Graphs show mean values and 95% confidence intervals for baseline outcomes by score. Horizontal lines indicate group means for treated and control units.
Source. Authors' calculations based on PFIS proposal forms and SNIG data.

3.2.4 Method

Our primary unit of analysis is the agricultural production unit, defined as a commercial operation larger than one hectare that shares labor, capital, and inputs. To estimate the causal effect of PFIS on technology adoption and production outcomes at this level, we implement a regression discontinuity design (RDD). This approach exploits the sharp eligibility rule applied during the second PFIS call, under which only producers that scored 66 or higher were selected. The central assumption of the RDD framework is that applicants who scored just above and just below the threshold are comparable in all respects other than treatment status.

The discontinuous change in the probability of receiving treatment, from zero to one between scores of 65 and 66, supports the application of a sharp RDD under a local randomization framework. The assignment rule was exogenous, since the cutoff was determined after scoring. Moreover, the distribution of scores is balanced around the threshold, and manipulation tests confirm that applicants were unable to influence their position relative to the cutoff. Pretreatment covariates are also balanced between those scoring 65 and 66, reinforcing the plausibility of the local randomization assumption.

We incorporate baseline control variables to enhance statistical power, improve precision, and more accurately identify the treatment effect while accounting for sources of heterogeneity. Our baseline control variables are herd size (bovine livestock units, BLUs), land area, labor, improved pasture share, productive orientation (ovine to bovine ratio, OBR), production system (steers to breeding cow ratio, SBCR), and the CONEAT index (natural soil fertility).

Because the assignment variable is discrete, it does not meet the continuity assumptions required for traditional RDD approaches.[14] To address this, we adopt the local randomization framework proposed by Cattaneo et al. (2016), which considers treatment assignment within a narrow window around the threshold as effectively random. In this setting, potential outcomes are assumed to be independent of the treatment assignment within the window and depend only on whether the cutoff was crossed, not on the specific value of the score (Skovron & Titiunik, 2015).

[14] When the score is discrete rather than continuous, the standard smoothness assumptions required for non-parametric estimation of conditional expectations near the cutoff become harder to justify. This challenges the validity of traditional continuity-based RDD approaches.

Specifically, we define a randomization window of one point on either side of the cutoff, comparing applicants who scored 66 (treated) with those who scored 65 (controls). Within this window, we estimate the Local Average Treatment Effect (*LATE**), defined as follows:

$$LATE^{*}=E(Y|x = 66) - E(Y|x =65)$$

To improve precision and reduce bias in small samples, we estimate this effect using Lin's estimator (Lin, 2013), which adjusts for covariates and their interaction with the treatment indicator, and control for the Freedman sample bias of the ordinary least squares estimator for the treatment.[15] Let Y_i represent the outcome of interest, T_i the treatment indicator, C_i^{Center} a vector of covariates centered at the threshold, and ε_i the error term. The estimation model is specified as follows:

$$Y_i = {}_{\tau}T_i + \beta C_i^{Center} + {}_{\gamma}T_i\, C_i^{Center} + \varepsilon_i$$

This specification allows for differential slopes by treatment status and improves efficiency while maintaining unbiasedness in small samples. Centering covariates reduces multicollinearity and enhances interpretability.

[15] The Freedman sample bias refers to a bias in Ordinary Least Squares (OLS) estimates that arises in small samples in the context of impact evaluation. Freedman (2008) showed that when estimating treatment effects using OLS with covariate adjustment in randomized experiments, the finite sample bias can be substantial. This occurs because OLS estimates rely on asymptotic properties that may not hold in small samples, leading to biased standard errors and confidence intervals. Although covariate adjustment can improve precision, Freedman cautioned that in small samples, it may introduce bias unless appropriate corrections, such as robust standard errors or permutation-based inference, are applied.

3.3 Results

We begin by analyzing the effect of PFIS on beef production per hectare. As reported in Table 7, the estimated local average treatment effect at the margin of eligibility is positive, approximately 5 kg/ha/year, but not statistically significant. The result remains stable across model specifications, including those that control for a range of pretreatment covariates and baseline production levels. This consistency suggests that the lack of statistical significance is not due to model misspecification but rather reflects the robustness of the null finding.

Table 7. Effect of PFIS on beef production in 2020 (kg/ha/year)

Variables	Model 1	Model 2	Model 3
PFIS	5.16	5.29	6.03
	(0.766)	(0.85)	(0.81)
N	80	73	67
R^2	0.001	0.252	0.318
Mean(y)	103.2	104.6	105.2
Controls	No	Yes	Yes
Beef/ha	No	No	Yes

Note: p-values in parentheses. *** p<0.01, ** p<0.05, * p<0.1.
The controls variables are: BeefProductionSystem, ProductiveOrientation, RegionGroup, Land, BLU, GrazeAreaImprove, GrazeAreaImprove0, Coneat, Labor.
Source: Authors' calculations based on EGN, EBPMCN, and SNIG data.

We then examine the program's effect on emissions intensity, measured as GHG emissions per kilogram of beef produced. Results are presented in Table 8. The estimated effect is again not statistically significant, and remains so across models with and without covariates or baseline GHG intensity.

Table 8. Effect of PFIS on GHG intensity

VARIABLES	Model 1	Model 2	Model 3
PFIS	2.93	2.74	1.7
	(0.464)	(0.465)	(0.651)
N	96	94	90
R^2	0.006	0.03	0.106
Y mean	25.2	25.4	25.2
Controls	No	Yes	Yes
2016 GHG Intensity	No	No	Yes

Note: The outcome variable is kg CO2-equivalent emitted per kg of meat produced.
The controls variables are: BeefProductionSystem, ProductiveOrientation, RegionGroup, Land, BLU, GrazeAreaImprove, GrazeAreaImprove0, Coneat, Labor. p-values in parentheses.
*** pv<0.01, ** pv<0.05, * pv<0.1
Source: authors' estimation based on EGN, EBPMCN and SNIG data.

To address concerns related to the limited sample size and the narrow bandwidth around the eligibility threshold, we conducted several robustness checks. First, we performed a power analysis of the t-test used to estimate the average treatment effect for the beef effect (Annex 6). The results indicate a statistical power of 84.6% with a sample of 81 observations, suggesting that our analysis has a high probability of detecting a true effect if it exists. Second, we implemented exact permutation tests following (Imbens & Rubin, 2015), an approach well-suited for small samples because it does not rely on parametric assumptions and provides exact p-values. These results, presented in Annex 7, are qualitatively consistent with our main findings, further supporting their robustness. Overall, these additional analyses provide confidence that our results are not driven by sample size limitations or methodological artifacts.

In addition, we tested the sensitivity of the estimated effects on beef production and emissions intensity by progressively expanding the bandwidth around the eligibility cutoff from 1 to 5 points. These alternative specifications draw on baseline data from the PFIS application forms and outcome variables from the SNIG system. Results from these broader windows, presented in Annex 8, are directionally consistent and remain statistically significant, reinforcing our findings.

Like in the case of productivity and emissions intensity, we find no statistically significant effects of the PFIS on the use of artificial insemination, incidence of cattle health problems, participation in producer organizations, or engagement with agronomic advisers. However, the program did have a statistically significant impact on the adoption of three good practices for reproductive management and herd efficiency (Table 9): controlled mating (an increase of 22.4 percentage points, p-value = 0.018), ovarian activity diagnosis (16.3 percentage points, p-value = 0.015), and early weaning (8.7 percentage points, p-value = 0.055).

Table 9. **Effect of PFIS on technology adoption on Resultline**

Variables	Coefficient	p-values	R^2	N	Mean
Controlled Mating	0.2237**	0.018	0.057	98	0.442
Ovarian Activity Diagnosis	0.163**	0.015	0.082	72	0.185
Early Weaning	0.0869*	0.055	0.035	106	0.104
With Artificial Insemination	0.055	0.548	0.005	75	0.207
Cattle Health Problems	-0.088	0.345	0.008	119	0.471
In a producers' organization	0.064	0.494	0.004	119	0.490
With an agronomist	0.059	0.256	0.011	119	0.118

Note: p-values in parentheses. *** pv<0.01, ** pv<0.05, * pv<0.1

3.4 Conclusions and discussion

Technology transfer programs are widely employed to enhance livestock productivity and promote sustainability. However, robust empirical evidence on their effectiveness remains limited. Rigorous evaluation is crucial not only for ensuring transparency and accountability but also for informing the design of cost-effective policies.

This study contributes to bridging this evidence gap by assessing the effect of Uruguay's PFIS on small and medium-sized beef producers on productivity, emissions intensity, and the adoption of specific technology and management practices. Leveraging a natural experiment from the second PFIS call, where treatment assignment followed a discontinuous rule, we estimate causal effects using an RDD.

Our results show that PFIS did not produce statistically significant effects on beef output per hectare or on GHG intensity, indicating that it did not achieve productivity or sustainability gains in the three-year window after the end of the program. Importantly, however, the program drove behavioral changes, with statistically significant increases in the adoption of: early weaning (+8.7 percentage points), controlled mating (+22.4 pp), and ovarian activity diagnosis (+16.3 pp).

The absence of detectable effects on beef production and GHG emissions intensity despite the program's effectiveness in fostering the adoption of the above technology and management practices, raises the question of the necessary length of time between when a farmer adopts these technologies and they materialize in productivity and emissions intensity gains. It may be the case that there is a necessary time lag between the adoption of these practices and their eventual impact on productivity and emissions reduction. On the other hand, three years may be a sufficient time for these effects to materialize in part, at least, and the behavioral change fostered by the program is not enough to lay a foundation for future productivity improvements.

In any case, our findings reinforce the value of carefully designed, evidence-based public interventions and underscore the importance of embedding rigorous impact evaluation into policy design and implementation cycles.

Future impact evaluations could adopt a wider perspective by including metrics for profitability, biodiversity, animal health, and other sustainability dimensions. Additionally, assessing heterogeneous effects across different producer segments can help identify which support strategies yield the most durable benefits across diverse beef systems. Understanding whether early behavioral changes translate into long-term improvements will also require longitudinal data and follow-up studies.

Acknowledgments

We especially acknowledge the valuable suggestions and feedback provided by Paul Winters, Allen Blackman, and colleagues at the IDB sustainable cattle technology workshop. We also thank Camila Amiassorho and Francisco Grizutti from the University of Montevideo, for research support. We are also grateful for the financial and technical support provided by the Inter American Development Bank.

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Appendix

Table S. Impact evaluations of livestock programs for beef cattle production

	Article	Method	Output	Findings
1	**Country and period:** Uruguay: 2001-2003. **Program name:** Livestock Uruguay Program (Programa Uruguay Rural). **Component 1:** Promote Innovation in cow-calf production. **Type of data**: Panel. **Observations:** N=990 (treated=520 and controls=470). **Universe**: Cow-calf and complete cycle up to 1250 ha CONEAT. **Analysis period**: 2001-2003			
	Lopez & Maffioli (2008)	Propensity score matching with difference in differences	Physical events record Economic events record Calves/CowBreeding PER=Calves/CowsOver1Year Degree of specialization Dose effect (subsidy amount)	25.3pp 18.7pp No effect No effect -5.5pp No effect
2	**Country and period:** Uruguay: 2006-2010. **Program name**: Uruguay Rural Program (Programa Uruguay Rural). **Type of dat**a: Panel. **Observations:** N=22020 (treated=413 and controls=21607). **Universe:** Cow-calf and complete cycle up to 1250 ha CONEAT. **Analysis period:** 2006-2010			
	Lopez & Maffioli (2008)	Inverse probability weighting with difference in differences	Calf Births Net Calf Sales	(11.79;14.2) 4.59
3	**Country and period:** Uruguay: 2015-2016. **Program name:** Sustainable Family Program (PFIS, Programa Familiar Integral y Sustentable). **Type of data:** Panel data. **Observations:** N=19133 (treated=648 and controls=18485). **Universe:** Cow-calf and complete cycle up to 1250 ha CONEAT. **Analysis period:** 2015-2017			
	Durán et. al (2018)	Entropy balance with difference in differences	Beef/ha	11.1 (pv=3.87%)
4	**Country and period:** Uruguay: 2014-2015. **Program name:** Inclusion of Forests in Agricultural Production Systems. **Type of data**: Panel data. **Observations:** N=18097 (treated=123 and controls=17974). **Universe:** Beef producers **Analysis period:** 2015-2017			
	Durán et. al (2018)	Entropy balance with difference in differences	sheep meat and Beef/ha	No effect
5	**Country and period:** Uruguay: 2013-2019. **Program name:** Family Livestock Farmers and Climate Change Project. **Type of data:** Panel data. **Observations:** N=344 (treated=157 and controls=190). **Universe:** Sheep meat and beef producers **Analysis period:** 2015-2017			
	Durán & Laguna (2021)	Entropy balance with difference in differences	Continuous Breeding Ovarian Activity Diagnosis Pregnancy Diagnosis Livestock management by body condition Single Herd Grazing Early Weaning Temporary Weaning Supplementation	No effect No effect 0,228 (pv <5%) No effect No effect No effect No effect No effect

Source: Authors.

Annex 1. Evaluation criteria and methodological framework for evaluating PFIS proposals

The assessment framework comprised two main components: individual criteria and the overall proposal coherence.

Individual criteria	
Clarity and quality of diagnostic information	The proposal provides a clear diagnosis, outlining the main constraints and opportunities. There is internal consistency between the diagnosis, the proposed strategy, and the planned actions and objectives.
Coherence between diagnosis, actions, and budget	The proposed activities align with the identified constraints and objectives. Budget estimates are realistic, appropriate to the production context, and justified.
Application of tactical and strategic measures	The proposal includes both short and medium-term actions appropriate to the productive context and implementable with available resources.
Pertinence, feasibility and sustainability of the proposed activities	Activities are relevant, technically feasible, and economically viable. They contribute to the long-term sustainability of the system, with consideration of infrastructure, experience, cost justification, and the presence of measurable indicators.
Overall coherence	
Technical coherence and integrality	The proposal effectively integrates technological innovation, resource management, and climate adaptation strategies aligned with the program's objectives.
Technological management (closing the technology gap)	Adoption of relevant, context specific technologies that enhance productivity while sustainably reducing the technological gap.
Climate change adaptation	The proposed actions are consistent with the environmental risk profile of the production system and include mitigation or adaptation strategies where necessary.

Annex 2. PFIS investments and practices among beef production unit

This annex summarizes the main practices and investments made by livestock producers who participated in the PFIS program.

Table S2. Livestock producers, by type of practices and investments

	Producers	Expenditure (US$)
Natural resources technical assistance	982 (94%)	1,105,175 (10%)
Technological and productive technical assistance	975 (93%)	446,593 (4%)
Water management	500 (48%)	2,158,025 (20%)
Irrigation	36 (3%)	26,397 (0.2%)
Manure management	12 (1%)	9,547 (0.1%)
Pasture management	595 (57%)	1,680,780 (16%)
Soil conservation practices	310 (30%)	874,984 (8%)
Technological and productive investments and practices	980 (94%)	4,524,978 (42%)
Total	**1046**	**10,826,479**

Table S3. Categories and subcategories for investments and practices

Water management	Water sources investments Water distribution investments Animal waterer infrastructure
Irrigation	Irrigation investments
Manure management	Manure management investments
Pasture and biodiversity management	Natural pastures management Natural forest biodiversity conservation and management
Soil conservation practices	Soil erosion minimization practices Crop and pasture rotation
Technological and productive investments and practices	Genetics Managerial capacities Infrastructure Productive processes improvements Nutrition Organizational and associative practices Animal health

Annex 3. Methodology for estimating beef production

The estimation of beef production in kilograms of live weight is based on categorizing cattle by sex and age, assigning each group a representative average weight, and calculating the weighted contributions across several components of the production cycle. These components include changes in herd inventory, movements of lean animals, slaughter data, and on-farm consumption.

Mathematically, total live-weight meat production for each production unit is defined for the agricultural year (spanning from July 1 of year *t–1* to June 30 of year t) by aggregating the contributions from changes in animal stock, incoming and outgoing transfers of cattle, animals sent to slaughter, and animals consumed on-farm. Each term in the equation is indexed by category and production unit, with weights standardized using microdata from verified livestock sales and slaughter records. The latter are informed by annual national averages provided by INAC (Aguirre, 2022a).

$$Beef_k^{t-1,t} = \sum_{i=1}^{1} \alpha_{i,k}^{\text{Stock}} \Delta Stock_k^{t-1,t} + \sum_{i=1}^{1} \alpha_{i,k}^{\text{Replacement}} \left(Exit_{i,k}^{t-1,t} - Entry_{i,k}^{t-1,t} \right) + \sum_{i=1}^{1} \alpha_{i,k}^{sl} SL_{i,k}^{t-1,t} + \alpha_K^{cons} cons_k^{t-1,t}$$

To enable comparative analysis, total meat output is normalized by the area dedicated to cattle grazing, thus providing a measure of partial productivity expressed as kilograms of beef per hectare.

Annex 4. Methodology for estimating greenhouse gas emissions

GHG emissions from the livestock sector are calculated using annual data from DICOSE-SNIG. Emissions include methane from enteric fermentation, methane from manure management, and nitrous oxide from feces and urine deposited on pastures. The estimation framework adheres to IPCC guidelines (Calvo Buendia et al., 2019; Stocker et al., 2013; Eggleston et al., 2006) and uses global warming potential values over a 100-year horizon (GWP100-AR5), where 1 kg of CH_4 corresponds to 28 kg of CO_2 equivalent, and 1 kg of N_2O is equivalent to 265 kg of CO_2 equivalent.

Methane emissions from enteric fermentation are derived by combining IPCC default values with country-specific activity data, including animal numbers and feed characteristics. Emissions factors depend on gross energy intake, which in turn is influenced by physiological energy demands (maintenance, lactation, pregnancy, and growth) and the digestibility of consumed forage. National data on forage quality and allocation by animal category inform this calculation.

Methane emissions from manure are calculated considering the volatile solid content in feces and a methane conversion factor. In beef cattle, the methodology is simplified because manure remains in the field, without additional management. Nitrous oxide emissions, both direct and indirect, are also estimated based on Uruguay-specific data on the balance between nitrogen intake and retention by livestock, and the corresponding IPCC parameters.

Table S4. Emissions factors for CH4 enteric fermentation, by category and year

Category	2014	2015	2016	2017	2018	2019	2020	2021	2022
Steers 3+ years	74.55	74.55	75.73	75.69	74.98	75.09	73.02	74.36	74.03
Steers 1–2 years	45.28	45.28	45.96	45.93	45.00	44.96	44.23	44.84	44.69
Steers 2–3 years	57.22	57.22	58.18	58.72	58.27	58.29	56.99	58.09	57.92
Calves	38.65	38.65	38.88	38.87	38.58	38.61	37.65	38.56	38.55
Bulls	76.89	76.89	76.87	76.87	76.85	76.87	74.81	76.84	76.83
Breeding cows	62.29	62.29	62.27	62.27	62.25	62.27	60.53	62.24	62.23
Fattening cows	65.70	65.70	66.76	66.74	65.17	65.02	63.54	64.63	64.67
Heifers 2+ years	55.62	55.62	55.34	55.94	55.52	55.39	53.84	55.28	55.29
Heifers 1–2 years	45.66	45.66	45.68	44.84	44.47	44.48	43.22	44.42	44.36

Table S5. Emissions factor for CH4 manure management, by category and year

Category	2014	2015	2016	2017	2018	2019	2020	2021	2022
Steers 3+ years	1.41	1.41	1.45	1.45	1.42	1.42	1.35	1.40	1.39
Steers 1–2 years	0.85	0.85	0.87	0.87	0.84	0.84	0.81	0.83	0.83
Steers 2–3 years	1.08	1.08	1.11	1.12	1.09	1.09	1.05	1.09	1.08
Calves	0.76	0.76	0.77	0.77	0.76	0.76	0.73	0.76	0.76
Bulls	1.55	1.55	1.55	1.55	1.55	1.55	1.47	1.55	1.55
Breeding cows	1.25	1.25	1.25	1.25	1.25	1.25	1.19	1.25	1.25
Fattening cows	1.24	1.24	1.28	1.28	1.22	1.22	1.17	1.20	1.21
Heifers 2+ years	1.09	1.09	1.09	1.10	1.09	1.09	1.04	1.08	1.08
Heifers 1–2 years	0.90	0.90	0.90	0.88	0.87	0.87	0.83	0.87	0.87

Table S6. **Emissions factor for N2O of urine and dung by, category and year**

Category	2014	2015	2016	2017	2018	2019	2020	2021	2022
Steers 3+ years	2.75	2.75	2.68	2.68	2.72	2.74	2.70	2.76	2.77
Steers 1–2 years	1.71	1.71	1.66	1.66	1.73	1.74	1.72	1.74	1.75
Steers 2–3 years	2.08	2.08	2.01	2.10	2.19	2.19	2.19	2.20	2.21
Calves	1.16	1.16	1.15	1.15	1.17	1.18	1.15	1.18	1.18
Bulls	2.08	2.08	2.08	2.08	2.08	2.08	2.02	2.08	2.08
Breeding cows	1.68	1.68	1.68	1.68	1.68	1.68	1.64	1.68	1.68
Fattening cows	2.43	2.43	2.35	2.35	2.45	2.47	2.44	2.49	2.48
Heifers 2+ years	1.68	1.68	1.65	1.67	1.71	1.71	1.68	1.71	1.71
Heifers 1–2 years	1.39	1.39	1.36	1.34	1.38	1.38	1.35	1.38	1.38

Nitrous oxide emissions from the deposition of feces and urine are estimated using equations that consider the proportion of residues deposited in pastures. The data on quantities are country specific; factors and coefficients are taken from IPCC standard tables.

Detailed annual emissions factors for each category of cattle are compiled in separate tables. These tables report methane emissions from enteric fermentation and manure, nitrous oxide emissions from dung and urine, and the aggregated emissions expressed in CO_2-equivalents by animal type and year.

Table S7. **CO_2 equivalent compound emissions factors, by category and year (kg CO_2e GWP100AR5)**

Category	2014	2015	2016	2017	2018	2019	2020	2021	2022
Steers +3 years	2,856	2,856	2,871	2,870	2,861	2,867	2,797	2,852	2,846
Steers 1-2 years	1,745	1,745	1,751	1,751	1,741	1,744	1,717	1,740	1,738
Steers 2-3 years	2,183	2,183	2,193	2,232	2,242	2,244	2,205	2,240	2,238
Calves	1,411	1,411	1,414	1,414	1,412	1,414	1,379	1,412	1,412
Bulls	2,747	2,747	2,746	2,746	2,746	2,746	2,672	2,745	2,745
Breeding cows	2,226	2,226	2,225	2,225	2,224	2,225	2,162	2,224	2,224
Fattening cows	2,519	2,519	2,527	2,526	2,508	2,510	2,457	2,503	2,501
Heifers +2 years	2,034	2,034	2,016	2,039	2,037	2,033	1,981	2,031	2,031
Heifers 1-2 years	1,672	1,672	1,666	1,636	1,635	1,636	1,590	1,633	1,632

Annex 5. Comparability of treated and untreated producers

This section evaluates the balance of observable characteristics between treated and untreated groups around the eligibility threshold of the second PFIS call, defined by a cutoff score of 66 points. We examine covariate balance within progressively wider score windows centered at the cutoff: ±1, ±2, ±3, ±4, and ±5 points.

Table S8. Covariate Balance Around PFIS eligibility cutoff (second Call)

Window	Score Range (Treated vs. Control	Variable	Treated Mean	SD	Control Mean	SD	p-value
±1	66 vs. 65	Livestock Units	91.8	186.8	87.2	132.7	0.86
		Land (CONEAT 100)	74	146	87.4	151	0.58
		Beef / Land	116	82.7	91	54.2	0.18
		GHG Intensity	25.4	8.9	26.5	12	0.6
±2	66–67 vs. 64–65	Livestock Units	95.8	177	88	147.9	0.9
		Land (CONEAT 100)	83.9	149.3	101.8	168.1	0.41
		Beef / Land	117	77.4	101.2	57.9	0.29
		GHG Intensity	25	10	25.7	13.5	0.79
±3	66–68 vs. 63–65	Livestock Units	93.5	158.9	79.2	135.4	0.39
		Land (CONEAT 100)	87.8	151.4	86.7	153.7	0.96
		Beef / Land	106.4	72.8	103.2	58.3	0.76
		GHG Intensity	27.2	15	26.1	13.95	0.66
±4	66–69 vs. 62–65	Livestock Units	92.8	153	77.4	125.6	0.27
		Land (CONEAT 100)	93.9	152.1	82	137.5	0.41
		Beef / land	106.9	71.7	102.9	57.9	0.66
		GHG Intensity	26.5	14.5	27	14.1	0.79
±5	66–70 vs. 61–65	Livestock Units	89.2	146	83	137.8	0.64
		Land (CONEAT 100)	90.5	145.2	86.4	144.8	0.76
		Beef / land	107.9	70.9	104.9	58.1	0.73
		GHG Intensity	27.2	16	26.6	13.6	0.75

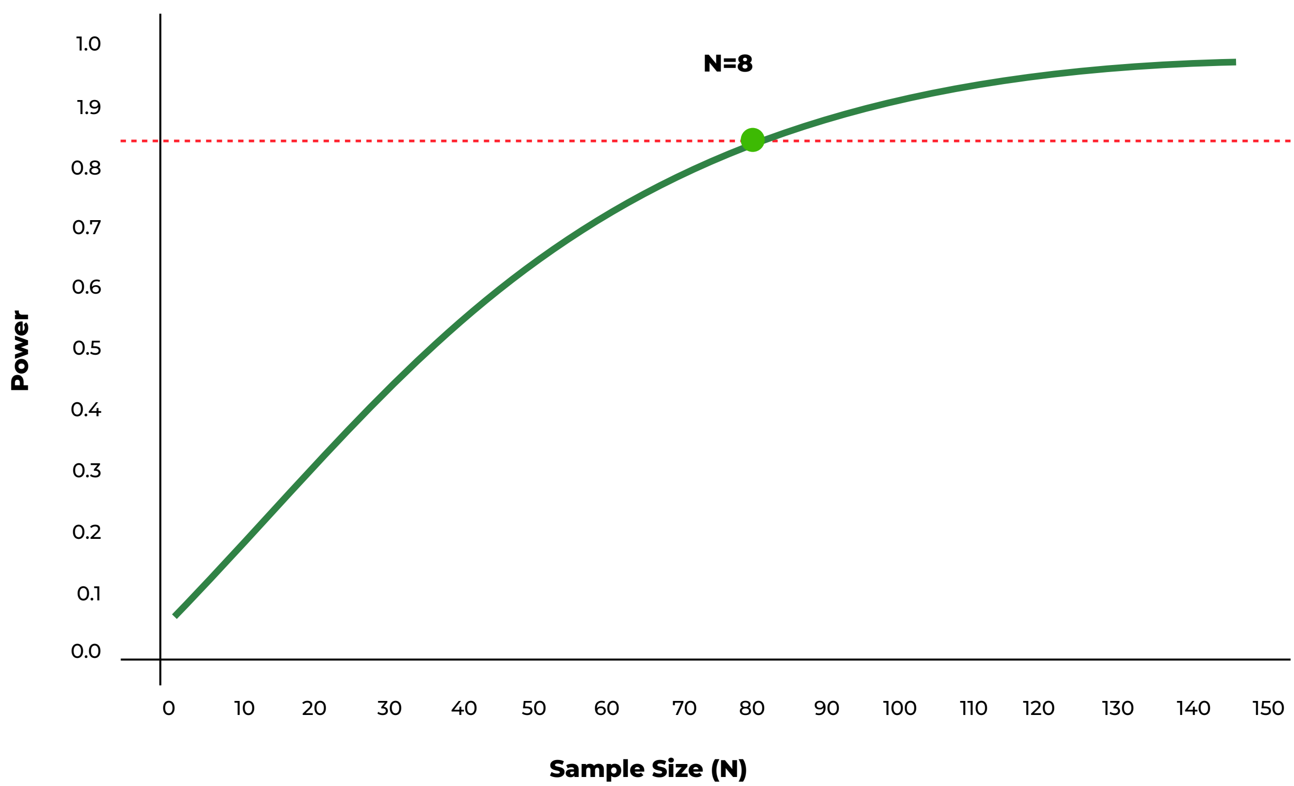
Within each window, we conduct difference-in-means tests on four baseline variables: livestock units, land area (measured in CONEAT 100-adjusted hectares), beef output per hectare, and GHG emissions intensity (see Table S6). These tests provide evidence on whether units just above and below the threshold are statistically similar in their pre-treatment characteristics, a necessary condition for the validity of a regression discontinuity design. The results show no statistically significant differences across all score windows and variables, indicating that treated and control groups near the cutoff are comparable. This supports the internal validity of the RDD strategy employed.

Annex 6. Power analysis

To assess the likelihood of rejecting the null hypothesis of no treatment effect when a true effect exists (the statistical power), we conducted a power analysis based on a two-tailed classical t-test.

We assume a treatment effect equivalent to a 10% increase in beef production per hectare, a standard deviation of 0.3, and a significance level of $\alpha = 0.05$. Given a sample size of N = 81, the resulting power is approximately 85%. This means there is an 85% probability of correctly rejecting the null hypothesis of no treatment effect when the effect is truly different from zero.

Figure S 1 Statistical power of t-test for PFIS impact evaluation



Annex 7. Exact inference

We re-estimate the p-values of the mean comparison test statistic used to assess the effect of PFIS on beef output per hectare and GHG emissions intensity, employing the randomization inference for regression discontinuity designs under local randomization approach (Cattaneo et al., 2016). This method assumes an exact inference framework within the local randomization window. The resulting p-values are qualitatively similar to those obtained under asymptotic inference.

Table S9. **p-values for selected outcome variables**

Variable	Impact	Asymptotic p-value	Randomized p-value	N
Beef/ha	5.156	0.76	0.73	80
GHG intensity	2.928	0.47	0.46	96

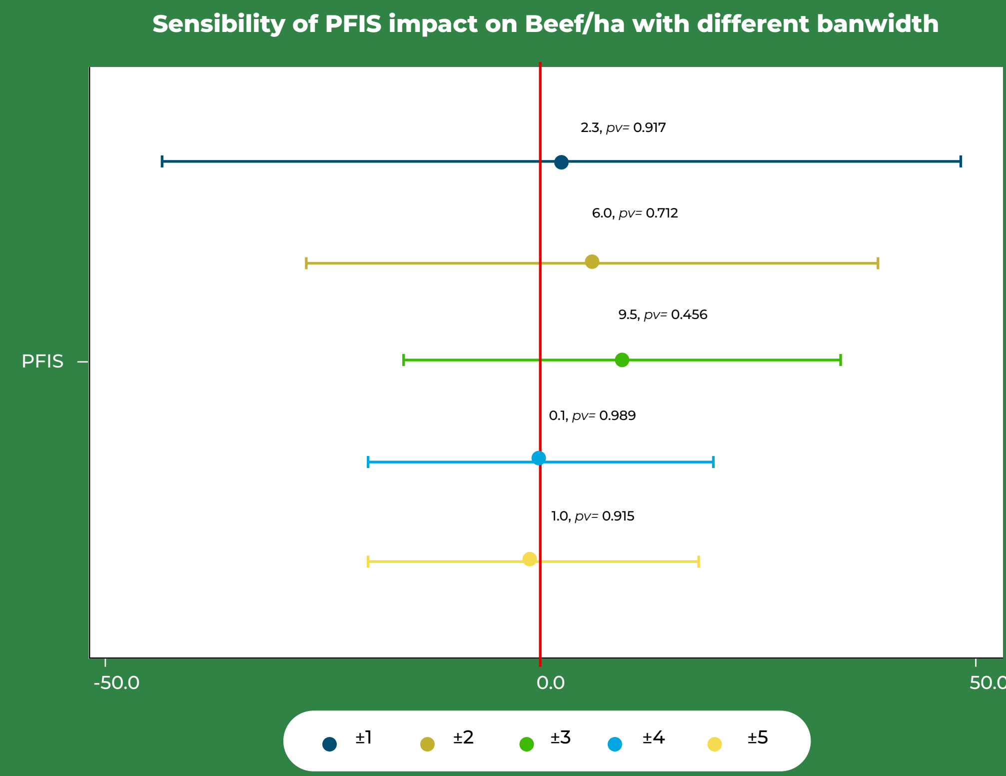
Annex 8. Sensitivity analysis of PFIS effect on beef/ha and GHG intensity

To test the robustness of our main findings, we perform a sensitivity analysis of PFIS's effect on beef production per hectare and GHG emissions intensity. We use pretreatment variables from PFIS application forms and the SNIG system to account for observable differences between treated and control groups.

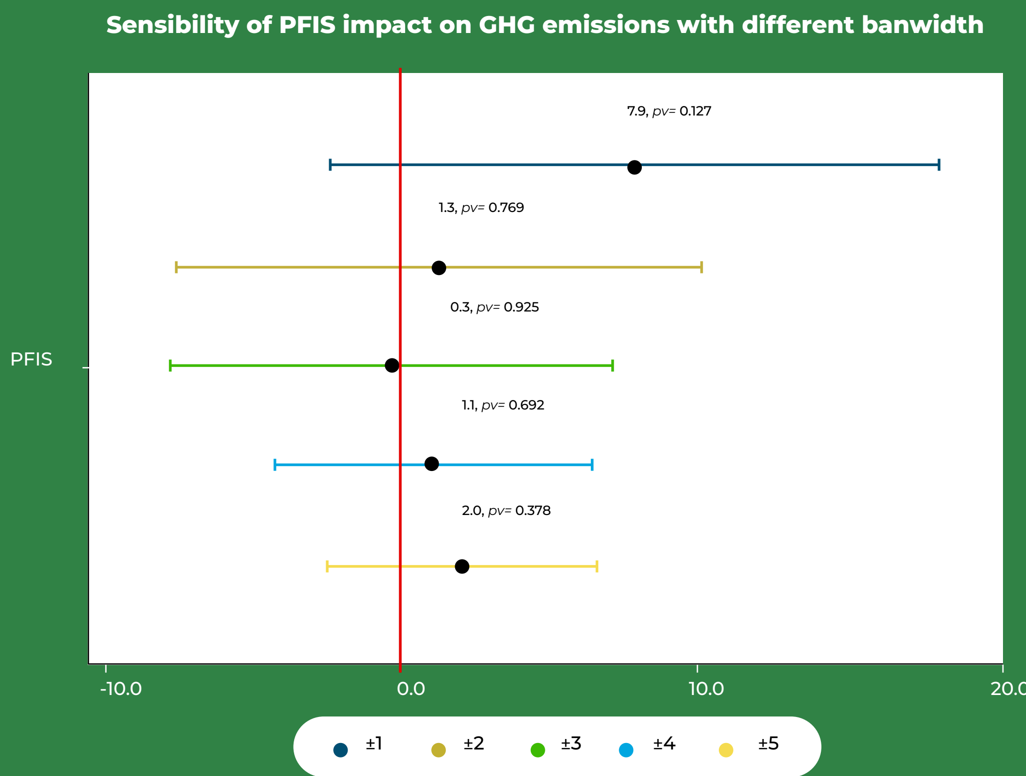
We apply entropy balance to reweight the control group so that the distribution of covariates (livestock units, livestock area, soil quality [CONEAT], proportion of forage-improved area, and baseline beef output and GHG intensity) matches that of the treated group. This method minimizes the Kullback-Leibler divergence from a uniform weight distribution while ensuring covariate balance (Hainmueller, 2012).

Using these weights, we estimate treatment effects through weighted linear regression models. To assess sensitivity, we repeat the analysis in progressively wider score bandwidths around the eligibility cutoff (±1 to ±5 points).

Across all specifications, results remain qualitatively consistent and statistically nonsignificant for both beef output per hectare and GHG intensity. These findings reinforce the robustness of our main conclusions.



Sensibility of PFIS impact on Beef/ha with different banwidth
2.3, pv= 0.917
6.0, pv= 0.712
9.5, pv= 0.456
0.1, pv= 0.989
1.0, pv= 0.915
PFIS
-50.0
0.0
50.0
±1
±2
±3
±4
±5



Sensibility of PFIS impact on GHG emissions with different banwidth
7.9, pv= 0.127
1.3, pv= 0.769
0.3, pv= 0.925
1.1, pv= 0.692
2.0, pv= 0.378
PFIS
-10.0
0.0
10.0
20.0
±1
±2
±3
±4
±5

4

CONSTRAINTS ON SUSTAINABILITY IN LIVESTOCK FARMING: EVIDENCE FROM MEXICO

Saúl Basurto-Hernández, Allan Beltrán and Luis Peña-Lévano

Abstract

This paper examines barriers to the adoption of sustainable grazing practices. Using Mexico's 2007 and 2022 Censuses of Agriculture, we construct a panel data set of 2,454 municipalities and develop a municipality-level environmental sustainability index based on grazing practices. This index serves as the dependent variable in a two-way fixed effects fractional panel regression model, which estimates the effect of structural, financial, informational, and institutional adoption barriers. Among our main results: Municipalities with larger grazing areas tend to engage in unsustainable practices. Land tenure regimes act as structural constraints. Access to financial support, such as credit and subsidies, and extension services significantly improve sustainability. Agricultural insurance, however, is negatively associated with the adoption of sustainable practices. Those results remain robust across different farm sizes, production systems, and alternative weighting schemes for sustainable practices in the index. The findings highlight the need for tailored policy interventions that address barriers to sustainable livestock production and inform broader efforts to promote environmentally sustainable agricultural practices in developing economies.

Introduction

Sustainable grazing practices have gained attention in the global effort to mitigate climate change, enhance environmental sustainability, and support rural livelihoods. Despite their potential to reduce greenhouse gas (GHG) emissions, prevent soil degradation, and improve ecosystem resilience, adoption of sustainable grazing methods remains limited in many regions. Existing studies highlight technical and economic barriers, but comprehensive, large-scale analyses that integrate socioeconomic, institutional, and environmental factors are scarce. This paper contributes to the literature by addressing that gap, providing one of the first empirical assessments of barriers to adopting sustainable grazing practices, using a novel data set. Mexico, a country with extensive cattle grazing, serves as an illustrative case. The study sheds light on the structural, financial, and demographic factors influencing the uptake of sustainable practices. The findings not only provide actionable evidence for policymakers in Mexico but also offer broader insights that can inform sustainable initiatives in other countries.

We define sustainable grazing practices as those that reduce environmental damage (e.g., soil erosion), improve pasture regeneration, and mitigate GHG emissions. Using farm-level data from agricultural censuses, we construct a municipality-level panel data set comprising more than 1 million farms per year (INEGI, 2007, 2022). Following Lebacq et al. (2012), we develop an environmental sustainability index (ESI) that assigns weights to production practices based on their inherent sustainability. To identify barriers to the adoption of sustainable practices, we rely on a fractional regression model in which the dependent variable is the ESI and the set of controls includes grazing area, proportion of farmland under ejidal and communal tenure, and access to insurance, credit, extension services, and subsidies, as well as farmers' characteristics such as age, education, gender, and ethnicity.

Our findings highlight several barriers to sustainability. Municipalities with larger grazing areas are more likely to engage in unsustainable practices. Land tenure is a significant structural barrier, with ejidal lands showing lower sustainability compared with private or communal lands. Access to credit, subsidies, and extension services positively influence sustainability, facilitating the adoption of advanced practices and investments in sustainable infrastructure. Conversely, agricultural insurance is negatively associated with sustainability. Education is consistently linked to higher sustainability, emphasizing the importance of knowledge and technical capacity. The analysis of heterogeneity reveals that financial and technical support is particularly effective for small and mixed farms, and dual-purpose farms benefit the most from a combination of subsidies and extension services. The results indicate the need for tailored interventions that address the unique challenges faced by farms of different sizes and production systems. The outcomes of this paper provide actionable evidence of policies and programs aimed at promoting sustainable cattle practices.

The remainder of the paper is organized as follows.

Section 4.1 provides an overview of previous studies, looking at sustainability indicators and barriers to sustainable grazing practices.

Section 4.2 describes the panel data set and the fractional response model we use in this analysis

Section 4.3 introduces our case study

Sections 4.5 present and discuss the set of results, respectively

Section 4.6 concludes

4.1 Literature Review

This literature review is divided into two sections. The first section focuses on sustainability indicators, discussing how sustainability is measured and the different frameworks used to evaluate the environmental performance of livestock farming systems. The second section explores the barriers to implementing sustainable practices, drawing on empirical studies that highlight the practical challenges faced by farmers. Together, these two strands of literature establish the basis for assessing the sustainability of grazing practices in Mexico and inform the construction of a sustainability index that is both grounded in theory and responsive to the practical realities of livestock farming.

2.1. Sustainability indicators for livestock farming

Sustainable agriculture is concerned with the ability of agroecosystems to remain productive in the long term. Many authors distinguish ecological (or environmental), economic, and social sustainability. Ecological sustainability is defined as the maintenance of the global ecosystem or of the "natural capital" that serves both as a "source" of inputs and as a "sink" for waste (Goodland, 1995). The ecological dimension of sustainability is fundamental to overall sustainability, since it is a prerequisite for the economic and social dimensions.

Sustainability indices serve as quantitative tools that measure the progress of farming practices toward sustainable development (Zhen and Routray, 2003). Various classifications of environmental indicators and objectives exist in the literature (Alkan Olsoon et al., 2009; Meul et al., 2008; Sadok et al., 2008; van der Werf and Petit, 2002). For livestock farming, these indices can be categorized as either means based or effect based, each offering distinct approaches to assessing environmental effects. Means-based indicators focus on farmers' production practices, such as livestock stocking rates; effect-based indicators evaluate the outcomes of these practices, like nitrate concentrations in groundwater (Lebacq et al., 2012).

Effect-based and means-based indicators differ in their measurability and environmental relevance. The former have high environmental relevance because of their direct link with the objectives and their context specificity but are difficult to implement from a methodological or practical point of view. The latter are easy to implement because of data availability and ease of calculation but have low quality of prediction of environmental impacts (van der Werf and Petit, 2002; van der Werf et al., 2009)..

Effect-based indicators are commonly used to assess farm sustainability at the micro level but require complex data, making them impractical for large-scale studies. From the perspective of farms, the commonly assessed parameters include soil erosion, soil quality, water quality, quality of farming practices, fertilizer use, crop rotation, and growing methods (van der Werf and Petit, 2002; Hayati, 2017). Studies using effect-based indicators often have limited sample sizes. For instance, Bravo-Medina et al. (2017) analyzed data from 10 farms in Ecuador, and Chand et al. (2011, 2015) assessed 120 and 60 dairy farms in India. Similarly, Jara de Garcia et al. (2023) evaluated 60 farms in Peru, Sulewski and Kłoczko-Gajewska (2018) focused on 600 farms in Poland, and Vences et al. (2015) analyzed 29 farms in Mexico. These small sample sizes highlight the challenges of scaling up sustainability assessments to larger populations, since gathering comprehensive data across broader regions remains difficult. Effect-based indicators do not enable cause-effect relationships to be monitored, making them hard to use to formulate specific advice for farmers (Bockstaller et al., 2008).

Means-based indicators are widely used for assessing environmental sustainability because they are easy to implement and directly tied to production practices. These indicators rely on accessible data, such as fertilizer use and crop rotation, and are simpler to apply across large-scale studies. As a result, many data-driven approaches prioritize means-based indicators for evaluating environmental sustainability in farming. Among 12 indicators explored by van der Werf and Petit (2002), three are particularly relevant for our study because they are based on means-based indicators, focus on environmental sustainability, and use farm-level data. The farmer sustainability index of Taylor et al. (1993) assigns scores to 33 farming practices involved in cabbage production, with each practice contributing positively or negatively to an overall ecological sustainability score. The "ecopoints" method evaluates both farming practices and landscape maintenance, assigning scores accordingly (Mayrhofer et al., 1996).

Vilani's indicators of farm sustainability assess agroecological, socioterritorial, and economic sustainability by scoring farming practices and behaviors, making this method applicable to various farm types (Vilani, 1999). These approaches demonstrate the versatility and practicality of means-based indicators in sustainability assessments.

Overall, existing literature indicates that implementing the principles of sustainable development in agriculture requires, in practice, appropriate indices enabling the assessment and monitoring of the state of the sector and farms.

2.2. Barriers to sustainable grazing practices

A growing body of research has examined the barriers to adoption of sustainable grazing practices, which, despite their well-documented economic and environmental benefits, continue to face limited uptake worldwide. These barriers are multifaceted, encompassing behavioral, financial, informational, infrastructural, and institutional challenges that interact within complex socioeconomic, agro-ecological, and political contexts. Studies have employed a combination of quantitative approaches, such as econometric analysis of large data sets, and qualitative methods, including focus groups and surveys, to gain insights.

Quantitative approaches have identified credit constraints, lack of technical assistance, and insufficient awareness as significant barriers to innovation adoption (Karali et al., 2014; Kollmuss and Agyeman, 2002). Qualitative techniques have revealed nuanced perspectives on overcoming obstacles via participatory farmer education and extension programs tailored to localized priorities and capabilities (Blackstock et al., 2010; Chevalier and Buckles, 2013). Evidence from Latin America echoes global trends in land tenure insecurity and misaligned government policies (de Janvry and Sadoulet, 2001). However, structural changes in agriculture, such as increasing herd sizes, also affect grazing practices in developed countries like Germany (Eggers et al., 2014).

Behavioral obstacles encompass risk attitudes affecting farmers' openness to innovations, future time perspectives shaping investment decisions, and competing pressures on operational priorities (Karali et al., 2014; Wreford et al., 2017). Additionally, attitudinal resistance often stems from rational assessments rather than motivational issues (Gillespie et al., 2007). Financial barriers feature the high upfront costs of certain sustainable practices, especially for farmers without access to credit or government support programs (Mills et al., 2017; Stuart et al., 2014). Even seemingly "win-win" options may confront hidden transaction costs thwarting diffusion (MacLeod et al., 2015). Relevant expenses include information search, administration, monitoring, and reporting requirements (Wreford et al., 2017).

Informational obstacles, particularly limited awareness and knowledge requirements, dominate research on sustainable agricultural adoption (Prokopy et al., 2008; Rochecouste et al., 2015). Means of transferring information and demonstrating innovations include extension services and farmer-to-farmer learning networks (Baumgart-Getz et al., 2012). Infrastructural impediments include insecure land tenure precluding long-term investments, scarce irrigation water, inadequate electricity and farm-to-market road infrastructure, and remote locations lacking access to agricultural input and output markets (Aguilar-Gallegos et al., 2015; Wreford et al., 2017). Expanding operational scale and herd sizes in Germany's dairy sector demonstrate how structural shifts can influence grazing practices over time (Eggers et al., 2014).

Institutional obstacles include insufficient government support programs, in terms of funding, design, or targeting (Stuart et al., 2014). Conflicting agricultural policies may inadvertently entrench barriers by encouraging expanded production or subsidizing inputs without climate adaptation or sustainability provisions (Wreford et al., 2017). Sociodemographic characteristics like age, education, gender, and culture can pose adoption barriers (Adesina and Baidu-Forson, 1995; Baumgart-Getz et al., 2012; Knowler and Bradshaw, 2007). Older farmers often show resistance to innovations. Formal agriculture training and active information search are associated with higher adoption likelihood. Gender roles, household decision-making dynamics, and cultural traditions shape judgments regarding appropriate farming practices.

Overall, a multidimensional perspective is essential, since barriers interlink through socioeconomic, agro-ecological, and political frameworks that require integration of information instruments, economic incentives, and institutional reforms (Kollmuss and Agyeman, 2002). Quantitative and qualitative techniques can diagnose region-specific obstacles in farming systems to inform policies for overcoming barriers and promoting sustainable practices. Overcoming barriers requires identifying locally relevant obstacles, prioritizing impediments, and designing policies that address information gaps, cost constraints, and institutional failures (Gillespie et al., 2007; Mills et al., 2017). Participatory, tailored government initiatives can strengthen extension services and provide necessary economic incentives while reforming policies not aligned with sustainability goals (Chevalier and Buckles, 2013; Rochecouste et al., 2015).

4.2 Data and Methodology

We use 2007 and 2022 agricultural census data (INEGI, 2007, 2022) from 1.13 million and 1 million farms, respectively, that raise cattle and report information on grazing practices and farm management to construct a municipality-level panel data set. Our analysis relies on the municipality-level panel rather than pooling cross-sectional units, since the censuses do not allow for tracking farms over time.

The censuses report data on the number of cattle under six grazing practices: free grazing, controlled grazing, confined and semiconfined management, use of balanced feed, and paddock rotation (see Table A1 in the Appendix for an overview). Additionally, the data include variables related to area and land tenure, such as the total grazing area and farmland classified under different tenure regimes (ejidal,[4] communal, and private). The censuses also provide information on farmers' access to financial instruments, including agricultural insurance and credit, as well as access to government support in the form of subsidies and extension services. Finally, sociodemographic characteristics of farmers are recorded, including years of education, gender, whether the farmer speaks an Indigenous language, and age[5]. The data set further identifies farm production types, distinguishing among beef, dairy, dual-purpose, and mixed[6] production systems, offering additional insights into the heterogeneity of cattle farming operations.

[4] This is land that the government allocated to communities after the Mexican Revolution in 1910–1921. Beneficiaries of this land allocation can either use or rent their land, and as of recently, they can sell it with approval of the General Assembly of ejidatarios.

[5] Although INEGI's agricultural censuses include data for 1991 (INEGI, 1991), the data lack sufficient detail for direct comparison with more recent data. Specifically, the 1991 census omits information on two of six grazing practices and six of 12 control variables. Additionally, it provides only aggregate data on the number of cattle under grazing, without differentiating between free and controlled grazing systems. Given these limitations, our analysis uses data from the 2007 and 2022 censuses.

[6] The mixed farm category comprises operations where beef, dairy, or dual-purpose production coexists with other types of livestock, such as bulls (breeding males) or oxen, reflecting the diverse production strategies used by farmers.

For our analysis, we first aggregate farm-level data to the municipal level. Specifically, we compute municipal-level aggregates for the main variables, including the proportion of farms implementing any of the six grazing practices, total grazing area, and land tenure type. Additionally, we incorporate data on the proportion of farms with access to agricultural insurance, credit, subsidies, and extension services. Sociodemographic characteristics are also considered, including the average years of education and age of farmers, as well as the proportion of male farmers and those who speak an Indigenous language. Our final panel data set consists of aggregated census data on farm populations for 2,464 municipalities across 2007 and 2022.

Using our data set, we developed an environmental sustainability index (ESI) to reflect the level of sustainability of grazing practices. Following the approach of Lebacq et al. (2012), our ESI assigns weights to farming practices based on their inherent sustainability. This approach is grounded in established frameworks by Taylor et al. (1993), Mayrhofer et al. (1996), and Vilani (1999), which use means-based sustainability indicators.

Our index focuses on multiple dimensions of sustainability but is constrained by data availability to grazing and feeding practices. Recognizing that sustainability encompasses various dimensions, we conceptualize farmers' practices as existing along a continuum, from "very sustainable" to "very unsustainable." Thus, the ESI reflects the overall sustainability level of each municipality, considering the prevalent practices. Our approach allows us to model how socioeconomic, financial, and institutional constraints affect environmental sustainability in livestock farming through their effect on the ESI. We define the ESI as follows:

$$ESI_{it} = \Sigma_j^J w_j y_{jit}$$

where w_j is the specific weight of the j_{th} practice, and y_{jit} denotes the proportion of farms implementing practice j in municipality i at time t. The sustainability of each practice is captured by the weight w_j, which is determined based on existing literature.

For the main weighting scenario, López (2025) indicates that, on average, a calf under free grazing reaches optimal weight at 42 months, during which it emits 11.5 tCO_2e. But if the calf is confined at an early stage—say, at 20 months—emissions would fall by 54% because confined management speeds up the calf's fattening. Once the calf is confined, technological innovation, appropriate manure management, and the use of balanced feed can further reduce emissions, from 1.5 to 0.4 tCO_2e. Steinfeld et al. (2006) find that extensive and intensive systems generate 13% and 5% of total anthropogenic emissions worldwide, respectively, which adds further support to the argument that free grazing tends to be more detrimental to the environment than confined practices.

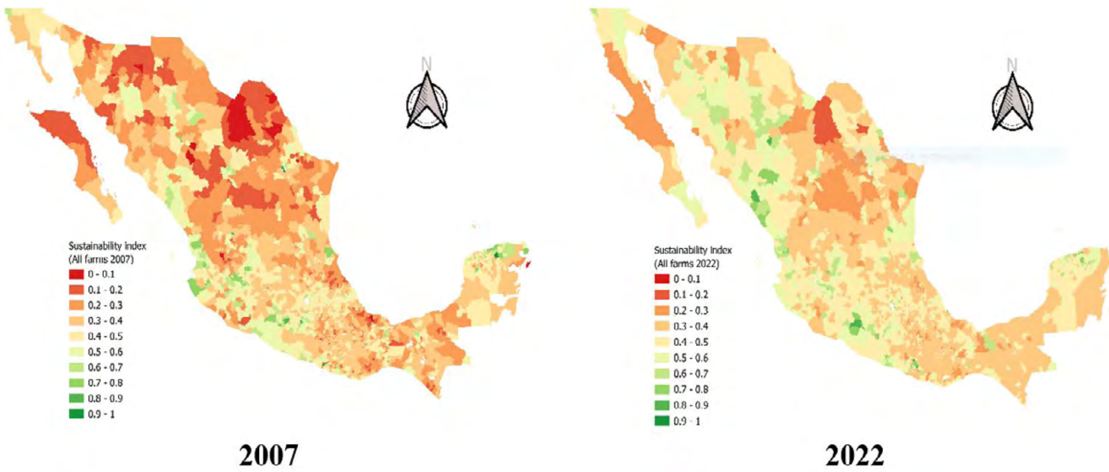
Regarding soil erosion and pasture regeneration, Lai and Kumar (2020) conducted a meta-analysis based on 287 articles to evaluate the effects of grazing on soil properties and consequently on pasture regeneration. Their results indicate that heavy grazing is more detrimental to soil quality than moderate, light, and no grazing because it reduces soil organic carbon, total nitrogen, the carbon-nitrogen ratio, water content, and potassium. Conversely, light grazing increases soil organic carbon and ammonium, which improves soil quality. Lai and Kumar (2020) also showed that heavy grazing has a higher probability of overgrazing (70%) compared with moderate (14%) and light (10%) grazing. Thus, uncontrolled free grazing seems to be more detrimental than other grazing practices in terms of GHG emissions, soil quality, and pasture regeneration. López (2025) finds that the use of balanced feed can further reduce GHG emissions.

Table A2 in the Appendix presents an overview of the sustainability considerations associated with each practice, as reported in the literature, alongside the corresponding weights w_j. The most sustainable practice is the use of balanced feed ($w_j = 3$), which ranks highest because of its positive contributions to livestock efficiency and environmental impact reduction (López, 2025). In contrast, free grazing is identified as the least sustainable practice ($wj = -2$), primarily because of its association with overgrazing and environmental degradation, explained above (Lai and Kumar, 2020). The remaining practices fall between these two extremes, representing a spectrum of sustainability levels. Practices such as controlled grazing and paddock rotation are relatively sustainable and promote better pasture management and environmental outcomes, whereas semiconfined and confined systems pose challenges in manure management and resource efficiency. Because of debate on the relative sustainability of the grazing practices included in our analysis, we consider three alternative weighting scenarios, which allow for a robustness test of our results under different assumptions of the sustainability weights assigned to each practice (discussed in Section 6, below).

For our analysis, we normalize the values of the ESI by subtracting the minimum ESI value in the sample from each ESI observation and divide the result by the maximum ESI value, using the following formula: $\frac{\widetilde{ESI}_{it} - \min(\widetilde{ESI})}{max(\widetilde{ESI})}$, where $(\widetilde{ESI}_{it})$ are the original values.[7] Thus, the values of our index range between 0 and 1, where 0 represents the least sustainable practices and 1 represents the most sustainable ones. This transformation facilitates the interpretation of the index and the econometric results. Figure 1 shows the spatial distribution of the normalized ESI. The map reveals an overall increase in the sustainability index over time, suggesting a shift from less sustainable to more sustainable grazing practices among farmers. Furthermore, unsustainable practices are more prevalent in the northern regions of Mexico, particularly in Coahuila and Chihuahua, where free grazing remains the dominant practice.

[7] Note that $\min(\widetilde{ESI})$ is negative.

Figure 1. **Environmental sustainability index: Spatial distribution, 2007 and 2022**



Source: own elaboration based on INEGI (2007, 2022)

To identify the barriers to adoption of sustainable practices, we follow Papke and Wooldridge (1996, 2008) and adopt a fractional response panel data model to appropriately account for the bounded nature of the dependent variable. This approach is particularly suited for data sets with a large cross-sectional dimension and a limited number of time periods, as is the case in our study. Papke and Wooldridge (2008) indicate that conventional linear panel fixed effects models may lead to imprecise estimates, potentially generating predicted values outside the valid range of the dependent variable. In contrast, the fractional response model ensures that predicted values remain within the unit interval, and it addresses issues related to serial dependence. Thus, given a set of explanatory variables x_{it}, the model is specified as follows:

$$E(ESI_{it}\,|x_{it},c_i\,)=\Phi(x_{it}\,\beta+c_i)$$

where $\Phi(.)$ stands for the standard normal cumulative distribution function, ESI_{it} is the ESI index, c_i is the unobserved effect, and β are the parameters. To identify β, Papke and Wooldridge (2008) assume that conditional on c_i, x_{it} is strictly exogenous, and that c_i follows a conditional distribution, as in Chamberlain (1980)—that is, $c_i\,|x_{it}$~Normal$(\psi+(x_i\,)^{-}\xi,\sigma\hat{}2\,)$. For its empirical implementation, we estimate the following model:

$$E(ESI_{it}\,|x_{i1},\ldots,x_{iT}\,)=\Phi(x_{it}\,\beta+\alpha_i+y_{t}+\lambda_{mt})$$

where α_i, γ_t, and λ_{mt} represent the municipal, year, and state-year fixed effects, respectively. The set of independent variables, x_{it}, comprises grazing area; land tenure regime of farmland; access to credit, insurance, subsidies, and extension services; and sociodemographic characteristics. Interpreting the coefficients in a fractional response model can be complex because of the nonlinear nature of the probit specification. Therefore, in our analysis, we focus on interpreting the sign of the coefficients and comparing the relative magnitude across different explanatory variables.

Table A3 in the Appendix shows the summary statistics of the variables in our model. On average, the most prevalent grazing practice in Mexico is free grazing (32% of all farms), followed by paddock rotation (17%) and balanced feed (17%). These practices are not mutually exclusive: both sustainable and unsustainable practices can coexist on a single farm. The average grazing area per municipality is 13,600 hectares. Most farmland is private (47% of total farmland); *ejidal* and communal lands together represent 52% of total farmland. In terms of access to resources, 41% of farms in municipalities received subsidies, and 4% had access to credit. However, access to extension services and agricultural insurance remains very low, with only 4% and 1% of farms benefiting from these resources, respectively. This suggests that even though cattle production in Mexico is heavily subsidized, there is a significant gap in the provision of extension services. With respect to sociodemographic characteristics, the average farmer is male and 55 years old, with five years of education. Only 23% of farmers speak a native language, this variable serves as our indicator for Indigenous ethnicity.

4.3 Results

Using our panel data set, we estimate a set of models to identify barriers to the adoption of sustainable grazing practices. Figure 2 provides a graphical representation of the main results from the fractional regression model, and Table A4 in the Appendix presents the full econometric results, including those from a standard linear panel model. Although the results of the linear models and the fractional panel models show some differences, the majority of findings remain consistent across both specifications. Our discussion of the results focuses on the fractional panel model, which is better suited to account for the bounded nature of the ESI. The findings offer valuable insights into the role of farm characteristics, access to resources and government support, and sociodemographic factors in shaping sustainability outcomes across municipalities.

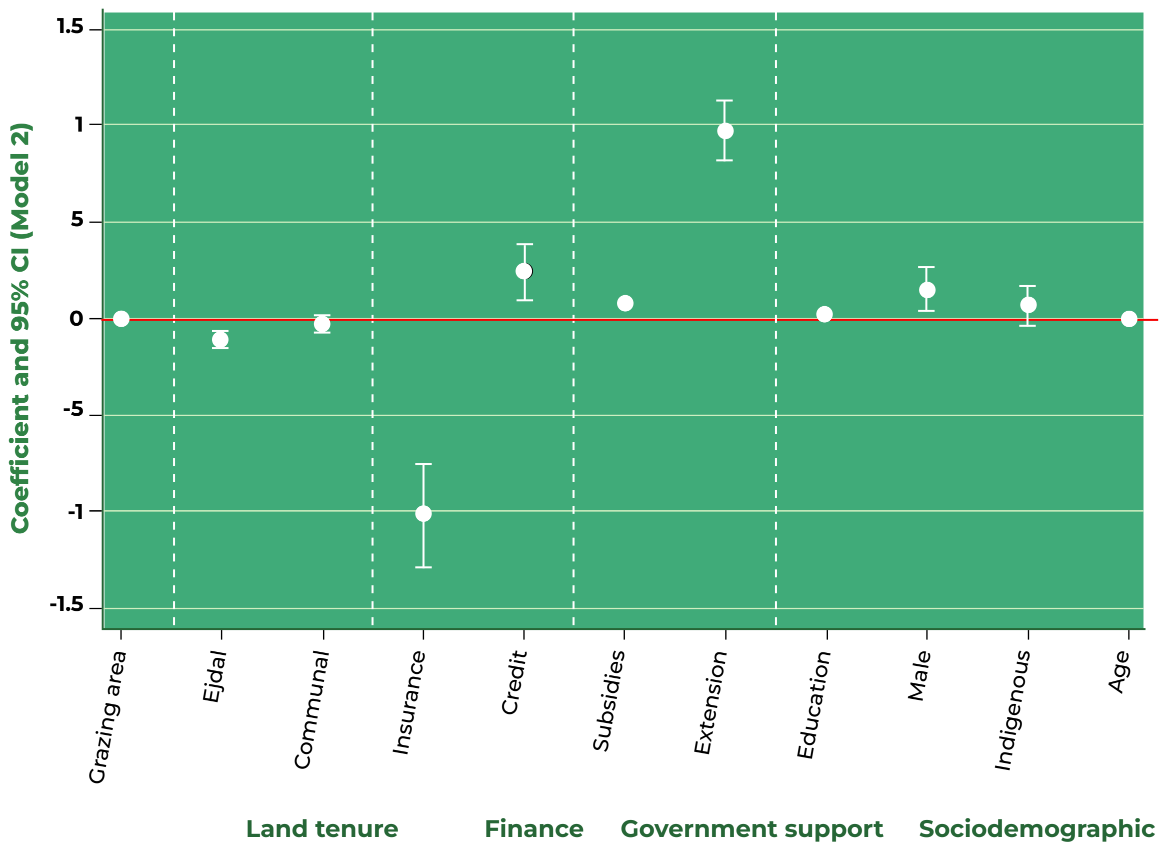
The results suggest that municipalities with larger *grazing areas* are more likely to use unsustainable practices. This outcome may be explained by the tendency of municipalities with extensive grazing areas to rely on free grazing systems, where farmers may not fully consider pasture scarcity in their profit optimization decisions.

For land tenure regimes, some studies suggest that communal land management can lead to sustainable outcomes if landowners establish clear rules, norms, and enforcement mechanisms to prevent the overexploitation of common-pool resources, such as grazing areas (Gebremedhin et al., 2004). In contrast, other studies argue that open-access grazing systems often result in resource overuse, leading to feed shortages, soil degradation, and environmental decline. Our findings align with the latter concerns, indicating that livestock production on ejidal land is associated with lower sustainability compared with private land, but no significant difference is observed between private and communal land. Since ejidos are, in most cases, managed as common-pool resources, the absence of well-defined property rights may encourage farmers to adopt unsustainable practices. This result highlights the governance and coordination challenges that often hinder the implementation of sustainable grazing strategies in ejidal lands, emphasizing the need for stronger institutional frameworks to support collective land management.

Access to *financial* and *government support* plays a crucial role in shaping sustainability outcomes. The coefficient for agricultural insurance suggests that municipalities with higher insurance coverage tend to exhibit lower ESI values. This result may reflect a moral hazard: insured farmers may have less incentive to adopt sustainable practices, relying instead on financial compensation in the event of adverse environmental outcomes. Access to credit, subsidies, and extension services, however, all exhibit positive and significant effects on sustainability. The adoption of sustainable practices such as confined cattle, paddock rotation, and the use of balanced feed requires investments in either new infrastructure or more expensive inputs, which may explain the positive relationship between access to credit and the ESI. Even though only 3.7% of farms in the average municipality receive extension services, these outreach programs significantly contribute to the promotion of sustainable practices.

Regarding *sociodemographic characteristics*, farmers' education has a positive and significant effect: better-educated farmers are more likely to adopt sustainable practices. This finding aligns with existing literature suggesting that higher education levels contribute to greater awareness and a better understanding of the long-term benefits of environmentally friendly farming practices. Given that the average farmer has incomplete primary education, an additional year of schooling is important for increasing the likelihood of adopting sustainable practices. Neither speaking a native language nor age is statistically significant.

Figure 2. **Parameter estimates: Panel fractional regression**



Source: own elaboration based on INEGI (2007, 2022)

Overall, the results of our model suggest that financial and technical support, alongside educational initiatives, play a critical role in promoting sustainable grazing practices. However, two structural factors, land tenure regime and farm size, present significant barriers that need to be addressed through targeted policy interventions. Among all factors, the negative effect of agricultural insurance and the positive effect of extension services stand out for their relatively larger magnitudes, highlighting the importance of targeted policies that address both financial disincentives and knowledge dissemination to enhance sustainability outcomes.

4.4 Discussion

To further investigate the factors influencing adoption of sustainable practices, we analyze the heterogeneity of results by splitting the sample based on farm size and type. For farm size, we follow INEGI's criteria, classifying farms as small (fewer than 11 head), medium (11 to 84 head), or large (more than 84 head). For farm type, we use four mutually exclusive categories: beef, dairy, dual-purpose, and mixed farms.[8] A farm falls into one of these categories if at least 75% of its herd is the respective type; this ensures that the primary focus of production is accurately captured. Table 1 shows the results of the fractional panel regression model on the ESI split, by farm size and farm type.

The negative and significant effect of grazing area on sustainability across most models suggests that small and large farms face greater challenges, likely due to overgrazing and resource depletion. Extensive livestock farming is often associated with inefficient pastoral systems, overexploitation of resources, and inadequate manure management, which can contribute to GHG emissions, soil degradation, biodiversity loss, and a reduction in carrying capacity per head. In contrast, the effect is insignificant for medium-sized farms, which may implement better localized management practices.

Across farm types, increased grazing area for beef and dairy farmers (including dual purpose farms) lowers the ESI. On average, grass-fed systems require significantly more land for a longer period per unit of milk or meat to reach a target production, compared with grain-fed systems. The high resource demands of dairy production (Loera and Banda, 2017), combined with the complexity of managing larger grazing areas, contribute to lower sustainability.

[8] As defined above, a mixed farm includes operations where beef, dairy, or dual-purpose production coexists with other types of livestock, such as bulls (breeding males) or oxen.

The results for land tenure regimes show that the effect of ejidal land on sustainability varies across both farm size and type, highlighting the complexities associated with collective land management. For small and medium-sized farms, a higher proportion of ejidal land is associated with lower sustainability outcomes, suggesting that the challenges associated with common-pool resource management disproportionately affect these operations by limiting their ability to implement sustainable practices. In contrast, the proportion of communal land does not show a significant effect for small farms, suggesting that communal tenure may offer sustainability outcomes similar to private land (the reference category), potentially because of stronger local governance or established traditional management practices that mitigate resource depletion. For large farms, the proportion of ejidal land does not have a significant effect. On the other hand, a higher proportion of communal land in municipalities with large farms has a positive and significant effect, suggesting that larger communal landholdings with fewer landowners allow for better resource management.

The effect of land tenure regimes also varies across farm types. Beef, dairy, and mixed farms show no significant difference in sustainability outcomes among *ejidal*, communal, and private lands. In dual-purpose farms, the results reveal a contrasting effect of land tenure on sustainability, with a higher proportion of *ejidal* land associated with lower sustainability compared with private land, whereas communal land shows a positive and significant effect. The negative effect of ejidal land suggests that the dual production demands of beef and dairy place considerable pressure on shared resources. The positive effect of communal land, however, suggests that, under the right conditions, communal tenure arrangements can support more sustainable outcomes. This result may reflect better coordination among communal landowners, where smaller groups of stakeholders are able to establish and enforce collective grazing agreements that prevent overexploitation and promote rotational practices. Unlike ejidal systems, where governance structures can be more fragmented and politically influenced, communal lands may benefit from stronger traditional management practices that facilitate cooperation and long-term resource planning.

The effect of financial support on sustainability also varies significantly by farm size and type. For small farms, access to credit has a positive and significant effect. This finding suggests that financial resources are essential for small-scale operations, which often face financial constraints due to limited collateral and cash flow. Credit enables these farmers to invest in sustainable practices, such as paddock rotation, improved forage quality, and efficient irrigation systems. In contrast, insurance does not have a significant effect, indicating that small farmers may not heavily rely on it to influence the sustainability of their production practices. For medium-sized farms, insurance has a negative and significant effect, indicating that insured farmers in this category may engage in unsustainable practices, such as overstocking, leading to overgrazing and resource depletion. Insurance coverage may reduce incentives for careful pasture management and long-term sustainability planning, since financial compensation provides a safety net against potential losses. Access to credit, however, does not have a significant effect for medium-sized farms. For large farms, neither credit nor insurance significantly affects sustainability.

For beef farms, access to credit has a positive and significant effect, suggesting that financial support helps beef producers invest in improved infrastructure and pasture management practices that contribute to better environmental outcomes. In contrast, insurance has a negative but insignificant effect. In dairy farms, access to insurance has a negative and significant effect, which supports the hypothesis that insured dairy farmers might overstock cattle or overexploit resources because of the financial safety net provided by insurance. Dairy production is highly resource-intensive and requires careful management of feed, water, and manure, which may not be prioritized when financial risks are perceived as being mitigated. Conversely, access to credit does not show a significant effect, suggesting that dairy farms may rely on alternative sources of investment for sustainability improvements. For dual-purpose farms, both credit and insurance have positive and significant effects. The positive effect of insurance in this category might indicate that diversified production systems provide better financial stability and resource management, allowing farmers to use insurance as a tool for resilience rather than taking risks. For mixed farms, credit has a positive and significant effect, whereas the effect of insurance is negative but insignificant.

PROGAN (Program to Incentivize Livestock Productivity) serves as the main subsidy program aimed at enhancing farm productivity, promoting sustainable land use, and improving environmental outcomes, alongside the provision of extension services, such as training on rotational grazing techniques, water conservation practices, and improved manure management systems. The results indicate a critical role of government support in promoting sustainable grazing practices, with subsidies and extension services having significant benefits across various farm sizes and types. Although both mechanisms contribute positively to sustainability, their effects vary across different operational scales and production systems, reflecting differences in resource access, knowledge, and operational needs.

For small farms, both subsidies and extension services significantly enhance sustainability. This reflects their dependence on financial support to adopt even basic sustainable practices and their higher sensitivity to the knowledge provided by extension services, given their limited access to expertise and infrastructure. In contrast, medium-sized farms benefit only from extension services, since subsidies are not significant for this group. This suggests that medium farms still lack the scale or financial incentives to make substantial investments in sustainability and rely instead on technical guidance to optimize their practices. For large farms, both subsidies and extension services show significant positive effects, but the nature of their effect differs. Large farms use subsidies to finance advanced, resource-intensive technologies like precision feeding and automated waste management, and extension services complement these efforts by providing the technical knowledge required to implement these innovations effectively.

For beef farms, sustainability is significantly enhanced by extension services, likely because of their role in improving grazing management and manure handling, but subsidies show no significant effect, reflecting the limitations of financial support in addressing structural issues inherent to extensive grazing systems. For dairy farms, too, extension services are important for sustainability, addressing the high resource demands of production, and subsidies remain insignificant, suggesting that financial incentives alone do not effectively drive change in these intensive systems. For dual-purpose farms, however, both subsidies and extension services have significant benefits, reflecting the alignment of financial and technical support in facilitating integrated management practices that balance the demands of beef and dairy production. Finally, for mixed farms, the positive effect of both subsidies and extension services highlights their combined role in supporting diversified production systems, enabling investments in feeding systems, and sustainable management strategies.

The results reveal notable differences in sustainability outcomes linked to sociodemographic factors, reflecting broader structural and cultural dynamics in Mexico. Gender plays a significant role, particularly in smaller operations, where male farmers are better positioned to adopt sustainable practices because of their greater access to land and financial resources. In rural Mexico, historical and cultural norms often limit women's participation in landownership and decisionmaking, and their responsibilities for household and farm work constrain their ability to focus on implementing sustainability-driven efforts. In medium and large farms, however, gender-driven disparities do not have a significant effect on sustainability. These operations are often run as formal businesses, where women may hold managerial or co-ownership positions.

Education shows a consistently positive and significant effect on sustainability across most farm sizes and types. In medium and large farms, educated farmers are more likely to perceive sustainability as a long-term investment and have the financial literacy needed to access loans and adopt advanced practices. This relationship is particularly strong in dual-purpose systems, where managing the complexities of both beef and dairy production requires higher levels of technical knowledge. Small farms are the exception here: education is negative and significant because limited formal schooling and financial constraints often lead farmers to rely on traditional low-intensity methods. This highlights the structural barriers that small farmers face in relying on education to achieve sustainability.

Age is typically negatively correlated with sustainability, since older farmers tend to be more reluctant to adopt new farming practices. This effect is particularly significant for small farmers, where the lack of formal education may reinforce resistance to change, and for large farmers, who are more likely to maintain traditional management practices. In contrast, younger farmers, especially those with environmental concerns, are more inclined to make improvements to their farms and adopt sustainable practices that align with market demands. Finally, although the results show no significant effect of Indigenous identity on sustainability overall, the negative effect observed in dual-purpose systems highlights the resource pressures associated with shared ejidal lands, which are often linked to Indigenous communities. Table A5 in the Appendix shows the results by size and type using the linear panel model; overall, the results are consistent.

Table 1. **Parameter estimates based on ESI: Panel fractional regression (size and type)**

Variable	Small	Medium	Large	Beef	Dairy	Dual-purpose	Mixed
area_grazing	-0.00209*	4.61e-05	-0.000784***	-0.000367***	-0.0174***	-0.00245***	-4.88e-05
	(0.00125)	(0.000300)	(0.000179)	(0.000116)	(0.00378)	(0.000692)	(0.000133)
ejidal_p	-0.0677***	-0.0567*	0.00680	-0.0264	-0.00377	-0.111***	-0.0417
	(0.0222)	(0.0312)	(0.0414)	(0.0184)	(0.0234)	(0.0282)	(0.0265)
communal_p	-0.0107	-0.120**	0.150**	-4.76e-06	-0.0509	0.0995*	-0.0445
	(0.0222)	(0.0562)	(0.0616)	(0.0392)	(0.0482)	(0.0578)	(0.0386)
farms_insurance_p	-0.156	-0.559***	-0.140	-0.00394	-0.242**	0.205*	-0.0852
	(0.124)	(0.118)	(0.117)	(0.112)	(0.101)	(0.111)	(0.169)
farms_credit_p	0.240***	0.113	0.0855	0.116**	0.0537	0.126**	0.140*
	(0.0819)	(0.0930)	(0.0750)	(0.0585)	(0.0648)	(0.0621)	(0.0743)
farms_subsid_p	0.0842***	-0.0410	0.0971***	0.0302	-0.0144	0.101***	0.0573**
	(0.0183)	(0.0341)	(0.0367)	(0.0242)	(0.0274)	(0.0308)	(0.0265)
farms_exten_p	0.602**	0.298***	0.233***	0.619***	0.407***	0.401***	0.529***
	(0.248)	(0.0520)	(0.0479)	(0.0583)	(0.0491)	(0.0645)	(0.0535)
farmers_educ	-0.00785**	0.0188***	0.00647**	0.0185***	0.0162***	0.0227***	0.0165***
	(0.00346)	(0.00378)	(0.00326)	(0.00321)	(0.00342)	(0.00281)	(0.00369)
farmers_male_p	0.139***	0.0420	-0.0116	-0.00181	-0.0251	0.0787	0.104**
	(0.0506)	(0.0700)	(0.0614)	(0.0432)	(0.0417)	(0.0603)	(0.0501)
farmers_indigenous_p	-0.00379	-0.0210	-0.0298	0.0112	-0.0222	-0.166***	0.00832
	(0.0374)	(0.0838)	(0.0818)	(0.0496)	(0.0583)	(0.0546)	(0.0560)
farmers_age	-0.00442***	0.000518	-0.00465***	-0.00173	0.000106	-0.000230	-0.00241
	(0.00132)	(0.00148)	(0.00135)	(0.00110)	(0.000981)	(0.00134)	(0.00147)
Constant	0.0773	-0.217*	0.260**	-0.458***	-0.0578	-0.590**	-0.0973
	(0.0909)	(0.119)	(0.107)	(0.0816)	(0.0780)	(0.237)	(0.107)
Observations	4,880	4,486	2,823	4,543	3,161	3,712	4,705
Year FE	YES	YES	YES	YES	YES	YES	YES
Mun FE	YES	YES	YES	YES	YES	YES	YES
State X Year FE	YES	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses*** p<0.01, ** p<0.05, * p<0.1
Note: Dependent variable is the corresponding ESI.

To verify the robustness of our results, we tested the ranking order of sustainability under three sensitivity scenarios, which vary the order of one management practice from the previous scenario, as shown in Table A2.

Sensitivity 1: Paddock rotation ranks higher than controlled grazing. This adjustment is justified because paddock rotation promotes frequent livestock movement, ensuring more uniform manure distribution, better nutrient cycling, and improved water retention. In contrast, controlled grazing may allow longer grazing periods in each section, potentially leading to localized degradation if not properly managed. Thus, paddock rotation can offer superior pasture recovery and land efficiency, making it a more sustainable option.

Sensitivity 2: Semiconfined management ranks higher than confined systems. Although both systems involve limited grazing areas, semiconfined systems provide outdoor access, reducing the risks associated with manure accumulation, water contamination, and air pollution found in fully confined systems. Additionally, semiconfined systems allow livestock to graze naturally, which can contribute to better pasture utilization and animal welfare, aligning better with sustainability goals.

Sensitivity 3: Confined systems rank as the least sustainable. This shift reflects the fact that confined systems require intensive resource management for waste disposal, feed sourcing, and emissions control. Unlike free grazing and semiconfined systems, confined systems fully depend on external feed inputs and create high concentrations of waste, leading to greater environmental risks if manure management is inadequate.

The sensitivity analysis highlights the importance of contextualizing sustainability rankings based on factors such as nutrient cycling, manure management, feed dependency, and land-use efficiency, ensuring that sustainability assessments account for practical variations in grazing system performance. Table A6 in the Appendix shows the results of the sensitivity analysis. We find that our main results are consistent under different sustainability criteria. Thus, the outcomes of this paper can make an important contribution by generating actionable evidence of policies and programs that may promote sustainable cattle practices. Because livestock farming is vital to rural livelihoods and food security and also affects climate change, findings could have significant policy and practical implications for transitioning toward environmental sustainability across Mexico's cattle sector.

4.5 Conclusion

This study examines the barriers to adopting sustainable grazing practices in Mexico, using a municipal-level data set constructed from farm-level data in the 2007 and 2022 agricultural censuses. From this data set, we develop an environmental sustainability index to assess the adoption of sustainable grazing practices. Using a fractional panel regression model, we analyze the influence of structural, financial, and sociodemographic factors on sustainability outcomes. Our findings shed light on the complex challenges surrounding sustainability in livestock production.

The results show that municipalities with larger grazing areas are more likely to have unsustainable practices, reflecting the resource pressures associated with extensive grazing systems. Land tenure regimes also present significant structural barriers; ejidal lands exhibit lower sustainability compared with private or communal lands, highlighting governance challenges and inefficiencies in common-pool resource management. Conversely, access to financial and technical support, such as credit, subsidies, and extension services, significantly improves sustainability by enabling farmers to adopt advanced practices and invest in sustainable infrastructure. However, agricultural insurance has a negative association with sustainability, likely because of the moral hazard: financial safety nets reduce incentives to adopt sustainable practices.

Analysis of heterogeneity across farm sizes and types reveals nuanced dynamics. Small farms benefit disproportionately from extension services and subsidies, reflecting their reliance on external support to overcome resource and knowledge constraints. Medium-sized farms primarily benefit from technical support, since financial limitations and lack of economies of scale hinder substantial investments in sustainability. For large farms, both subsidies and extension services facilitate the adoption of advanced technologies, emphasizing the importance of integrated financial and technical support. Across farm types, dual-purpose and mixed farms show the most significant gains from government support, reflecting their ability to balance resource-intensive demands with sustainable management practices. Additionally, education consistently enhances sustainability, particularly for medium and large farms, and younger farmers demonstrate greater adaptability to sustainable practices, likely driven by environmental awareness and market opportunities.

Policy recommendations include strengthening governance structures for ejidal lands to address the management challenges of common-pool resources and improve coordination among land users. Expanding access to credit and extension services is crucial, since these resources significantly improve sustainability across all farm sizes and types by facilitating investments in advanced practices and giving farmers essential technical knowledge. However, access remains limited, with only 4% of farms currently benefiting from extension services. Designing tailored programs that cater to the specific needs of small, medium, and large farms is also important to ensure equitable access to support mechanisms and effective adoption of sustainable practices. These recommendations could be incorporated into policy by modifying the operating rules of PROGAN, the Mexican government's primary initiative for enhancing livestock productivity, to better align its objectives with sustainability goals.

Future research should explore the long-term benefits of these interventions, particularly their effectiveness in promoting better grazing practices and improving environmental outcomes over time. Additionally, investigating the role of market-based incentives, such as carbon credits, certification schemes, or sustainability-linked subsidies, could offer valuable insights into how economic mechanisms might further encourage the adoption of sustainable practices.

Acknowledgments

This research was funded by the Inter-American Development Bank through the Sustainable Cattle Production Technologies in LAC project. We are grateful to Samanta Pacheco Morales for helping with the data cleaning and literature search. We would like to thank the Scientific Committee at the IADB for helpful comments and suggestions. We are also indebted to participants in the 2025 AERE, EAERE and AAEA congresses for their feedback on earlier versions of this manuscript. This project would not have been possible without the support of the National Institute of Statistics and Geography (INEGI), which provided access to agricultural census microdata.

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Appendix

Table A1. Table A1. Mexico: Distribution of farming practices, by state

State	Percentage of total farms in the state						Farms (thousands)	Head (thousands)
	Free grazing	Controlled grazing	Confined	Semi-confined	Balanced feed	Paddock rotation		
Aguascalientes	37.6	12.7	28.1	16.2	34.8	22.1	7.4	273.6
Baja California	46.9	10.9	20.7	10.3	36.8	23.3	1.5	259.2
Baja California Sur	78.4	4.3	4.7	8.1	60.2	11.8	2.9	122.7
Campeche	66.0	28.3	6.3	9.4	12.7	40.3	17.2	572.4
Coahuila	59.3	8.6	8.7	6.2	25.2	17.0	8.8	621.2
Colima	63.3	20.9	7.1	4.5	32.8	46.7	4.7	124.7
Chiapas	44.4	12.9	3.1	5.9	9.9	35.4	93.5	1,614.5
Chihuahua	63.6	10.7	11.9	8.3	45.4	36.8	34.8	1,742.5
Ciudad de México	5.3	4.2	11.1	5.3	16.8	5.6	0.7	6.4
Durango	63.6	10.7	10.1	10.1	37.4	35.1	34.4	1,576.3
Guanajuato	23.6	6.5	14.1	6.6	19.2	10.7	35.3	551.8
Guerrero	32.3	16.8	6.6	4.8	23.5	33.5	63.7	982.5
Hidalgo	17.9	4.3	8.6	4.0	11.7	14.6	35.7	352.1
Jalisco	60.7	20.5	21.7	18.3	38.7	37.8	57.0	2,116.0
México	9.3	3.5	5.8	2.9	12.4	6.9	58.1	413.6
Michoacán	37.1	8.7	6.7	5.5	27.3	30.4	50.8	1,238.9
Morelos	25.7	11.2	11.9	11.9	29.3	19.8	7.3	108.9
Nayarit	49.9	29.6	3.9	3.4	22.3	56.7	17.1	458.8
Nuevo León	54.3	11.2	7.8	5.3	20.9	23.6	11.4	541.1
Oaxaca	28.6	10.8	5.2	3.2	7.7	23.6	80.1	905.5
Puebla	13.7	3.2	7.9	2.9	10.0	7.3	41.6	369.0
Querétaro	24.9	5.6	9.2	6.0	16.5	15.0	10.6	326.9
Quintana Roo	56.1	23.2	4.4	14.9	13.8	36.6	3.7	86.2
San Luis Potosí	37.0	9.2	7.6	5.0	16.5	23.2	37.8	963.3
Sinaloa	50.8	21.2	5.6	10.1	40.2	49.2	20.4	938.3
Sonora	81.4	15.8	11.8	13.3	54.3	46.8	20.0	1,251.3
Tabasco	65.4	31.0	7.2	7.6	8.7	34.3	50.7	1,382.0
Tamaulipas	57.4	21.3	4.1	3.6	23.3	40.9	18.0	621.0
Tlaxcala	2.9	0.9	10.0	2.5	12.4	0.7	10.3	61.7
Veracruz	55.7	19.2	2.7	2.9	18.2	43.3	115.0	2,694.0
Yucatán	40.1	19.2	7.1	12.9	25.6	37.7	13.4	381.5
Zacatecas	55.4	7.3	9.4	6.1	19.8	31.3	38.5	895.7
Total	**42.9**	**13.6**	**7.7**	**6.3**	**20.6**	**30.0**	**1,002.7**	**24,553.6**

Source: Own elaboration based on INEGI (2022). Note: The figures represent the share of total farms implementing each practice in each state. Since farms may adopt multiple practices and the practices are not mutually exclusive, the totals per state exceed 100%.

Table A2. Environmental sustainability index: Practice-specific weights

Practice	Sustainability features	w_j	Sensitivity 1	Sensitivity 2	Sensitivity 3
Free grazing	Often leads to overgrazing, soil degradation, water contamination, and loss of vegetation cover. Concentration of livestock can harm soil health and local ecosystems (Billota et al., 2007; Prokopy et al., 2019).	-2	-2	-2	-1
Semiconfined	Offers some environmental benefits, such as reducing soil compaction and overgrazing, but manure concentration increases management challenges (Alvez et al., 2014).	-1	-1	0.5	-0.5
Confined	Concentration of manure often leads to air pollution (ammonia and methane) and water contamination. Requires significant resources to manage waste and mitigate environmental effects (Borhan et al., 2012).	-0.5	-0.5	-0.5	-2
Paddock rotation	Promotes nutrient cycling, reduces overgrazing, and improves water retention in soils. Relatively sustainable option (Teague et al., 2013).	1	2	2	2
Controlled grazing	Rotation of livestock optimizes pasture use and allows time for regeneration. Improves soil health, reduces erosion, and enhances manure distribution, lowering pollution risks (Sanjari et al., 2009).	2	1	1	1
Balanced feed	Improves animal nutrition and reduces methane emissions and manure waste. Promotes efficient feed conversion, reducing environmental harms of livestock farming, such as pollution from nutrient overloading and methane emissions. Highly sustainable option (Garg et al., 2014).	3	3	3	3

Table A3. Summary statistics

Variable	Description	N	mean	sd	min	max
sust_index_0722	ESI 2007 and 2022	4,890	0.402	0.112	0.00	1.00
farms_grazing_p	Farms with free grazing (proportion)	4,890	0.320	0.266	0.00	1.00
farms_grazingc_p	Farms with controlled grazing (proportion)	4,890	0.095	0.116	0.00	0.87
farms_stabled_p	Farms with confined cattle (proportion)	4,890	0.077	0.105	0.00	1.00
farms_semi_p	Farms with semi-confined cattle (proportion)	4,890	0.058	0.075	0.00	1.00
farms_balfeed_p	Farms with balanced feed (proportion)	4,890	0.166	0.175	0.00	1.00
farms_padrot_p	Farms with paddock rotation (proportion)	4,890	0.171	0.196	0.00	0.92
area_grazing	Grazing area (1,000 hectares)	4,890	13.600	56.690	0.00	1078
ejidal_p	Ejidal farmland (proportion)	4,890	0.348	0.308	0.00	1.00
communal_p	Communal farmland (proportion)	4,890	0.170	0.322	0.00	1.00
private_p	Private farmland (proportion)	4,890	0.475	0.331	0.00	1.00
farms_insurance_p	Farms with insurance (proportion)	4,890	0.008	0.024	0.00	0.45
farms_credit_p	Farms with credit (proportion)	4,890	0.043	0.063	0.00	0.53
farms_subsid_p	Farms with subsidies (proportion)	4,890	0.408	0.225	0.00	1.00
farms_exten_p	Farms with extension services (proportion)	4,890	0.037	0.052	0.00	0.83
farmers_educ	Average years of farmers' education	4,890	5.060	2.201	0.00	17.0
farmers_male_p	Male farmers (proportion)	4,890	0.885	0.068	0.25	1.00
farmers_indigenous_p	Indigenous (proportion of farmers speaking a native language)	4,890	0.233	0.346	0.00	1.00
farmers_age	Average farmers' age	4,890	55.510	4.179	36.0	79.0

Source: Own elaboration based on INEGI (2007, 2022).

Table A4. **Parameter estimates based on ESI: Linear and fractional panel models**

Variable	Linear panel (Model 1)	Fractional panel (Model 2)
area_grazing	-0.000165***	-0.000655***
	(3.07e-05)	(0.000216)
ejidal_p	0.00338	-0.105***
	(0.00620)	(0.0298)
communal_p	-0.0151**	-0.0337
	(0.00679)	(0.0252)
farms_insurance_p	-0.357***	-1.012***
	(0.0713)	(0.160)
farms_credit_p	0.123***	0.238***
	(0.0320)	(0.0878)
farms_subsid_p	0.00390	0.0811***
	(0.00838)	(0.0237)
farms_exten_p	0.464***	0.979***
	(0.0382)	(0.0932)
farmers_educ	0.00737***	0.0193***
	(0.00132)	(0.00426)
farmers_male_p	0.0397*	0.152**
	(0.0241)	(0.0703)
farmers_indigenous_p	-0.0241***	0.0734
	(0.00566)	(0.0615)
farmers_age	-0.00107**	-0.000859
	(0.000462)	(0.00152)
Constant	0.441***	-0.107
	(0.0467)	(0.118)
Observations	4,890	4,890
Year FE	YES	YES
Mun FE	YES	YES
State X Year FE	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: Dependent variable is the ESI.

Table A5. Parameter estimates based on ESI: Linear panel model, by size and type

Variable	Small	Medium	Large	Beef	Dairy	Dual-purpose	Mixed
area_grazing	-0.000646	1.28e-05	-0.000281***	-0.000111*	-0.00620***	-0.000833**	-1.56e-05
	(0.000660)	(0.000146)	(9.60e-05)	(5.73e-05)	(0.00183)	(0.000343)	(6.48e-05)
ejidal_p	-0.0239**	-0.0196	0.00236	-0.0101	-0.00133	-0.0394***	-0.0139
	(0.0116)	(0.0161)	(0.0220)	(0.00919)	(0.0119)	(0.0143)	(0.0134)
communal_p	-0.00381	-0.0408	0.0539*	-0.00226	-0.0180	0.0359	-0.0164
	(0.0118)	(0.0280)	(0.0318)	(0.0190)	(0.0249)	(0.0294)	(0.0186)
farms_insurance_p	-0.0632	-0.204***	-0.0500	0.00485	-0.0861	0.0771	-0.0385
	(0.0622)	(0.0597)	(0.0629)	(0.0568)	(0.0530)	(0.0580)	(0.0733)
farms_credit_p	0.0910**	0.0416	0.0314	0.0420	0.0173	0.0442	0.0507
	(0.0425)	(0.0486)	(0.0389)	(0.0290)	(0.0333)	(0.0311)	(0.0375)
farms_subsid_p	0.0304***	-0.0158	0.0367*	0.0107	-0.00469	0.0368**	0.0187
	(0.00965)	(0.0171)	(0.0195)	(0.0119)	(0.0137)	(0.0155)	(0.0131)
farms_exten_p	0.229*	0.108***	0.0885***	0.228***	0.149***	0.150***	0.197***
	(0.135)	(0.0265)	(0.0251)	(0.0307)	(0.0257)	(0.0339)	(0.0275)
farmers_educ	-0.00256	0.00648***	0.00240	0.00668***	0.00578***	0.00818***	0.00587***
	(0.00179)	(0.00187)	(0.00173)	(0.00163)	(0.00174)	(0.00142)	(0.00184)
farmers_male_p	0.0497*	0.0128	-0.00545	-0.000807	-0.00876	0.0278	0.0356
	(0.0264)	(0.0350)	(0.0326)	(0.0211)	(0.0209)	(0.0300)	(0.0246)
farmers_indigenous_p	-0.000464	-0.00323	-0.0121	0.00290	-0.00757	-0.0580**	0.00353
	(0.0200)	(0.0412)	(0.0430)	(0.0248)	(0.0292)	(0.0268)	(0.0273)
farmers_age	-0.00160**	0.000196	-0.00172**	-0.000622	4.00e-05	-6.61e-05	-0.000841
	(0.000693)	(0.000739)	(0.000702)	(0.000549)	(0.000495)	(0.000675)	(0.000727)
Constant	0.431***	0.317***	0.510***	0.329***	0.342***	0.312***	0.330***
	(0.0431)	(0.0540)	(0.0537)	(0.0386)	(0.0380)	(0.0478)	(0.0495)
Observations	4,880	4,486	2,823	4,543	3,161	3,712	4,705
R-squared	0.243	0.176	0.158	0.294	0.232	0.171	0.159
Municipalities	2,461	2,335	1,588	2,426	1,881	2,152	2,445
Year FE	YES	YES	YES	YES	YES	YES	YES
Mun FE	YES	YES	YES	YES	YES	YES	YES
Edo X Year FE	YES	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: Dependent variable is the corresponding ESI.

Table A6. Sensitivity analysis

Variable	ESI 1		ESI 2		ESI 3	
	Panel	Fractional	Panel	Fractional	Panel	Fractional
area_grazing	-0.000239**	-0.000727***	-0.000209*	-0.000634***	-0.000195*	-0.000563**
	(0.000120)	(0.000233)	(0.000118)	(0.000227)	(0.000116)	(0.000224)
ejidal_p	-0.0398**	-0.107***	-0.0334**	-0.0883***	-0.0400**	-0.112***
	(0.0157)	(0.0298)	(0.0155)	(0.0294)	(0.0162)	(0.0320)
communal_p	-0.00948	-0.0251	-0.0126	-0.0331	-0.00863	-0.0242
	(0.0124)	(0.0236)	(0.0119)	(0.0226)	(0.0124)	(0.0260)
farms_insurance_p	-0.404***	-1.127***	-0.394***	-1.104***	-0.392***	-1.109***
	(0.0895)	(0.170)	(0.100)	(0.191)	(0.0927)	(0.180)
farms_credit_p	0.0628	0.175**	0.0599	0.165**	0.0547	0.160**
	(0.0432)	(0.0812)	(0.0443)	(0.0828)	(0.0396)	(0.0779)
farms_subsid_p	0.0453***	0.125***	0.0387***	0.106***	0.0458***	0.129***
	(0.0123)	(0.0235)	(0.0126)	(0.0240)	(0.0121)	(0.0243)
farms_exten_p	0.450***	1.193***	0.470***	1.248***	0.469***	1.235***
	(0.0491)	(0.0931)	(0.0512)	(0.0967)	(0.0508)	(0.0988)
farmers_educ	0.0156***	0.0413***	0.0111***	0.0294***	0.0204***	0.0584***
	(0.00227)	(0.00433)	(0.00231)	(0.00438)	(0.00232)	(0.00461)
farmers_male_p	0.0510	0.141**	0.0550	0.147*	0.0648*	0.188**
	(0.0376)	(0.0715)	(0.0423)	(0.0800)	(0.0364)	(0.0731)
farmers_indigenous_p	0.0386	0.0990*	0.0231	0.0578	0.0345	0.0924*
	(0.0310)	(0.0591)	(0.0312)	(0.0594)	(0.0261)	(0.0527)
farmers_age	-4.10e-05	-0.000103	-0.000370	-0.000878	0.00106	0.00290*
	(0.000766)	(0.00145)	(0.000775)	(0.00146)	(0.000756)	(0.00151)
Constant	0.263***	-0.273**	0.309***	-0.112	0.112**	-0.853***
	(0.0579)	(0.115)	(0.0614)	(0.121)	(0.0568)	(0.117)
Observations	4,890	4,890	4,890	4,890	4,890	4,890
Municpalities	2,464		2,464		0.464	
Year FE	YES	YES	YES	YES	2,464	
Mun FE	YES	YES	YES	YES	YES	YES
Edo X Year FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

5

SUSTAINABLE LIVESTOCK DECISIONS IN A POST-CONFLICT FRONTIER: EVIDENCE FROM COLOMBIA'S ORINOQUÍA

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Abstract

The Orinoquia region, Colombia's last agricultural frontier, presents both opportunities and challenges for sustainable cattle production. Efforts to promote sustainable cattle production emphasize improved pasture management and ecologically appropriate stocking rates, yet adoption varies widely because of institutional, economic, and biophysical constraints. This study applies a dual binary choice modeling framework to examine two related decisions: adoption of sustainable pasture management and maintenance of sustainable stocking rates. Our approach allows for both sequential and independent estimation to assess whether these decisions are interconnected or driven by distinct factors. Results highlight the central role of tenure security: landownership significantly increases the likelihood of adopting sustainable practices. Institutional support—particularly technical assistance and technology use—also fosters adoption, though effects vary by context. Older, more experienced farmers are less likely to adopt, suggesting path dependency. For stocking rate decisions, rotational and alternating grazing systems are linked to lower probabilities of maintaining sustainable rates, likely reflecting implementation complexity and resource constraints. Larger finishing areas correlate with less sustainable outcomes, potentially because of inefficiencies in understocked systems that risk land degradation or deforestation. These findings are robust across specifications and provide actionable insights for designing targeted, context-sensitive interventions to promote sustainable cattle production in Colombia's Orinoquia and can inform more tailored policy interventions for frontier livestock regions.

Introduction

Livestock systems are among the largest contributors to global greenhouse gas (GHG) emissions, primarily through enteric fermentation, manure management, and land-use change. In 2018, livestock-related emissions totaled approximately 3.5 billion tonnes of CO_2 equivalent—accounting for 67% of all emissions from the agricultural sector and reflecting a 15% increase since 1990 (FAO, 2020). Addressing this footprint is a global priority. Mitigation strategies such as improved pasture management, crop-livestock-tree integration, and advances in animal nutrition can reduce emissions while enhancing carbon sequestration, reducing deforestation, and supporting sustainable intensification. The livestock sector alone could contribute up to 50% of the total mitigation potential in agriculture, forestry, and other land uses (AFOLU) (Nugrahaeningtyas et al., 2024).

Technological solutions are essential but insufficient: adoption depends on producers' incentives, capabilities, and the broader institutional environment. Practices such as rotational grazing and pasture rehabilitation yield environmental benefits, but their payoffs are often gradual, requiring upfront investments or temporary productivity trade-offs (Bahrami et al., 2025). Under liquidity constraints, insecure land rights, or short planning horizons, perceived returns to sustainability can appear limited—even when interventions are well designed (Bahrami et al., 2025; McConnell, 1983).

Latin America faces unique challenges in promoting sustainable transitions in agri-food systems. As a major exporter of beef, soy, and sugar, the region is deeply embedded in global value chains yet marked by structural inequality, informality, and repeated exposure to socio-environmental shocks (López-Roldán and Fachelli, 2021; Barrett et al., 2019). Many producers lack access to credit, technical assistance, or infrastructure and therefore have limited capacity to meet emerging sustainability standards or adapt to global disruptions (Lopez Barrera et al., 2022; Dumortier et al., 2024). These constraints are compounded by persistent land concentration, institutional fragmentation, and legacies of conflict that weaken the state's ability to steer inclusive development (Lopez Barrera, 2025).

Land tenure security is a major determinant of long-term investment. Secure tenure—whether formal or customary—is consistently associated with higher adoption of conservation practices, especially those with delayed payoffs (Lawry et al., 2017; Ali et al., 2022). Insecure tenure shortens planning horizons and discourages land improvements, particularly where displacement or contested ownership remains a risk. These dynamics are acute in Colombia's Orinoquia, a postconflict frontier with weak land governance, informal tenure, and active territorial disputes. Patterns of accumulation by dispossession—through displacement, land registry manipulation, and the use of ranching as territorial control—have marginalized smallholders and constrained access to credit and support (Triana-Ángel et al., 2025; Richani, 2013; Giraldo Mejía, 2019). Despite the 2016 Peace Accord with the FARC, successor armed groups and ongoing land restitution disputes perpetuate uncertainty (Restrepo et al., 2006; Rivera-Lozada et al., 2025).

This study examines how institutional, environmental, and managerial constraints shape the adoption of sustainable pasture management and ecologically appropriate stocking rate decisions among cattle producers in the Orinoquia. It contributes to the literature on how tenure security, agroecological conditions, and institutional support influence sustainability transitions in contexts of informality, weak governance, and conflict. Using a dual binary choice model applied to farm-level survey data merged with spatial indicators, we analyze how constraints shape distinct but complementary outcomes and draw policy-relevant lessons for promoting sustainable livestock development in Latin America and beyond.

The remainder of the paper is organized as follows:

- **Section 5.1**. Background
- **Section 5.2** Materials and Methods
- **Section 5.3**. Data
- **Sections 5.4** Results
- **Section 5.5** Discussion and Limitations
- **Section 5.6**. Conclusions

5.1 Background

Cattle production is a traditional and economically significant sector in Colombia, occupying 39 million hectares and contributing 1.7% to Colombia's gross domestic product (GDP), 20.2% to agricultural GDP, and 51.5% to livestock GDP. It supports 1.1 million jobs and generates 11 billion pesos annually (Sandoval et al., 2023; Campuzano et al., 2022; Becking et al., 2021; Fedegán, 2024). With a herd of 29.2 million head—ranking fourth in Latin America and 11th globally—the country has seen a 22.3% increase in inventory over the past eight years (González-Quintero et al., 2022; Durana et al., 2023; ICA, 2024). Yet the sector remains largely extensive and low in productivity, with an average stocking rate of 0.7 animal/ha and daily weight gain of 0.445 kg—well below Brazil's 1.22 animals/ha and 0.482 kg/day (Fedegán, 2023; ABIEC, 2024; Oliveira et al., 2018). Nearly 80% of Colombian farms have fewer than 50 animals, causing inefficiencies and posing environmental and economic challenges.

The Orinoquia region—comprising Arauca, Casanare, Meta, and Vichada—is critical for cattle production, holding 21.4% of the national herd (6.2 million head across 51,669 farms) on 24.68 million hectares, 19.8% of which is suitable for livestock (UPRA, 2016; ICA, 2024). Production systems range from cow-calf to dual-purpose (Fargetton et al., 2017), but development is constrained by poor infrastructure, limited access to credit, and limited financial resources, as well as a legacy of armed conflict (López-Barrera et al., 2022). Land tenure is a central barrier. Although peace processes and reforms spurred some agricultural expansion, only 4% of the 5.19 million hectares deemed suitable for agriculture in the Altillanura subregion is under cultivation (UPRA, 2016; Fontanilla-Díaz et al., 2021). In Meta, just 16% of plots have formal titles, and an estimated 73% of productive land lacks clear documentation (Bonilla-Mejía et al., 2024). Insecure tenure discourages investment and adoption of sustainable practices. Recent evidence shows that untitled land is more vulnerable to deforestation and land grabbing, whereas titled plots—especially those with institutional support—reduce forest loss (Clerici et al., 2020).

Cattle systems in the region also pose major environmental concerns. Between 2009 and 2018, AFOLU emissions rose notably after 2015, coinciding with the peace process (Biocarbono, 2024; Triana-Ángel et al., 2025). In 2018, livestock contributed 27% of AFOLU emissions, mostly from Meta and Casanare. Emissions intensities are high: 29.37 kg CO_2-eq/kg live weight compared with 23 in Argentina and 22.1 in Uruguay, and 3.67 kg CO_2-eq/kg fat- and protein-corrected milk compared with a global average of 2.8 (Biocarbono, 2024; FAO and NZAGRC, 2017; INAC, 2024; Opio et al., 2013). These levels underscore the urgency of mitigation.
Sustainable intensification—via rotational grazing or feed supplementation—could reduce emissions by 35% to 44% while boosting productivity (Souza et al., 2021; Mestra et al., 2019). Yet economic and behavioral constraints hinder adoption. High input costs, limited credit, and market volatility deter investment (Parodi et al., 2022; Tapasco et al., 2019). Only 30% of producers receive technical assistance, and 85% cite lack of knowledge as a major barrier. Although only 23% report resistance to change, behavioral inertia—especially among experienced producers—suggests risk aversion. These constraints are often compounded by insecure tenure, which weakens incentives for long-term management practices such as rotational grazing and pasture improvement.

Among the various sustainability behaviors in the region, two stand out as both empirically observable and policy relevant: adoption of sustainable pasture management and adjustment of stocking rates. Though conceptually linked, these practices differ in complexity, cost, and institutional exposure. Rotational grazing, for instance, requires infrastructure and labor changes, which are often a prerequisite for adjusting herd size. In contrast, stocking rate changes may respond to short-term pressures like forage availability or rainfall shocks but risk pasture degradation without foundational improvements. Understanding how these decisions are shaped by environmental, institutional, and economic factors is one key to advancing sustainable cattle systems.

We examine both practices using an empirical framework that tests whether they are adopted sequentially or independently and whether their drivers differ in policy-relevant ways. This approach offers insights into how tenure, environmental constraints, and institutional support influence sustainability transitions in Colombia's livestock sector.

5.2 Materials and Methods

5.2.1 Insights from Survey Used to Guide Empirical Strategy

To inform our empirical strategy, we conducted a perception-based survey with 70 cattle farmers across the Piedemonte, Altillanura, and Sabana Inundable subregions. The survey identified behavioral, institutional, financial, and environmental constraints affecting the adoption of sustainable grazing practices, including regional disparities, tenure insecurity, resistance to change, and limited access to technical assistance. These insights helped shape our model structure and variable selection, particularly regarding the potential sequencing between pasture management and stocking rate decisions. Detailed results of the prescreening survey are provided in Supplementary Materials, Section 4.1.

5.2.2 Econometric Model and Estimation

Sustainable pasture management—particularly rotational grazing—is widely recognized as a foundational intervention for both climate change mitigation and adaptation in cattle systems (Souza et al., 2021; Rincón et al., 2018). In contrast to continuous grazing, rotational systems enhance pasture recovery, increase forage quality and biomass, and improve soil organic carbon stocks, which collectively reduce enteric methane emissions per kilogram of beef produced (Mestra et al., 2019; Biocarbono, 2024; Rincón et al., 2025). These improvements also increase resilience to climatic shocks, such as droughts and heavy rainfall, through better soil structure and water retention capacity (Rincón et al., 2018).

The second decision relates to stocking rate—defined as the number of animals per hectare of pasture—a central indicator of grazing intensity, productivity, and environmental sustainability. In extensive production systems such as those in the Orinoquia region, optimal stocking rates are crucial to avoid both underutilization and overexploitation. Low stocking rates may indicate inefficient land use, leading to economic underperformance; high stocking densities can degrade soil quality, damage pasture regrowth, increase GHG emissions per unit of output, and intensify deforestation pressures because of the need for additional grazing land (Fedegán, 2023; Molina Romero et al., 2021). A sustainable stocking rate thus lies in a "sweet spot" that balances animal load with the regenerative capacity of the pasture system, allowing for increased productivity while safeguarding long-term ecosystem services.

Our empirical approach is informed by both agronomic rationale and behavioral insights gathered from a perception survey with regional producers. These insights indicated that many farmers perceive improved pasture conditions—particularly through rotational grazing—as a prerequisite for adjusting herd size. In low-input systems, forage availability is often the main constraint on herd expansion, meaning that without pasture improvement, higher stocking rates would lead to land degradation rather than sustainable intensification (Lopez-Barrera et al., 2022; Tapasco et al., 2019).

This conditional logic motivates us to examine the potential existence of a two-stage binary choice framework, in which the first stage models the adoption of sustainable pasture management, and the second stage estimates the decision to maintain a sustainable stocking rate, potentially conditional on the first. At the same time, we do not take this sequencing as an immutable structure. Rather, we explicitly test the interdependence between these behaviors through bivariate and selection models. To formally evaluate whether the two decisions are statistically interdependent, we estimate a bivariate probit model and test for correlation in the error terms. The result — the interdependence coefficient was not statistically significant ($p = 0.8289$) — suggests that unobserved factors do not jointly influence both decisions. Based on this evidence, we ultimately adopt a dual modeling strategy: we present a sequential two-stage model to reflect the behavioral logic suggested by producers and theory, and an independent binary choice specification to account for the lack of significant statistical interdependence. Control variables include farm characteristics, grazing systems, financial constraints, and access to technical support—as well as tenure-related indicators—to reflect the role of institutional uncertainty in shaping sustainability decisions, in line with established frameworks for modeling farmers' decisionmaking under uncertainty (Feder et al., 1985; Deressa et al., 2009).

5.2.2.1 Modeling Farmers' Decisions on Sustainable Livestock Practices

Farmers' decisionmaking regarding sustainable pasture management and stocking rate may follow either a sequential or an independent structure. To account for both possibilities, we estimate alternative econometric models. The first decision concerns the type of pasture management—classified as either extensive or nonextensive—and the second pertains to the stocking rate. Based on empirical and environmental criteria (Fedegán, 2023; Molina Romero et al., 2021), we categorize stocking rates below one or above four animals per hectare as nonsustainable, and those between one and four as sustainable. This range reflects a balance between resource use efficiency and pasture regenerative capacity.

Existing literature and field evidence in the Orinoquia region emphasize that sustainable pasture management, such as rotational grazing, improves forage quality and availability, which is often a precondition for adjusting stocking rates in low-input systems (Rincón et al., 2018; López-Barrera et al., 2022; Rincón et al., 2025). In parallel, institutional constraints, particularly land tenure insecurity, can shape the willingness and capacity of producers to adopt long-term management strategies, influencing both pasture and herd-level decisions. Given that tenure affects the perceived stability of land access, it may play a role in both the adoption of sustainable pasture practices and the calibration of stocking rates, albeit with varying degrees of influence.

However, because it is unclear whether these decisions are made sequentially or independently, we estimate both two-stage and separate binary choice models to identify the factors associated with each adoption decision (see Section 3.2.4 for details). This dual approach enables us to test whether distinct behavioral and structural factors—including tenure-related risks—operate differently across the two dimensions of sustainability.

5.2.2.2 Adoption of Sustainable Pasture Management

Sustainable pasture management refers to rotational or improved grazing systems that apply adequate stocking rates, allow appropriate rest and occupation periods, and avoid overgrazing. These practices improve pasture quality and availability, increase beef productivity per hectare, and contribute to climate change mitigation by enhancing soil carbon sequestration and reducing enteric methane emissions (Rincón et al., 2025).

We model the decision to adopt sustainable pasture management as a binary outcome. Specifically, we define a latent variable, W_n^*, which captures the unobserved propensity of farmer n to adopt these practices:

$$W_n^* = \gamma_1 z_n^{institutional} + \gamma_2 z_n^{economic} + \gamma_3 z_n^{structural} + \gamma_4 z_n^{sociodemographic} + \gamma_5 z_n^{environmental} + \epsilon_n$$

where W_n^* is a latent variable representing the farmer's unobserved propensity to adopt sustainable pasture management. The terms $z_n^{institutional}$, $z_n^{economic}$, $z_n^{structural}$, $z_n^{sociodemographic}$, and $z_n^{environmental}$ represent the institutional, economic, structural, sociodemographic, and environmental factors influencing the decision, including land tenure security, which is hypothesized to play a critical role in shaping long-term investment decisions. The coefficients γ_1, γ_2, γ_3, γ_4, and γ_5 capture the relative importance of these factors, and ϵ_n is a random error term following a logistic distribution. Since W_n^* is not directly observed, we estimate the binary outcome W_n as

$$W_n = \begin{cases} 1, \text{ if } W_n^* > 0 \ (\textit{farmer adopts sustainable pasture managment practices}) \\ 0, \quad \textit{otherwise} \end{cases}$$

The probability of adoption is estimated using a logit model:

$$P(W_n = 1 \mid z_n^{institutional}, z_n^{economic}, z_n^{structural}, z_n^{sociodemographic}, z_n^{environmental}) = \frac{e^{\gamma 0} + \gamma^1 Z_n^{institutional} + \gamma_2 Z_n^{economic} + \gamma_3 Z_n^{structural} + \gamma_4 Z_n^{sociodemographic} + \gamma_5 Z_n^{environmental})}{1 + e^{\gamma 0} + ^{\gamma}{}_1 Z_n^{institutional} + \gamma_2 Z_n^{economic} + \gamma_3 Z_n^{structural} + \gamma_4 Z_n^{sociodemographic} + \gamma_5 Z_n^{environmental}}$$

5.2.3 Sustainable Stocking Rate Decision

We examine the decision to maintain a sustainable stocking rate, defined as having one to four animals per hectare. The decision is modeled as a binary outcome using a latent variable Y_n^*, which captures the unobserved propensity of farmer n to adopt a sustainable stocking rate.

Although agronomic studies suggest that improved pasture management practices—particularly rotational grazing—can enhance forage availability, soil health, and carrying capacity (Beck et al., 2020; Rapiya et al., 2025), we do not impose a strict sequential structure a priori. Instead, we assess whether sustainable stocking rates are empirically associated with sustainable pasture management adoption or determined independently. Poor pasture management may reduce forage biomass and increase degradation risk, whereas improved practices may create conditions that support sustainable stocking densities. This motivates testing both independent and sequential modeling specifications.

We estimate two alternative specifications. In the independent model, the stocking rate decision is modeled without reference to pasture management:

$$Y^{n*} = \beta_0 + \beta_1 X_n^{institutional} + \beta_2 X_n^{economic} + \beta_3 X_n^{structural} + \beta_4 X_n^{sociodemographic} + \beta_5 X^{nenvironmental} + \eta_n$$

In the sequential model, we include the pasture management decision Wn as an explanatory variable to assess its potential influence on the stocking rate outcome:

$$Y_n^* = \theta_0 + \theta_1 W_n + \theta_2 X_n^{institutional} + \theta_3 X^{neconomic} + \theta_4 X_n^{structural} + \theta_5 X^{nsociodemographic} + \theta_6 X_n^{environmental} + v_n$$

where Y_n^* is the latent variable representing the decision to maintain a sustainable stocking rate. Wn is included to capture the effect of sustainable pasture management on stocking rate choices, $X_n^{institutional}$, $X_n^{economic}$,X_$X_n^{structural}$, X_n^sociodemographic $X_n^{sociodemographic}$, and $X^{nenvironmental}$ are vectors of explanatory variables that include institutional, economic, structural, sociodemographic, and environmental factors influencing the decision. The parameters β_0 and θ_1 are the intercept terms, and $\beta_1, \beta_2, _{\beta 3}, \beta_4, \beta_5, \theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6$ are estimated coefficients that quantify the effects of explanatory variables on stocking rate choices. The random error terms η_n and v_n follow a logistic distribution. Since Y_n^* is unobserved, we estimate the binary outcome Y_n as

$$Y_n = \begin{cases} 1, \ if\ Y_n^* > 0 \ (farmer\ maintains\ a\ sustainable\ stocking\ rate) \\ 0, \qquad otherwise \end{cases}$$

The probability of maintaining a sustainable stocking rate is estimated for the independent specification as

$$P(Y_n=1|\ X_n^{institutional}, X_n^{economic}, X_n^{structural}, X_n^{sociodemographic}, _{Xn}^{environmental}) = \frac{e^{\beta}{}_0 + {}^{\beta}{}_1 X_n^{institutional} + \beta_2 X_n^{economic} + \beta_3 X_n^{structural} + \beta_4 X_n^{sociodemographic} + \beta_5 X_n^{environmental}}{1 + e^{\beta}{}_0 + {}^{\beta}{}_1 X_n^{institutional} + \beta_2 X_n^{economic} + \beta_3 X_n^{structural} + \beta_4 X_n^{sociodemographic} + \beta_5 X_n^{environmental}}$$

And the probability of maintaining a sustainable stocking rate is estimated for the sequential specification as

$$P(Y_n=1|\ W_n, X\_{}_n^{institutional},\ X_n^{economic}, X_n^{structural},\ X_n^{sociodemographic}, X_n^{environmental}) = \frac{e^{\theta}{}_0 + {}^{\theta}{}_1 W_n + \theta_2 X_n^{institutional} + \theta_3 X_n^{economic} + \theta_4 X_n^{structural} + \theta_5 X_n^{sociodemographic} + \theta_6 X_n^{environmental}}{1 + e\theta_0 + \theta_1 W_n + \theta_{2\ Xn}^{institutional} + \theta_3 X_n^{economic} + \theta_4 X_n^{structural} + \theta_5 X_n^{sociodemographic} + \theta_6 X_n^{environmental}}$$

5.2.3.1 Estimation Strategy: Testing Sequential and Independent Decisions with Regional Clustering

To analyze farmers' adoption behavior, we estimate two binary choice models corresponding to the adoption of sustainable pasture management and sustainable stocking rates. Rather than assuming a predetermined behavioral sequence, we test both sequential and independent decision structures, as motivated by agronomic reasoning, perception survey insights, and contextual constraints observed in the Colombian Orinoquia. This strategy allows us to examine whether the decision to maintain a sustainable stocking rate is conditioned on prior adoption of sustainable pasture management or whether both behaviors are shaped independently by a common set of constraints.

In the first model, we estimate the likelihood of adopting sustainable pasture management as a function of institutional, economic, structural, sociodemographic, and environmental variables, as detailed in Supplementary Table S12. Notably, land tenure security is treated as an important institutional factor, given its relevance for shaping long-term decisions and influencing the adoption of sustainable practices.

In the second model, we estimate the probability of maintaining a sustainable stocking rate using two alternative specifications. The independent model treats this decision in isolation, and the sequential model includes sustainable pasture management as an explanatory variable to test whether it conditions stocking rate behavior. Both specifications incorporate the same five thematic categories of covariates, alongside additional controls related to grazing system, management type, financial inputs, and productivity indicators.

All models are estimated using binary logit specifications via maximum likelihood estimation. To account for spatial dependence and potential intra-municipality correlation in unobserved shocks, standard errors are clustered at the municipality level, in alignment with the survey's sampling design. This approach avoids the overfitting risks of spatial fixed effects while preserving inference validity. Variance inflation factor (VIF) diagnostics confirm that multicollinearity is not a concern among the selected regressors (Supplementary Table S13).

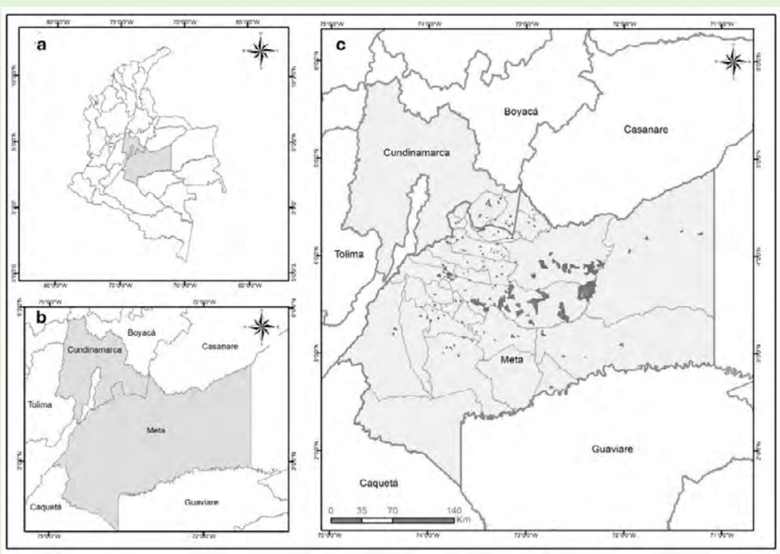
By allowing for multiple behavioral pathways and explicitly incorporating tenure-related institutional constraints, this estimation strategy provides a flexible and rigorous framework to uncover the drivers of sustainable practice adoption in the Colombian cattle sector.

5.3 Data

This study relies on two complementary data sources to analyze the decision-making of cattle farmers regarding the adoption of sustainable grazing practices. The core data set is derived from a structured farm-level survey conducted by AGROSAVIA across 23 municipalities in the departments of Meta and Cundinamarca, Colombia (Figure 1).

Sampling areas were defined based on the agricultural frontier (Figure S2), and the survey followed a stratified random sampling design consistent with methodologies from the National Administrative Department of Statistics (DANE, for its abbreviation in Spanish). A total of 327 farms were selected based on eligibility criteria, which included maintaining more than 10 weaned animals, reporting cattle sales between January 2016 and October 2017, and being engaged in finishing activities either exclusively or as part of a broader cattle production system. These criteria ensured comparability across units actively involved in the cattle fattening segment. Census and segmentations for the regions are detailed in Figures S3 and S4, and Figure S5 provides a geospatial reference of the San Martin area.

Figure 1. **Study area. Panel (a) highlights the departments of Meta and Cundinamarca in Colombia. Panel (b) provides a detailed view of the Meta department. Panel (c) displays the 21 municipalities in Meta and two in Cundinamarca included in the study, along with the 120 segments and clusters selected based on the National Agricultural Census (CNA) and the National Agricultural Survey (ENA). The polygons corresponding to the study area were georeferenced and visualized using ArcGIS 10.8.**



The survey includes a broad set of farm-level variables relevant to adoption and stocking rate decisions: herd characteristics, land use, grazing practices, input and labor use, production costs, and producer demographics (e.g., age, education, experience). Farms show wide heterogeneity in land size, herd composition, labor structure, and investment behavior. The average farm spans 237.8 hectares, with 22.4 hectares dedicated to finishing pastures; the remainder is typically natural forest and non-agricultural land. Cattle enter finishing at a mean age of 21.3 months and are slaughtered at 34.8 months, gaining weight from 270.7 kg to 452.4 kg. Rotational grazing is used by 75% of farms, and continuous and alternating systems by about 12% each. Differences in recordkeeping, digital tool use, and labor allocation further illustrate the diversity of production models.

To complement the survey, we integrate spatial and environmental variables from public macro data sets. Climate data—precipitation and average temperatures for 2016–2017—come from the CHIRPS satellite system, offering high-resolution insights into weather variability and long-term climate exposure. Soil data from Colombia's Agustín Codazzi geoportal include acidity, aluminum concentration, and terrain type—factors shaping pasture productivity and degradation risk. These environmental indicators are georeferenced to the municipalities and localities of the sampled farms, providing spatial context for estimating environmental constraints.

By combining the farm-level and environmental data sets (Supplementary Table S22), the empirical strategy examines how both management decisions and exogenous biophysical conditions shape adoption behavior. To account for spatially correlated decisionmaking, standard errors are clustered at the municipality level. Fixed effects were avoided because of limited within-municipality variation, which would absorb explanatory power. Clustering retains variation while correcting for spatial correlation (Cameron and Miller, 2015; Wooldridge, 2010).

5.3.1 Variables in the empirical estimations

Although the modeling framework is conceptually anchored in the distinction between adoption decisions and land-use intensity, we do not impose a sequential estimation structure a priori. Instead, we test whether the two decisions—adoption of sustainable pasture management practices and the maintenance of sustainable stocking rates—should be modeled jointly or independently. This is critical: although agronomic reasoning and farmers' narratives often suggest a progression from pasture management to stocking decisions, the actual behavioral interdependence may vary across contexts.

To empirically assess this, we estimated a bivariate probit model with both binary outcomes and examined the correlation coefficient (ρ) between the error terms. The estimate of ρ was approximately 0.29, based on the hyperbolic arctangent transformation (athrho) used in the estimation process. However, the corresponding Wald chi-squared test was not statistically significant ($\chi^2(1) = 0.08$; $p = 0.7734$), indicating no evidence of unobserved correlation between the two decisions. This result supports the hypothesis that farmers may approach these choices as distinct rather than structurally linked. Consequently, we proceed with separate estimations for each outcome using standard probit models. This approach accommodates differential explanatory pathways across the two outcomes and avoids potential efficiency losses or identification challenges associated with a misspecified joint model.

Previous diagnostics, such as the tetrachoric correlation (ρ = 0.27, p = 0.004), a reduced-form regression (p = 0.003), and a chi-squared test of independence (p = 0.003), suggested some degree of association between the observed outcomes. However, without statistically significant correlation in the underlying disturbances, the bivariate specification offers no clear advantage. We therefore interpret the decisions as empirically independent—while remaining theoretically connected—and analyze them in parallel. This structure offers both analytical flexibility and transparency in attributing effects to specific sets of covariates.

5.3.1.1 Factors Associated with Adoption of Sustainable Pasture Management

The first modeled decision concerns the adoption of sustainable pasture management practices. The dependent variable is a binary indicator equal to 1 if the farmer reports implementing actions such as rotational grazing, ground cover maintenance, or strategic paddock resting, and 0 otherwise. Classification is based on self-reports and observable management traits, with about 63% of farmers identified as adopters. This binary setup follows established livestock adoption literature (Knowler and Bradshaw, 2007; Kassie et al., 2013).

Among institutional variables, land tenure security stands out. A binary variable captures full landownership, a major enabler of long-term land investments. In the conflict-affected Colombian Orinoquia, secure tenure reduces risks linked to irreversible investments and is closely tied to conservation-oriented behavior. Prior work underscores the importance of tenure in contexts with institutional fragility and competing land claims (Clerici et al., 2020; Deininger and Feder, 2009).

Other institutional factors include access to technical assistance (defined as formal extension or training) and prior adoption of modern agricultural technologies (binary indicator). These reflect farmers' exposure to innovation networks and support systems under uncertainty.

Economic conditions are captured by the total value of productive farm assets and variable costs, which include expenditures on feed, veterinary inputs, and labor. These represent liquidity and asset endowments, aligning with prior findings on how financial constraints shape adoption (Latruffe and Nauges, 2014). Sociodemographic controls include age, gender, and a livestock experience ratio (share of life spent in cattle farming), capturing differences in knowledge, life stage, and risk tolerance (Genius et al., 2006). Structural variables describe agroecological and operational heterogeneity: production orientation (dairy, beef, dual-purpose), terrain type, soil acidity (pH), and aluminum saturation—physical conditions that shape the viability of sustainable pasture practices.

Environmental conditions are represented by georeferenced average temperature and rainfall (2016), capturing climate pressures relevant to pasture degradation. Supplementary Table S4 reports robustness checks using 2017 climate data. This multidimensional variable structure follows recent literature advocating for integrated institutional, economic, and environmental adoption models (Pannell et al., 2006; Kassie et al., 2013).

Models are estimated via maximum likelihood logit regressions. Standard errors are clustered at the municipality level to correct for intramunicipality error correlation, consistent with the stratified survey design. Variable definitions and coding details are available in Supplementary Tables S1–S2.

5.3.1.2 Factors Associated with Sustainable Stocking Rate

We estimate two model specifications to assess the determinants of sustainable stocking. The first includes adoption of sustainable pasture management as a covariate, testing for behavioral interdependence: resilient pasture systems may enable sustainable herd intensification. The second excludes pasture management, treating stocking as an independent decision potentially shaped by overlapping but distinct constraints. This dual-model strategy tests for interdependence without presupposing behavioral sequencing.

As in the pasture adoption model, land tenure security remains central. The institutional, sociodemographic, structural, environmental, and control variables are the same as in the pasture adoption model, with any differences noted below. Full landownership is included to reflect institutional security, which can influence stocking behavior through both investment capacity and risk attitudes. Producers with insecure land access may avoid herd adjustments because of uncertainty about the production base, aligning with broader findings on property rights and livestock intensification. Another institutional factor is access to technical assistance, defined as participation in formal extension or training. Such exposure may shape awareness of optimal stocking thresholds or adaptive responses to pasture conditions. Sociodemographic variables include producer age, gender, and livestock experience ratio—reflecting generational knowledge and risk preferences (Genius et al., 2006). Structural system characteristics—terrain type, soil pH, and aluminum saturation—reflect agroecological constraints on forage and carrying capacity. We also control for grazing system (continuous, alternating, rotational), management type (extensive, nonextensive), and production orientation (beef, dairy, dual-purpose), which influence stocking decisions and system performance (Rao et al., 2012). Environmental conditions are represented by georeferenced average temperature and rainfall in 2016, which shape biomass availability and seasonal forage cycles. Economic variables include variable costs (e.g., feed, labor, veterinary services) as a proxy for operating scale and intensity. We also include indicators of finishing efficiency (weight gain per finishing time) and finishing area size, capturing spatial and productivity constraints in herd management.

Models are estimated using maximum likelihood logit regressions. Standard errors are clustered at the municipality level to account for intracluster correlation and stratified survey design. This allows robust inference on whether sustainable stocking is shaped jointly or independently of pasture practices. By combining institutional, economic, biophysical, and behavioral factors, our approach provides a multidimensional understanding of the determinants of sustainable stocking decisions in the Colombian Orinoquia and similar frontier regions.

5.3.2 Data and Variable Description

The data set comprises 327 observations and a comprehensive set of variables to model adoption of sustainable pasture management and stocking rate decisions (Table 1). The first dependent variable is a binary indicator equal to 1 if the farmer reports adopting a suite of environmentally sustainable practices (mean = 0.63). The second, also binary, equals 1 if the farm maintains animal densities within a sustainable range (mean = 0.73), capturing both under- and overstocking relative to ecological benchmarks.

Table 1. **Summary Statistics Variables Used in the Models**

Constraint	Variable	Obs	Mean	Std. Dev	Min	Max
Dependent variables	sust. pasture mgment.	327	0.63	0.48	0	1
	stocking rate	327	0.73	0.44	0	1
Socio-demographic	age	327	55.29	12.79	21	91
	gender	327	0.83	0.38	0	1
	experience ratio	327	0.36	0.17	0.026	0.794
Institutional	land tenure	327	0.87	0.34	0	1
	technical assist.	327	4.98	0.97	1	6
	technology adopt.	327	0.08	0.27	0	1
Structural	terrain type	327	2.1	1.2	1	5
	soil acidity	327	2.58	0.76	1	3
	aluminum level	327	2.71	0.52	1	3
	grazing type	327	2.64	0.69	1	3
	mgment. type	327	1.9	0.45	1	4
	farm orientation	327	3.06	1.35	1	6
Environmental	avg. temp. 2016	327	23.82	3.76	16.91	29.38
	rainfall 2016	327	3275.62	359.92	1735.44	3840.29
Economic	variable costs	327	575997	563047	100429	5849225
	total resources	327	37400000	51600000	1495356	502000000
	finishing efficiency	327	191023	202643	14538	2003777
	finishing area	327	82.24	175.85	4	2000

Explanatory variables are grouped into five domains: sociodemographic, institutional, structural, environmental, and economic. Sociodemographic variables include farmer age (mean = 55.29, SD = 12.79), gender (83% male), and experience ratio (mean = 0.36, SD = 0.17), reflecting years in cattle relative to age. Land tenure is coded as a binary variable (1 = full ownership, 0 = all others). Though the original survey offered 10 tenure types (including rental, sharecropping, usufruct), the binary coding aligns with best practices (Lawry et al., 2017; Bonilla-Mejía et al., 2024) and enables a conservative test of tenure's role in sustainability adoption.

Institutional variables include access to technical assistance (mean = 4.98 on a 1–6 scale) and a binary variable for adoption of other technologies (mean = 0.08). Structural indicators cover terrain (mean = 2.10), soil acidity (2.58), aluminum toxicity (2.71), grazing system (2.64), management type (1.90), and farm orientation (3.06)—each measured on respective ordinal scales. Environmental variables include georeferenced 2016 temperature (mean = 23.82°C), rainfall (3,275.62 mm), and the above soil indicators. Economic conditions are captured via continuous measures: variable costs (mean = 575,997 COP; SD = 563,047), total farm resources (37.4 million COP; SD = 51.6 million), and two finishing-related indicators—finishing efficiency (mean = 191,023; SD = 202,643) and finishing area (82.24 ha; SD = 175.85).

This structure supports integrated modeling of adoption drivers. VIF diagnostics (Supplementary Table S13) indicate no multicollinearity concerns. Standard errors are clustered at the municipality level to correct for spatial correlation, avoiding fixed effects given limited within-municipality variation.

5.4 Results

This section presents empirical findings on sustainable pasture management and stocking rate decisions among cattle producers. The analysis proceeds in two parts. First, we test whether these decisions are conditionally dependent or independent. This flexible structure enables tailored specifications for each outcome and accommodates distinct constraints and enabling factors. Explanatory variables (sociodemographic, institutional, structural, environmental, and economic) allow us to assess the relative importance of each domain. To ensure robustness, we check for multicollinearity using VIFs and cluster standard errors at the municipality level to correct for spatial correlation across farmers in similar contexts. Fixed effects are not applied because of limited within-municipality variation, which would compromise model identifiability. Further robustness checks, including alternative specifications and variable definitions, are detailed in the Supplementary Materials, and Supplementary Table S12 provides definitions for each variable in Table 1.

5.4.1 Sustainable Pasture Management Decision

Table 2 reports marginal effects from a probit model estimating factors associated with the adoption of sustainable pasture management. The binary outcome equals 1 if the farmer reports using practices such as rotational grazing, paddock resting, or maintaining ground cover, and 0 otherwise. Land tenure is treated as a central institutional determinant, reflecting its hypothesized influence on time horizons and incentives for long-term land use. A binary indicator for full ownership (defined in Section 3.2.6) distinguishes owners from farmers with other tenure types. The remaining covariates follow those described in the pasture adoption model (Section 4.2), spanning sociodemographic, institutional, structural, environmental, and economic domains. Standard errors are clustered at the municipality level to address spatial autocorrelation, and multicollinearity is ruled out by low VIFs.

Table 2. **Marginal Effects of Factors Associated with Sustainable Pasture Management**

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
age	-0.00047	0.002	0.798	-0.004	0.003
gender	0.09850	0.079	0.212	-0.056	0.253
experience ratio	-0.20488	0.305	0.502	-0.803	0.393
land tenure	0.29156	0.058	0.000	0.178	0.405
technical assist.	-0.04440	0.021	0.037	-0.086	-0.003
technology adopt.	0.22543	0.109	0.039	0.011	0.440
terrain type	0.00216	0.037	0.953	-0.070	0.074
soil acidity	0.03418	0.051	0.506	-0.067	0.135
aluminum level	-0.38463	0.146	0.008	-0.670	-0.099
farm orientation	0.00670	0.016	0.669	-0.024	0.037
avg. temp. 2016	0.00624	0.031	0.840	-0.054	0.067
rainfall 2016	-0.00005	0.000	0.886	-0.001	0.001
variable costs	0.00000	0.000	0.332	0.000	0.000
total resources	0.00000	0.000	0.151	0.000	0.000
observations			327		

The marginal effects represent the change in predicted probability of adoption for a one-unit increase in each explanatory variable, holding others constant. Results are robust across alternative model specifications, including logit and bivariate probit. Although the analysis emphasizes statistically significant associations, our interpretations are cautious because of the cross-sectional design and potential endogeneity. No causal claims are made.

Land tenure shows the strongest positive association: owners are 29 percentage points more likely to adopt sustainable practices (dy/dx = 0.29, $p < 0.001$), consistent with established links between tenure security and long-term investment. This binary specification offers a conservative test, given the low frequency of alternative tenure arrangements.

Among environmental factors, aluminum saturation is significantly and negatively associated with adoption (dy/dx = –0.38, $p = 0.008$), suggesting that biophysical barriers may hinder uptake. Institutional variables are mixed: technology adoption is positively linked to adoption (dy/dx = 0.23, p = 0.039), but technical assistance shows a negative association (dy/dx = –0.04, p = 0.037). The latter may reflect unobserved heterogeneity or reverse causality in access to support services. Other covariates—demographic traits, structural features, climatic conditions, and economic indicators—do not show significant associations.

Overall, results indicate that land tenure, environmental constraints, and institutional factors significantly shape sustainable pasture adoption, with implications for designing targeted policy interventions. Associations are robust but noncausal, warranting further research on underlying mechanisms.

5.4.2 Sustainable Stocking Rate Decision

Table 3 presents marginal effects from a probit model estimating the determinants of sustainable stocking rate decisions. Two specifications are considered: one includes sustainable pasture management as a covariate to test for behavioral sequencing, while the other (reported in Supplementary Materials) treats stocking decisions independently. Results are consistent across both.

The binary outcome equals 1 if a farm meets the sustainable stocking threshold. Land tenure is treated as a central institutional determinant in this model, given its hypothesized influence on time horizons and incentives for long-term land use. A binary indicator for full ownership (defined in Section 3.2.6) distinguishes owners from farmers with other tenure types. All other covariates are as described in the pasture adoption model (Section 4.2). Standard errors are clustered at the municipality level to address spatial autocorrelation, and low VIF values confirm the absence of multicollinearity.

Standard errors are clustered at the municipality level to address spatial autocorrelation. Table 3 reports marginal effects, standard errors, p-values, and 95% confidence intervals, representing the change in predicted probability of sustainable stocking per one-unit increase in each covariate, holding others constant.

Table 3. **Marginal Effects of Factors Associated with Sustainable Stocking Rates**

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
sust. pasture mgment.	0.014	0.033	0.667	-0.050	0.078
age	0.001	0.001	0.523	-0.002	0.003
gender	0.034	0.037	0.345	-0.037	0.106
experience ratio	-0.220	0.099	0.026	-0.413	-0.026
land tenure	0.049	0.034	0.155	-0.018	0.116
technical assist.	0.010	0.026	0.710	-0.041	0.060
terrain type	0.022	0.027	0.415	-0.030	0.074
soil acidity	-0.074	0.033	0.025	-0.139	-0.009
aluminum level	0.043	0.062	0.491	-0.079	0.165
grazing type	-0.075	0.043	0.080	-0.158	0.009
mgment. type	0.018	0.038	0.643	-0.057	0.092
farm orientation	-0.020	0.014	0.153	-0.048	0.008
avg. temp. 2016	0.001	0.017	0.960	-0.033	0.035
rainfall 2016	0.000	0.000	0.075	0.000	0.000
variable costs	0.000	0.000	0.966	0.000	0.000
finishing efficiency	0.000	0.000	0.003	0.000	0.000
finishing area	-0.001	0.000	0.000	-0.002	-0.001
observations			327		

Results include a negative association between the experience ratio and sustainable stocking (dy/dx = –0.22, p = 0.026), suggesting that farmers with more experience may adhere to traditional, less sustainable herd densities. Soil acidity also shows a negative association (dy/dx = –0.074, p = 0.025), highlighting biophysical constraints on sustainable intensification. In contrast, finishing efficiency is positively associated with sustainable stocking (p = 0.003), but finishing area has a significant negative effect (p < 0.001), indicating that spatial limitations may encourage more intensive, more sustainable practices.

Land tenure shows a positive but statistically insignificant association (dy/dx = 0.049, p = 0.155). Though not conclusive, its consistent direction supports its relevance as a potential enabling factor. Sustainable pasture management, included as a covariate, is not statistically significant, suggesting that pasture and stocking decisions may be made independently.
Other variables—including demographic traits, terrain, climate, and costs—do not show statistically significant effects. Multicollinearity diagnostics (VIFs) confirm that linear dependence among regressors is not a concern.

Overall, findings indicate that biophysical constraints, efficiency measures, and farmers' characteristics shape stocking decisions. The absence of a statistically significant link to pasture management supports modeling the two behaviors separately. As with all cross-sectional studies, interpretations are correlational and not causal.

5.5 Discussion and Limitations

Among the cattle producers in our study, secure land tenure emerges as a consistent enabler of sustainability practices: landowning farmers are significantly more likely to adopt sustainable practices, aligning with the broader literature on the role of tenure in fostering long-term land stewardship. However, land rights alone are insufficient. Environmental constraints—particularly high aluminum saturation—and institutional gaps continue to hinder adoption, even among landowners.

Those patterns are especially relevant in postconflict regions like the Orinoquia, where incomplete titling and fragmented governance persist. The strong tenure–adoption link likely reflects deeper structural legacies of conflict and institutional fragility, suggesting broader relevance for other frontier regions navigating land-based development.

Innovation readiness also matters: access to modern technologies is positively associated with adoption. Conversely, technical assistance is negatively associated—possibly because of poor program quality, misalignment with farmers' needs, or reverse causality, where struggling farmers are more likely to seek support. These findings highlight the need to improve extension services in both design and delivery.

For stocking rate decisions, no significant link is found with sustainable pasture adoption, suggesting these sustainability behaviors are not automatically coupled. Instead, farmers' experience, soil acidity, and finishing area size are more predictive. In particular, larger finishing areas are associated with less sustainable outcomes—perhaps reflecting understocked extensive systems that contribute to pasture degradation or deforestation. This challenges assumptions that scale alone ensures efficiency and reinforces the need for performance-adjusted sustainability metrics.

Although causality cannot be inferred because of cross-sectional data, robustness checks—including probit, logit, and bivariate probit models—yield consistent results. A bivariate probit framework reveals limited statistical dependence between pasture and stocking decisions. VIF diagnostics indicate no multicollinearity, and standard errors clustered at the municipality level address potential intragroup correlation.

Overall, the findings underscore the importance of integrated policy strategies that simultaneously strengthen land tenure, address biophysical constraints, and enhance institutional support. The study contributes to growing evidence on the structural and institutional determinants of sustainable intensification, offering actionable insights for regions undergoing postconflict recovery and agricultural transformation.

5.6 Conclusions

This study provides empirical evidence on the factors influencing the adoption of sustainable pasture management and ecologically appropriate stocking rates by cattle producers in Colombia's Orinoquia region. Using a structured farm survey and dual binary choice models, we examine constraints and enabling conditions across sociodemographic, institutional, structural, and environmental domains.

Secure land tenure emerges as a strong and consistent determinant of pasture management adoption, echoing prior research that links tenure security to long-term land stewardship. However, landownership alone is insufficient. Biophysical limitations—particularly high aluminum saturation—and limited institutional support may hinder sustainable practice adoption, even among landowners.

These findings are particularly relevant in conflict-affected regions such as the Orinoquia, where displacement, informal tenure arrangements, and fragmented public services have weakened the institutional foundations needed for sustainable development. In such settings, tenure interventions must be integrated with strategies to rebuild state presence, restore degraded lands, and strengthen extension services. The structural and institutional constraints identified here may also apply to other postconflict or frontier regions undergoing agricultural transition.

In contrast, stocking rate outcomes exhibit weaker and more context-dependent relationships. Sustainable pasture management does not appear to significantly influence stocking decisions, suggesting limited behavioral spillovers between sustainability practices. Instead, farmers' experience, soil acidity, and finishing area are more predictive. Notably, larger finishing areas are associated with less sustainable stocking outcomes, possibly reflecting inefficiencies in understocked systems that may degrade land or encourage deforestation. This highlights the need for scale-sensitive policy design and a more nuanced understanding of extensive system dynamics.

Although the analysis is based on cross-sectional data and cannot support causal claims, the robustness of results across model specifications (logit, probit, bivariate probit), together with controls for multicollinearity and spatial clustering, strengthens the validity of our findings.

Overall, the results underscore the need for integrated policy strategies that combine secure land rights, responsive extension systems, and recognition of local agroecological constraints. Future work could leverage longitudinal and mixed-method approaches to deepen understanding of sustainability transitions in livestock systems and inform equitable, context-specific interventions.

Acknowledgments

We extend our gratitude to all participating producers for their valuable contributions, to Jorge Humberto Argüelles for his statistical guidance, and to Manuel Eduardo Ostos for his dedication to fieldwork and survey data systematization. We acknowledge the National Administrative Department of Statistics (DANE) for developing and implementing the survey methodology. We are also grateful for the financial and technical support provided by the Ministry of Agriculture and Rural Development of Colombia, AGROSAVIA, and the Inter-American Development Bank.

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Appendix

1. Descriptive Statistics and Sample Characteristics

The MEANS procedure of SAS Institute (2020) was used for descriptive statistics of selected variables. Tables 1–5 present descriptive statistics for selected variables related to land use, herd, pasture, grazing, farm, records, and information management. In general, beef farms surveyed for Meta and Cundinamarca departments were relatively large, with an average of 237.77 hectares and, close to 45 hectares of natural forest per farm. Some farms also have transitional and permanent crops and planted forests, with less than 10 hectares of each crop per farm (Table S1).

Table S1. Descriptive statistics for variables related to land use

Variable	n	Mean	SD	SE	Min.	Max.	LCL	UCL
Pastures, ha.	327	237.77	514.74	28.47	4	6000	181.77	293.76
Transitory crops, ha	327	2.76	22.08	1.22	0	350	0.36	5.17
Permanent crops, ha	327	2.50	22.79	1.26	0	300	0.023	4.98
Planted forest, ha	327	5.28	30.95	1.71	0	300	1.91	8.65
Fallow, ha	327	8.77	66.56	3.68	0	1000	1.52	16.01
Rest area, ha	327	8.84	49.69	2.75	0	600	3.43	14.24
Weeds, ha	327	12.11	59.71	3.30	0	800	5.61	18.60
Natural forest, ha	327	44.98	153.72	8.50	0	2000	28.26	61.71
Nonagricultural use, ha	327	4.53	34.91	1,93	0	620	0.73	8

SD: Standard deviation
SE: Standard error
Min: Minimum
Max: Maximum
LCL: Lower 95% confidence limit for mean
UCL: Upper 95% confidence limit for mean

In beef cattle systems of the Meta and Cundinamarca departments, productive parameters are relatively low. Males (bullocks, bulls, and steers) and females (cows, heifers) begin the finishing phase at relatively high ages, which leads to a finishing period close to one year and a slaughter age of three years or more (Table S2). The sale price of females and males per kilogram of live weight in 2017 was USD 1.39 and USD 1.55, respectively.

Table S2. **Descriptive statistics for variables related to herd management**

Variable	n	Mean	SD	SE	Min.	Max.	LCL	UCL
Initial age females, months	76	32.22	27.47	3.15	7	138	26.05	38.39
Initial age males, months	290	21.31	11.14	0.65	4	96	20.03	22.59
Final age females, months	76	43.65	25.35	2.91	12	141	37.86	49.45
Final age males, months	290	34.75	10.16	0.60	10	100	33.57	35.92
Initial weight females, kg	76	291.95	81.14	9.31	118	460	273.31	310.19
Initial weight males, kg	290	270.72	76.05	4.47	100	560	261.97	279.47
Final weight females, kg	76	431.79	60.66	6.96	300	550	80.23	120.47
Final weight males, kg	290	452.35	73,88	4.34	206	650	383.81	418.51
Live females' sale price, USDa	75	602.8	142.8	16.5	323	866.7	570	635.7
Live males' sale price, USDa	290	701.6	154.5	9.1	308.2	1,725	683.7	719.3

a In 2017, 1 USD = 3,000 COP.
SD: Standard deviation
SE: Standard error
Min: Minimum
Max: Maximum
LCL: Lower 95% confidence limit for mean
UCL: Upper 95% confidence limit for mean

The area dedicated to grassland maintenance on the farm was greater than the area used for the fattening phase. The number of paddocks used for finishing was approximately nine, with short rotational grazing periods averaging 20 days. This is significantly shorter than the average rotation period of 30 days observed in the Orinoquia region (Rincón et al., 2018). Mineral salt supplementation was consistently provided at a relatively high level (Table S3), exceeding the regional average of 60 g/d (Rincón et al., 2012).

Table S3. **Descriptive statistics for variables related to pasture and grazing management**

Variable	n	Mean	SD	SE	Min.	Max.	LCL	UCL
Maintenance pastures, ha	327	51.45	93.57	5.17	0	800	41.27	61.63
Maintenance pasture finishing, ha	327	22.36	37.48	2.07	0	250	18.28	26.43
Paddocks pastures finishing	327	9.19	31.84	1.76	1	480	5.73	12.66
Days rotation pastures finishing	327	20.53	24.04	1.33	0	365	18	23.15
Mineral salt intake, g/d	313	114.04	127.9	7.23	30	213	99.82	128.27
Mineral salt intake, days per month	310	29.29	4	0.23	1	60	28.84	29.74

SD: Standard deviation
SE: Standard error
Min: Minimum
Max: Maximum
LCL: Lower 95% confidence limit for mean
UCL: Upper 95% confidence limit for mean

In the surveyed farms, the number of contracted laborers was notably higher than the regional average for finishing systems, which is approximately 30 per month (Fedegán, 2024). Family labor participation was relatively low. However, a significant proportion of farm employees were hired on a permanent basis, contrasting with the regional average of two workers per farm (Fedegán, 2024). Capital investment in finishing activities exhibited high variability, as did the costs associated with land and transportation (Table S4).

Table S4. Descriptive statistics for variables related to farm management

Variable	n	Mean	SD	SE	Min.	Max.	LCL	UCL
Number of contracted daily wages	324	50.38	91.32	1	1	365	40.40	60.36
Family labor, %	327	12.97	28.5	0	0	100	9.87	16.07
Permanent labor fattening, %	327	79.53	36.3	0	0	100	75.58	83.48
Temporal labor fattening, %	327	6.23	18.55	0	0	100	4.22	8.25
Own resour. fattening, USD[ab]	237	9,524	12,903	333.3	333.3	112,000	7,873	11,175
Transportation cost, USD[a]	216	81.7	101.4	1.7	1.7	1,000	68.01	95.3
Land cost, USD[a]	324	276.4	264.8	1.0	1.0	3,560	247.5	305.4

a In 2017, 1 USD = 3,000 COP
b Producer's own resources
SD: Standard deviation
SE: Standard error
Min: Minimum
Max: Maximum
LCL: Lower 95% confidence limit for mean
UCL: Upper 95% confidence limit for mean

In general, farmers in the surveyed beef cattle operations use technical and software records in low percentages. Information sources on state and private platforms were used occasionally (Table S5).

Table S5. Descriptive statistics for variables related to use of records and information management

Variable	n	Mean	SD	SE	Min.	Max.	LCL	UCL
Technical records use, %	327	30.45	44.31	2.45	0	100	25.63	35.27
Software records use, %	327	3.46	14.29	0.79	0	100	1.91	5.02
Other records use, %a	327	23.80	41.47	2.29	0	100	19.29	28.31
Source informationb SIPSA, %	327	3.73	18.44	1.02	0	100	1.72	5.73
Source information supply center, %	327	11.31	29.55	1.63	0	100	8.10	14.52
Source information market plaza, %	327	10.06	25.9	1.43	0	100	7.24	12.87
Source information sellers, %	327	16.26	31.94	1.77	0	100	12.79	19.74

a Includes financial and accounting records
b Includes the platforms or web pages on which the producer accesses technical information
SD: Standard deviation
SE: Standard error
Min: Minimum
Max: Maximum
LCL: Lower 95% confidence limit for mean
UCL: Upper 95% confidence limit for mean

Using the PROC FREQ procedure of SAS Institute (2020), a chi-square test of dependence, including Pearson chi-square, likelihood ratio chi-square, and Mantel-Haenszel chi-square tests, was evaluated for qualitative variables. This revealed an association between the type of productive system and grazing practices. Farms that have a productive system based on a complete cycle (cow-calf, stocker, and fattening) were more likely to adopt a rotational grazing system for the fattening phase than the other systems (Table S6; X2 (10, N = 327) = 323.48, p <.00004).

Table S6. Productive system, by grazing practice

Grazing practicea	Dairy	Complete cycleb	Beef stockerc	Beef finishingd	Beef othere	Dual-purposef	Total
ALTERNATE							
Frequency	2	15	1	12	7	3	40
Percentage	0.61	4.59	0.31	3.67	2.14	0.92	12.23
Row %g	5.00	37.50	2.50	30.00	17.50	7.50	
Column %h	10.53	10.34	3.70	13.19	28.00	15.00	
CONTINUOUS							
Frequency	2	18	2	4	5	8	39
Percentage	0.61	5.50	0.61	1.22	1.53	2.45	11.93
Row %	5.13	46.15	5.13	10.26	12.82	20.51	
Column %	10.53	12.41	7.41	4.40	20.00	40.00	
ROTATIONAL							
Frequency	15	112	24	75	13	9	248
Percentage	4.59	34.25	7.34	22.94	3.98	2.75	75.84
Row %	6.05	45.16	9.68	30.24	5.24	3.63	
Column %	78.95	77.24	88.89	82.42	52.00	45.00	
Total	19	145	27	91	25	20	327
	5.81	44.34	8.26	27.83	7.65	6.12	100.00

a In alternance grazing, pastures are divided into two paddocks and cattle are moved between them. In continuous grazing, cattle have permanent access to a single large pasture throughout the year. In rotational grazing, a pasture is divided into three or more paddocks and cattle are moved from one to the other.
b Complete cycle is the entire process of raising cattle for beef, from breeding and birth to slaughter, and includes cow-calf, stocker, and finishing phases.
c After weaning, calves enter grazing pastures to gain weight before entering the finishing phase at around 350 kg of live weight.
d Cattle graze pastures to achieve the desired market weight (450 to 500 kg of live weight).
e "Other" includes the cow-calf system, in which calves are raised alongside their mothers until weaning.
f Dual-purpose cattle are crossbred for both beef and dairy production.
g Represents the percentage of the type of productive system.
h Represents the percentage of grazing practices.

We found an association between grazing practices and the level of intensification of the productive system. Farms that use an intensive system were more likely to adopt rotational grazing for the finishing phase than other levels of intensification (Table S7; X2 (6, N = 327) = 2,475.41, p <.00001). Cattle production systems in the Orinoquia range from extensive, relying heavily on natural resources with low inputs and slow growth rates, to intensive systems characterized by high stocking rates, supplemental feeding, and significant labor (Vera-Infanzón and Ramírez-Restrepo, 2020). Confinement systems maximize production but require high external inputs (González-Salazar et al., 2021). Semiconfinement systems, combining elements of both extensive and intensive approaches, offer a potential balance between productivity and sustainability.

The optimal production strategy depends on a multifaceted assessment of available resources, market demands, environmental considerations, and economic feasibility. Flórez et al. (2024) proposed a sustainable intensification of cattle systems in the Orinoquia, comprising silvopastoral systems (SPS), improved pastures, and good cattle practices for increased animal productivity and stocking rates would generate benefits (e.g., increased income for rural families, poverty reduction) and mitigates harms (e.g., deforestation and GHG emissions).

Table S7. Intensification system, by grazing practice

Grazing practicea	Extensive[a]	Intensive[b]	Confinement[c]	Semi-confinementd	Total
ALTERNATE					
Frequency	3	37	0	0	40
Percentage	0.92	11.31	0.00	0.00	12.23
Row %e	7.50	92.50	0.00	0.00	
Column %f	6.67	13.45	0.00	0.00	
CONTINUOUS					
Frequency	37	2	0	0	39
Percentage	11.31	0.61	0.00	0.00	11.93
Row %	94.87	5.13	0.00	0.00	
Column%	82.22	0.73	0.00	0.00	
ROTATIONAL					
Frequency	5	236	1	6	248
Percentage	1.53	72.17	0.31	1.83	75.84
Row %	2.02	95.16	0.40	2.42	
Column %	11.11	85.82	100.00	100.00	
Total	45	275	1	6	327
	13.76	84.10	0.31	1.83	100.00

a Extensive system mainly depends on natural resources with minimal inputs and has low productive indices compare to intensive productive systems.
b Intensive system uses high levels of inputs and management and have high productive indices compare to extensive systems
c Confinement system is a specific type of intensive system where cattle are confined to a corral or feedlot limited space for the entire fattening phase.
d Semi-confinement is a system where cattle spend part of the fattening phase confined in a corral or feedlot, and the rest of their time grazing on pastures.
e Represents the percentage of the type of intensification system
f Represents the percentage of grazing practices

Farmers acquire their cattle for finishing in diverse ways. Farmers who raise their own cattle were more likely to adopt a rotational grazing system for the finishing phase, compared with farmers who acquire cattle for finishing in other ways (Table S8; X2 (14, N = 324) = 263.720, p <.0232).

Table S8. Source of cattle for finishing, by grazing practice

Grazing practice	Auction	Fair	Farm	Other farm	Local buy	Regional buy	Other	Total
ALTERNATE								
Frequency	5	2	17	5	6	4	1	40
Percentage	1.54	0.62	5.25	1.54	1.85	1.23	0.31	12.35
Row %a	12.50	5.00	42.50	12.50	15.00	10.00	2.50	
Column %b	17.24	40.00	11.18	35.71	14.29	10.00	2.30	
CONTINUOUS								
Frequency	2	0	27	1	5	2	2	39
Percentage	0.62	0.00	8.33	0.31	1.54	0.62	0.62	12.04
Row %	5.13	0.00	69.23	2.56	12.82	5.13	5.13	
Column %	6.90	0.00	17.76	7.14	11.90	5.00	4.76	
ROTATIONAL								
Frequency	22	3	108	8	31	34	39	245
Percentage	6.79	0.93	33.33	2.47	9.57	10.49	12.03	75.62
Row %	8.98	1.22	44.08	3.27	12.65	13.88	15.92	
Column %	75.86	60.00	71.05	57.14	73.81	85.00	92.85	
Total	29	5	152	14	42	40	42	324
	8.95	1.54	46.91	4.32	12.96	12.35	12.96	100.00

a Represents the percentage of the origin of cattle.
b Represents the percentage of grazing practices.

Farmers may finish both bulls and steers, but farmers who finish steers only were more likely to adopt a rotational grazing system (Table S9; X2 (2, N = 282) = 168.842, p <.0002). Although bulls have greater weight gain than steers (Blanco et al., 2020), steers are generally preferred for finishing cattle because steer beef tends to be more tender (Flórez Diaz et al., 2015), and steers are typically more docile and easier to handle than bulls (León-Llanos and Flórez-Díaz, 2016).

Table S9. Finishing cattle, by grazing practice

Grazing practicea	Bulls	Steers	Total
ALTERNATE			
Frequency	20	18	38
Percentage	7.09	6.38	13.48
Row %[a]	52.63	47.37	
Column %[b]	23.53	9.14	
CONTINUOUS			
Frequency	3	32	35
Percentage	1.06	11.35	12.41
Row %	8.57	91.43	
Column%	3.53	16.24	
ROTATIONAL			
Frequency	62	147	209
Percentage	21.99	52.13	74.11
Row %	29.67	70.33	
Column %	72.94	74.62	
Total	85	197	282
	30.14	69.86	100.00

a Represents the percentage of sex condition of cattle

b Represents the percentage of grazing practices

Costs for the finishing phase vary. Farmers who invest more in animal management were more likely to adopt a rotational grazing system than farmers who invest in technical assistance, public services, taxes, etc. (Table S10; X2 (12, N = 324) = 272.336, p <.0072).

Table S10. Investments, by grazing practice

Grazing practice	Land	Animal management	Technical assistance	Honorarium	Public services	Taxes	Other	Total
ALTERNATE								
Frequency	6	13	0	14	0	7	0	40
Percentage	1.85	4.01	0.00	4.32	0.00	2.16	0.00	12.35
Row %	15.00	32.50	0.00	35.00	0.00	17.50	0.00	
Col %	20.00	11.11	0.00	10.53	0.00	21.21	0.00	
CONTINUOUS								
Frequency	1	5	2	25	2	4	0	39
Percentage	0.31	1.54	0.62	7.72	0.62	1.23	0.00	12.04
Row %	2.56	12.82	5.13	64.10	5.13	10.26	0.00	
Col %	3.33	4.27	40.00	18.80	40.00	12.12	0.00	
ROTATIONAL								
Frequency	23	99	3	94	3	22	1	245
Percentage	7.10	30.56	0.93	29.01	0.93	6.79	0.31	75.62
Row %	9.39	40.41	1.22	38.37	1.22	8.98	0.41	
Col %	76.67	84.62	60.00	70.68	60.00	66.67	100.00	
Total	30	117	5	133	5	33	1	324
	9.26	36.11	1.54	41.05	1.54	10.19	0.31	100.00

Farmers use various sources to supply water to cattle. Farmers who use irrigation systems were more likely to adopt a rotational grazing system than farmers who use other systems (Table S11; X2 (10, N = 308) = 200.958, p <.0284). Farmers using irrigation systems mainly during the dry season are more likely to adopt rotational grazing practices because irrigation increases forage production, enabling effective pasture division and animal movement (Torregroza et al., 2015). Also, irrigation increases productivity and the nutritional value of pasture, with higher livestock production per area in periods of water deficit (Bones et al., 2023). By mitigating the variability associated with rainfall dependence, irrigation systems create a more stable environment conducive to implementing and maintaining planned grazing rotations.

Table S11. Sources of water, by grazing practice

Grazing practicea	Aqueduct	Pond	Rain	River	Tank car	Irrigation	Total
ALTERNATE							
Frequency	2	0	2	16	0	16	36
Percentage	0.65	0.00	0.65	5.19	0.00	5.19	11.69
Row %	5.56	0.00	5.56	44.44	0.00	44.44	
Col %	11.76	0.00	13.33	14.55	0.00	11.03	
CONTINUOUS							
Frequency	0	0	0	22	2	15	39
Percentage	0.00	0.00	0.00	7.14	0.65	4.87	12.66
Row %	0.00	0.00	0.00	56.41	5.13	38.46	
Col %	0.00	0.00	0.00	20.00	33.33	10.34	
ROTATIONAL							
Frequency	15	15	13	72	4	114	233
Percentage	4.87	4.87	4.22	23.38	1.30	37.01	75.65
Row %	6.44	6.44	5.58	30.90	1.72	48.93	
Col %	88.24	100.00	86.67	65.45	66.67	78.62	
Total	17	15	15	110	6	145	308
	5.52	4.87	4.87	35.71	1.95	47.08	100.00

2. Methodological Details and Additional Background

Table S12. Variables used in the two-stage econometric model

	Variable	Description	Model decision 1	Model decision 2
Dependent variables	*sustainable pasture managemen*	Whether farmer adopts sustainable pasture management practices: 1 = sustainable, including soil conservation, erosion control, and biodiversity preservation; 0 = nonsustainable.	N/A	Yes/No
	stocking rate	Whether number of animals per hectare falls within sustainable range: 1 = sustainable, within predefined minimums and maximums; 0 = nonsustainable, below minimum or above maximum.	N/A	Yes

Socio-demographic	*age*	Age of farmer.	Yes	Yes
	gender	Binary variable (1= men and 0 = women).	Yes	Yes
	experience ratio	Farmer's years of experience in cattle farming, scaled as ratio.	Yes	Yes
Institutional	*land tenure*	Farmer's land tenure status: 1 = owned; 0 = other tenure forms, including rented or shared use, such as lease, sharecropping, or loan-based agreements, and alternative tenure arrangements, such as informal, collective, or legally distinct ownership.	Yes	Yes
	technical assist.	Whether farmer has received technical assistance services: 1 = some form of technical assistance or relevant academic training from public or private sector; 0 = no technical assistance.	Yes	Yes
	technology adopt	Whether farmer adopts modern agricultural technologies.	Yes	No
Structural	*terrain type*	Dominant landform on farm: 1 = alluvial fans, 2 = colluvial glacis, 3 = hills, 4 = floodplain, 5 = terraces.	Yes	Yes
	soil acidity	Level of soil acidity: 1 = acidic, 2 = strongly acidic and acidic, and 3 = strongly acidic.	Yes	Yes
	aluminum level	Level of aluminum in the soil: 1 = low, 2 = medium, and 3 = high.	Yes	Yes
	grazing type	Grazing system used in cattle finishing: 1 = continuous grazing, 2 = alternating grazing, 3 = rotational grazing.	No	Yes
	management type	Cattle management system: 0 = extensive (traditional grazing-based system), 1 = nonextensive (including nonextensive grazing, confinement, and semi-confinement systems).	No	Yes
	farm orientation	Farm's primary production system: 1 = dairy production, 2 = complete and/or partial beef cycle (including breeding, rearing, and fattening), and 3 = dual-purpose (both milk and meat production).	Yes	Yes
Environmental	*avg. temp. 2016*	Geo-referenced average temperature, 2016.	Yes	Yes
	rainfall 2016	Geo-referenced average precipitation, 2016.	Yes	Yes
Economic	*variable costs*	Costs that fluctuate with production (e.g., feed, veterinary expenses, labor).	Yes	Yes
	total resources	Total financial and material resources available for farm operation.	Yes	No
	finishing efficiency	Efficiency of cattle finishing process.	No	Yes
	finishing area	Total area used for cattle finishing operations.	No	Yes
	municipality code	Geographic location of farm, used as fixed effect to control for regional heterogeneity in analysis.	Clustered	Clustered

Table S13. Variance inflation factor (VIF) estimates for multicollinearity assessment sustainable pasture management model

	VIF	1/VIF
age	1.07	0.934
gender	1.04	0.959
experience ratio	1.11	0.898
land tenure	1.10	0.907
technical assist.	1.13	0.885
technology adopt.	1.45	0.691
terrain type	1.87	0.536
soil acidity	1.52	0.659
aluminum level	1.92	0.521
farm orientation	1.10	0.912
avg. temp. 2016	3.73	0.268
rainfall 2016	2.76	0.362
variable costs	1.38	0.726
total resources	1.09	0.916
Mean VIF	1.59	

Table S14. Variance inflation factor (VIF) estimates for multicollinearity assessment stocking rate model

	VIF	1/VIF
sust. pasture mgment.	1.36	0.734
age	1.06	0.942
gender	1.06	0.946
experience ratio	1.16	0.861
land tenure	1.19	0.841
technical assist.	1.11	0.898
terrain type	1.91	0.523
soil acidity	1.53	0.654
aluminum level	2.11	0.474
grazing type	1.85	0.540
mgment. type	1.83	0.546
farm orientation	1.12	0.897
avg. temp. 2016	3.63	0.275
rainfall 2016	2.73	0.366
variable costs	1.14	0.879
finishing efficiency	1.06	0.943
finishing area	1.15	0.870
Mean VIF	1.59	

2.1. Data Based on Geographic Information

Geographic information refers attributes that allow for the description of study processes; cartographic information pertains to the graphical outputs or maps of geographic information. In this study, we refer to vector and raster data, where we relate geographic information from variables such as soil type, ambient temperature, and rainfall to biophysically characterize the areas of segments and clusters from the National Agricultural Census (CNA) and the National Agricultural Survey (ENA). These data are used in the livestock finishing cost structuring project and complement the survey analysis through an econometric model.

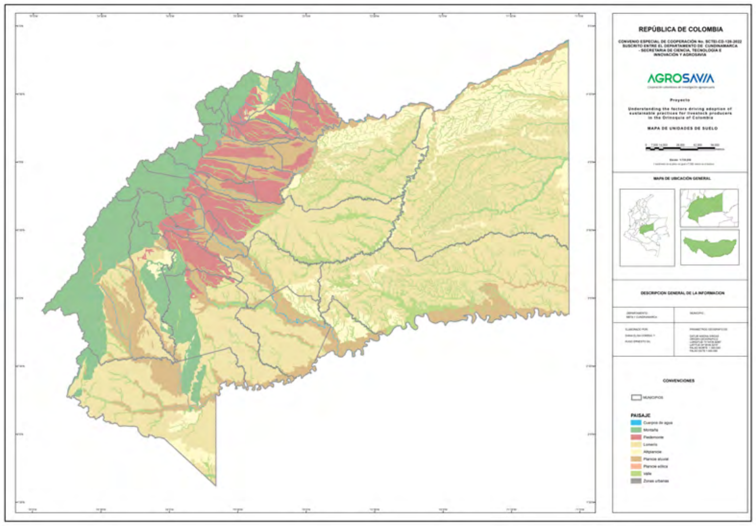
The following table presents the variables to be evaluated, the data type, format, and information sources used to characterize the study area or included in the econometric model.

Table S15. Variables, data, format, and information source of geographic variables

Variable	Data type	Format	Data source
Departmental and municipal boundaries	Vectorial	Shapefile	DANE Geoportal - Geovisor Consulta del Marco Geoestadístico Nacional(MGN)
Soil units of Meta and Cundinamarca department	Vectorial	Shapefile	IGAC Datos Abiertos Agrología | GEOPORTAL
Agricultural frontier	Vectorial	Shapefile	UPRA SIPRA
Rainfall	Raster	TIF	CHIRPS - Climate Hazards Center. UC Santa Barbara CHIRPS: Rainfall Estimates from Rain Gauge and Satellite Observations | Climate Hazards Center - UC Santa Barbara
Ambient temperature	Raster	TIF	NASA Power https://power.larc.nasa.gov/data-access-viewer/

The process of collecting basic and thematic cartographic information at a scale of 1:100,000 was initiated with the shapefile files of soil studies for Meta and Cundinamarca from the Agustín Codazzi Geographic Institute, https://geoportal.igac.gov.co/contenido/datos-abiertos-agrologia open data geoportal (Figure S1).

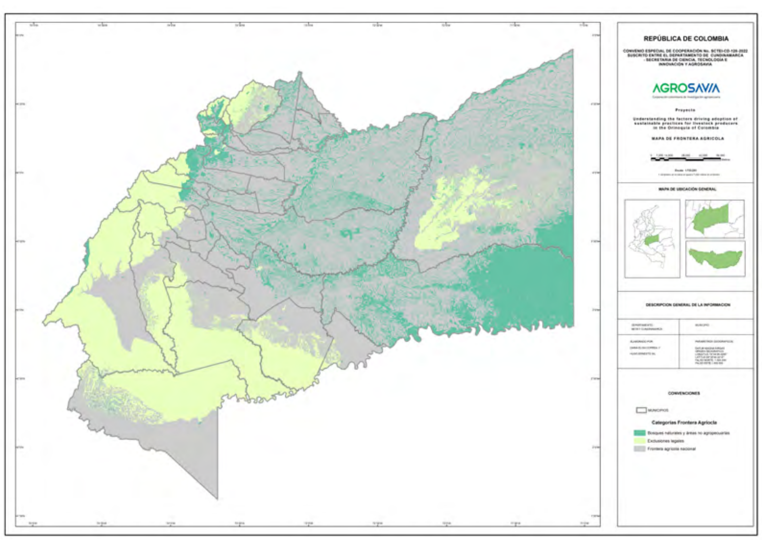
Figure S1. **Soil units for Meta and Cundinamarca departments**



IGAC https://geoportal.igac.gov.co/contenido/datos-abiertos-agrologia

Also, for Meta department, beginning with the municipality of San Martín, where more surveys were developed (51), the agricultural frontier established by the Rural Planning Unit of the Ministry of Agriculture and Rural Development (UPRA) was taken from https://sipra.upra.gov.co/nacional (Figure S2).

Figure S2. **Agricultural frontier for Meta department including municipality of San Martín**



SIPRA, UPRA. https://sipra.upra.gov.co/territorial

Figure S3. Segment and conglomerate areas of the National Agricultural Census (CNA) and the National Agricultural Survey (ENA) for Cundinamarca department. Green areas correspond to Medina y Paratebueno municipalities (Molina Romero et al., 2021).

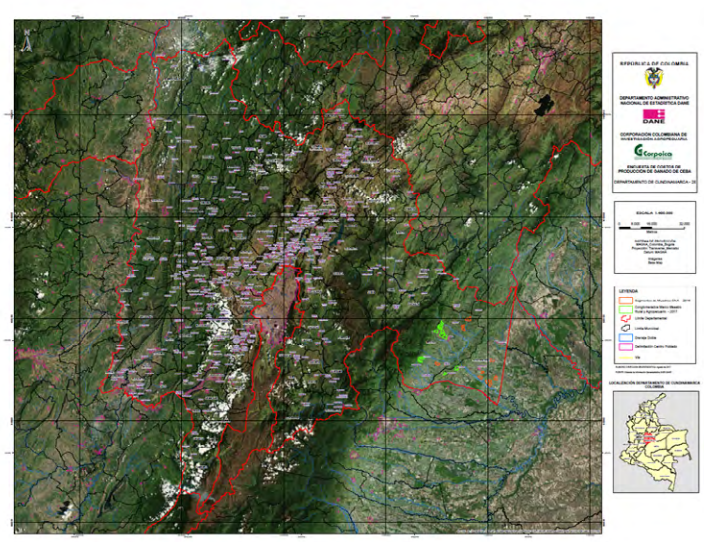


Figure S4. Segment and conglomerate areas of the National Agricultural Census (CNA) and the National Agricultural Survey (ENA) for Meta department. Green areas correspond to municipalities selected (Molina Romero et al., 2021).

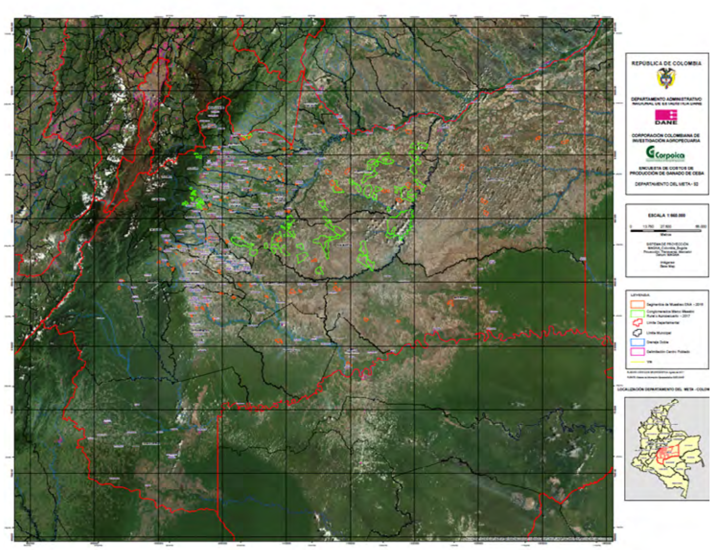


Figure S5. Segments and conglomerates of San Martín (Meta) georeferencing in ArcGis 10.8 software

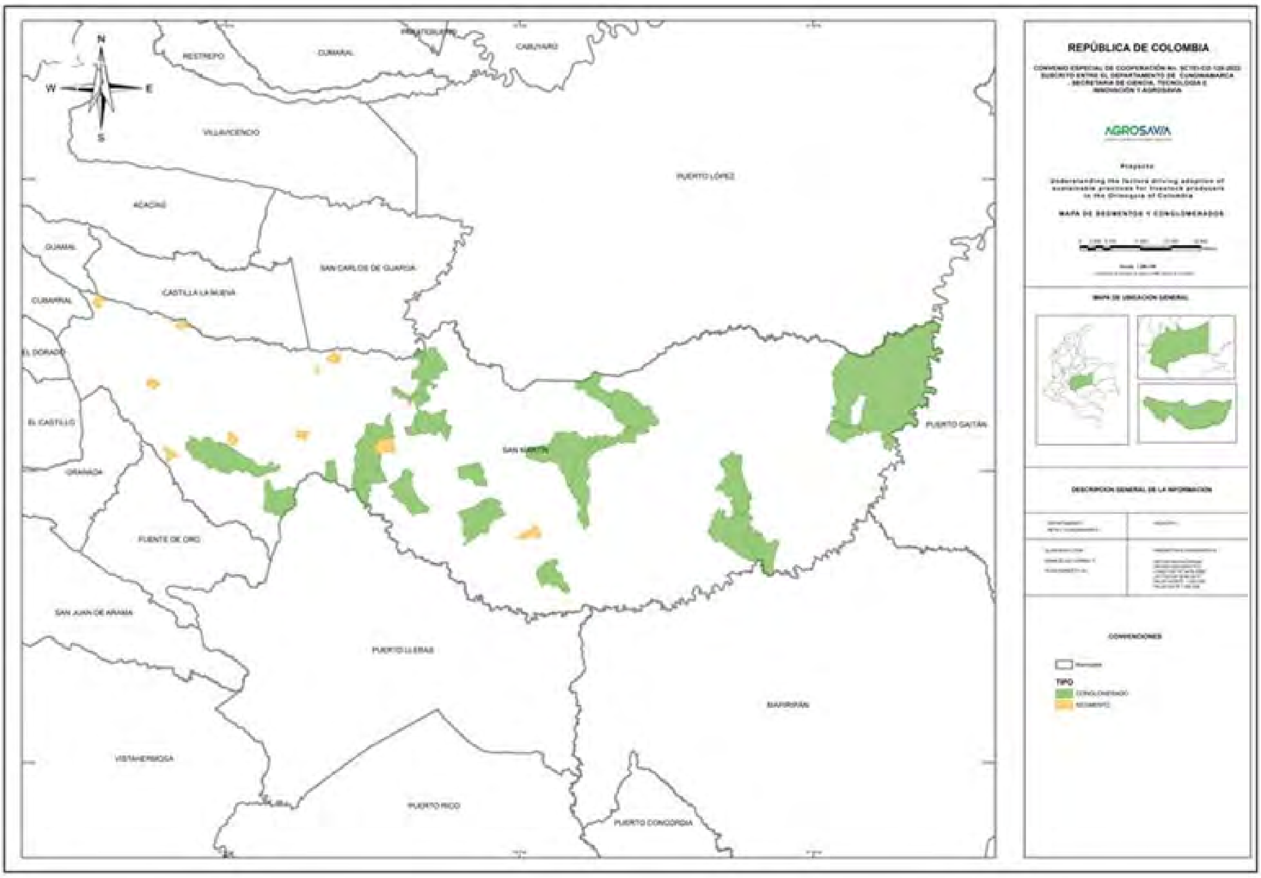


Table S16. Total area of segments and conglomerates of municipality of San Martin, Meta

FID	TYPE	CODE	Area (hectares)
0	SEGMENT	50080502	286.90
1	SEGMENT	50086202	241.88
2	SEGMENT	50905801	231.86
3	SEGMENT	50100401	35.16
4	CONGLOMERATE	506890121	963.16
5	CONGLOMERATE	506890107	449.96
6	CONGLOMERATE	506890051	3,065.66
7	SEGMENT	50097404	278.61
8	SEGMENT	50097304	74.40
9	CONGLOMERATE	506890098	4,490.90
10	CONGLOMERATE	506890094	1,992.69
11	CONGLOMERATE	506890176	1,609.15
12	CONGLOMERATE	506890181	5,812.14
13	CONGLOMERATE	506890168	1,682.68
14	CONGLOMERATE	506890012	28,124.89
15	SEGMENT	50111003	292.47
16	CONGLOMERATE	506890189	6,056.26
17	SEGMENT	50110602	284.96
18	SEGMENT	50110104	268.35
19	CONGLOMERATE	5068900233	2,777.86
20	CONGLOMERATE	506890232	1086.17
21	CONGLOMERATE	506890211	799.50
22	CONGLOMERATE	506890223	2,916.64
23	CONGLOMERATE	506890218	1,625.04
24	CONGLOMERATE	506890157	4,329.07
25	SEGMENT	50207401	862.67
26	CONGLOMERATE	506890161	509.77
27	CONGLOMERATE	506890016	1,157.14
28	CONGLOMERATE	506890145	1,289.13
29	CONGLOMERATE	506890217	1,560.38
30	CONGLOMERATE	506890245	4,050.81
31	CONGLOMERATE	506890197	3,696.76
32	SEGMENT	50223503	502.23
33	CONGLOMERATE	506890272	2,048.95
34	CONGLOMERATE	506890205	4,343.82
35	CONGLOMERATE	506890247	4,964.00
36	CONGLOMERATE	506890261	2,818.19
Total			**97,580.24**

Table S17. Bivariate probit model marginal effects on sustainable pasture management

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
age	-0.002	0.006	0.796	-0.013	0.010
gender	0.319	0.256	0.214	-0.184	0.821
experience ratio	-0.660	0.997	0.508	-2.614	1.294
land tenure	0.940	0.178	0.000	0.592	1.289
technical assist.	-0.143	0.067	0.034	-0.275	-0.011
technology adopt.	0.726	0.350	0.038	0.040	1.413
terrain type	0.006	0.118	0.958	-0.224	0.237
soil acidity	0.111	0.164	0.497	-0.210	0.432
aluminum level	-1.241	0.505	0.014	-2.231	-0.251
farm orientation	0.022	0.050	0.667	-0.077	0.120
avg. temp. 2016	0.020	0.100	0.840	-0.176	0.216
rainfall 2016	0.000	0.001	0.888	-0.002	0.002
variable costs	0.000	0.000	0.332	0.000	0.000
total resources	0.000	0.000	0.154	0.000	0.000
observations			327		

Table S18. Bivariate probit model marginal effects on stocking rate

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
age	0.003	0.005	0.511	-0.006	0.012
gender	0.151	0.151	0.319	-0.146	0.448
experience ratio	-0.915	0.405	0.024	-1.709	-0.121
land tenure	0.218	0.153	0.154	-0.082	0.519
technical assist.	0.036	0.105	0.732	-0.169	0.241
terrain type	0.089	0.112	0.425	-0.130	0.309
soil acidity	-0.303	0.139	0.030	-0.576	-0.030
aluminum level	0.159	0.253	0.531	-0.337	0.654
grazing type	-0.307	0.168	0.068	-0.636	0.023
mgment. type	0.076	0.156	0.626	-0.230	0.381
farm orientation	-0.084	0.054	0.122	-0.190	0.022
avg. temp. 2016	0.005	0.071	0.943	-0.135	0.145
rainfall 2016	-0.001	0.001	0.071	-0.002	0.000
variable costs	0.000	0.000	0.964	0.000	0.000
finishing efficiency	0.000	0.000	0.005	0.000	0.000
finishing area	-0.006	0.002	0.000	-0.009	-0.003
observations			**327**		

Table S19. Marginal effects from logit model sustainable pasture management

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
age	0.000	0.002	0.931	-0.004	0.003
gender	0.106	0.078	0.172	-0.046	0.258
experience ratio	-0.211	0.289	0.465	-0.777	0.355
land tenure	0.265	0.072	0.000	0.123	0.406
technical assist.	-0.045	0.020	0.026	-0.084	-0.005
technology adopt.	0.213	0.132	0.106	-0.045	0.471
terrain type	0.007	0.041	0.856	-0.073	0.087
soil acidity	0.054	0.065	0.405	-0.073	0.182
aluminum level	-0.455	0.180	0.011	-0.807	-0.103
farm orientation	0.006	0.014	0.681	-0.021	0.033
avg. temp. 2016	0.028	0.051	0.586	-0.072	0.128
rainfall 2016	0.000	0.001	0.615	-0.002	0.001
variable costs	0.000	0.000	0.230	0.000	0.000
total resources	0.000	0.000	0.294	0.000	0.000
observations			327		

Table S20. Marginal effects from logit model stocking rate with sustainable pasture management as regressor

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
sust. pasture mgment.	0.012	0.031	0.703	-0.049	0.072
age	0.001	0.001	0.488	-0.001	0.003
gender	0.032	0.035	0.357	-0.036	0.100
experience ratio	-0.209	0.107	0.050	-0.418	0.000
land tenure	0.047	0.032	0.147	-0.017	0.110
technical assist.	0.006	0.025	0.806	-0.043	0.055
terrain type	0.024	0.033	0.468	-0.041	0.090
soil acidity	-0.074	0.041	0.075	-0.155	0.007
aluminum level	0.043	0.070	0.540	-0.095	0.181
grazing type	-0.071	0.045	0.113	-0.159	0.017
mgment. type	0.023	0.038	0.537	-0.051	0.097
farm orientation	-0.019	0.015	0.219	-0.049	0.011
avg. temp. 2016	0.000	0.019	0.985	-0.037	0.036
rainfall 2016	0.000	0.000	0.111	0.000	0.000
variable costs	0.000	0.000	0.984	0.000	0.000
finishing efficiency	0.000	0.000	0.007	0.000	0.000
finishing area	-0.001	0.000	0.002	-0.002	-0.001
observations			**327**		

Table S21. Marginal effects from probit model stocking rate without sustainable pasture management as regressor

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
age	0.001	0.001	0.514	-0.002	0.003
gender	0.037	0.036	0.293	-0.032	0.107
experience ratio	-0.222	0.101	0.027	-0.420	-0.025
land tenure	0.053	0.036	0.144	-0.018	0.124
technical assist.	0.009	0.025	0.728	-0.040	0.058
terrain type	0.022	0.027	0.421	-0.031	0.074
soil acidity	-0.074	0.033	0.025	-0.138	-0.009
aluminum level	0.038	0.061	0.534	-0.082	0.159
grazing type	-0.074	0.043	0.083	-0.158	0.010
mgment. type	0.020	0.036	0.571	-0.050	0.090
farm orientation	-0.020	0.014	0.152	-0.048	0.008
avg. temp. 2016	0.002	0.018	0.924	-0.033	0.036
rainfall 2016	0.000	0.000	0.063	0.000	0.000
variable costs	0.000	0.000	0.959	0.000	0.000
finishing efficiency	0.000	0.000	0.003	0.000	0.000
finishing area	-0.001	0.000	0.000	-0.002	-0.001
observations			**327**		

Table S22. Marginal effects from logit model stocking rate without sustainable pasture management as regressor

Variable	dy/dx	Std. err.	P>|z|	95% conf. interval	
age	0.001	0.001	0.487	-0.001	0.003
gender	0.035	0.034	0.312	-0.033	0.102
experience ratio	-0.212	0.109	0.052	-0.426	0.002
land tenure	0.051	0.035	0.145	-0.017	0.118
technical assist.	0.006	0.024	0.820	-0.042	0.053
terrain type	0.024	0.033	0.472	-0.042	0.090
soil acidity	-0.074	0.041	0.075	-0.155	0.007
aluminum level	0.039	0.069	0.572	-0.097	0.175
grazing type	-0.071	0.045	0.118	-0.159	0.018
mgment. type	0.025	0.036	0.480	-0.045	0.096
farm orientation	-0.019	0.015	0.219	-0.049	0.011
avg. temp. 2016	0.000	0.019	0.986	-0.037	0.037
rainfall 2016	0.000	0.000	0.096	0.000	0.000
variable costs	0.000	0.000	0.977	0.000	0.000
finishing efficiency	0.000	0.000	0.008	0.000	0.000
finishing area	-0.001	0.000	0.002	-0.002	-0.001
observations			**327**		

4. Farmers' Decision Context and Management Practices

4.1. Perceptions of Adoption Barriers and Decision Logic

To inform our empirical strategy, we conducted a perception-based survey with 70 cattle farmers from the Piedemonte, Altillanura, and Sabana Inundable subregions of the Colombian Orinoquia. The survey served a dual purpose: first, as a behavioral diagnostic to understand the self-reported barriers that producers face when considering sustainable grazing practices; and second, as a foundation for selecting explanatory variables and structuring the identification strategy. Rather than assuming a decision framework ex ante, we allowed farmers' responses to reveal the logic and sequencing of adoption decisions.

One of the most salient insights was the presence of regional disparities in the constraints cited by producers. In Altillanura, 37% of farmers reported market volatility as a primary barrier to adopting sustainable practices, and 35% cited infrastructure deficiencies. In contrast, 65% of producers in Sabana Inundable pointed to extreme weather events as their main concern, followed by 50% who identified soil and water degradation. These differences highlight the importance of accounting for environmental and market context, supporting the inclusion of regional fixed effects and natural capital variables in the empirical model.

Financial constraints emerged as a pervasive concern across all subregions. In Sabana Inundable, 50% of farmers reported limited credit access and another 50% pointed to high production costs as major adoption barriers. Credit limitations were also cited by 35% of farmers in Piedemonte and 32% in Altillanura. These figures reinforce well-established findings in the literature on liquidity constraints and their effect on technology adoption (Feder et al., 1985), justifying the inclusion of variables capturing financial access and input cost conditions.

Institutional and informational barriers also proved substantial. Forty-eight percent of surveyed farmers stated that they lacked sufficient knowledge of sustainable grazing techniques, and 54% were not affiliated with any producer association. These constraints imply limited exposure to innovation channels, supporting the inclusion of variables measuring access to technical assistance, extension services, and organizational networks. The role of institutional presence is particularly relevant, given that only a minority of producers in the sample reported having ever participated in formal sustainability programs.

Sociocultural and behavioral factors added another layer of complexity. Resistance to change was a recurrent theme, especially among older and more experienced producers. This reluctance was reported by 68% of farmers in Sabana Inundable, 52% in Piedemonte, and 50% in Altillanura. These responses suggest a high degree of behavioral inertia and support the integration of demographic variables (e.g., age, years of experience) into the empirical model, consistent with literature on path dependency and risk aversion in agriculture (García-Winder & Chavarría, 2017).

Concerns about land tenure security also emerged during the conversations with farmers, particularly in Altillanura, where formal titling remains limited and informal occupation is widespread. Although it was not captured through a fixed-response question, many producers alluded to the uncertainty of landownership as a factor discouraging long-term investment in sustainable practices such as rotational grazing and pasture recovery. This informal but recurring theme aligns with broader findings in the literature on the role of tenure security in enabling sustainable land management (Bonilla-Mejía et al., 2024; Clerici et al., 2020).

Importantly, the perception survey revealed that many producers view improved pasture management as a necessary precursor to adjusting animal stocking rates, suggesting a possible sequential structure in their decisionmaking. To reflect this behavioral insight while maintaining empirical flexibility, we structured our analysis to test both sequential and independent modeling approaches. This decision, grounded in farmers' own perceptions, allowed us to explore whether these practices represent distinct or interrelated adoption processes, while ensuring that the empirical strategy remained aligned with producers' realities. Table S23 summarizes the farm-level variables.

Table S23. Summary statistics of farm-level variables

Variable	Mean	SD	Min.	Max.
Land use				
Farm size (ha)	237.8	514.7	4	6,000
Pastures for finishing (ha)	22.4	37.5	0	250
Natural forest (ha)	45	153.7	0	2,000
Nonagricultural land (ha)	4.5	34.9	0	620
Herd management				
Initial age of males (months)	21.3	11.1	4	96
Final age of males (months)	34.8	10.2	10	100
Initial weight of males (kg)	270.7	76.1	100	560
Final weight of males (kg)	452.4	73.9	206	650
Live males' sale price (USD)	701.6	154.5	308.2	1,725
Grazing practices				
Rotational grazing (%)	75%			
Continuous grazing (%)	12%			
Alternate grazing (%)	12%			
Number of paddocks used	9.2	31.8	1	480
Days of rotation	20.5	24	0	365
Mineral salt intake (g/day)	114	127.9	30	213
Farm management				
Contracted labor (wages/month)	50.4	91.3	1	365
Family labor (%)	13	28.5	0	100
Permanent labor (%)	79.5	36.3	0	100
Temporary labor (%)	6.2	18.6	0	100
Transportation cost (USD)	81.7	101.4	1.7	1,000
Land cost (USD)	276.4	264.8	1	3,560
Records and information management				
Use of technical records (%)	30.5		0	100
Use of software records (%)	3.5		0	100
Other records use (%)	23.8	41.5	0	100

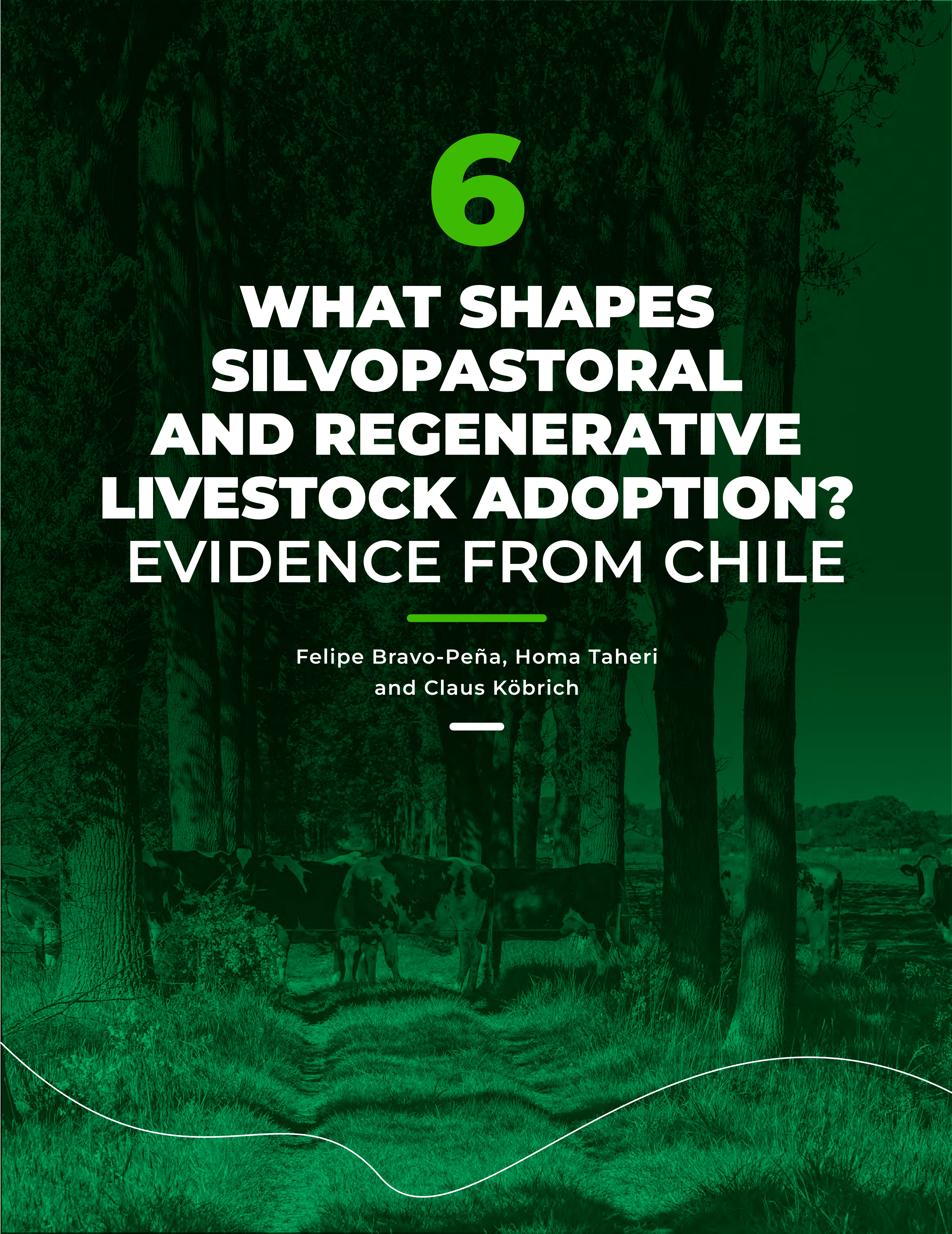
4.2. Farm Heterogeneity and Constraints on Sustainable Practice Adoption

Table S23 presents descriptive statistics of our farm-level variables, revealing considerable heterogeneity in land use, herd management, grazing practices, labor structure, and recordkeeping. The average farm size is 237.8 hectares, but the distribution is highly skewed (SD = 514.7), with some farms exceeding 6,000 hectares. Finishing pastures occupy an average of 22.4 hectares, but the overall land-use composition is more diverse than initially apparent. Farms also report small but nonnegligible areas in transitory crops such as corn, rice, and soybeans (2.76 ha on average), permanent crops like citrus and papaya (2.50 ha), planted forests for timber (5.28 ha), fallow land (8.77 ha), rest areas (8.84 ha), and land dominated by weeds (12.11 ha). These figures suggest that although cattle finishing remains the dominant activity, mixed-use systems and diversification strategies are present on a subset of farms. Natural forest areas account for an average of 45 hectares, underscoring the environmental importance of land-use decisions in the region.

Nonagricultural land (mean = 4.53 ha) includes infrastructure, internal roads, and housing, but in some cases, it also reflects leased land arrangements—particularly relevant for finishing operations, where producers may temporarily rent pastureland. However, because of limitations in the survey design, we cannot disaggregate rental contracts from permanent holdings. The reported land cost variable (mean = $276.4/ha) captures either the imputed rental cost (for those leasing land) or the opportunity cost of owned land, as reported by the producer. This heterogeneity in interpretation suggests that land cost should be treated cautiously in modeling exercises.

Labor dynamics also reveal important sociodemographic dimensions. Although the average number of paid contracted workers is modest (50.4 wages/month), family labor remains relevant in 13% of farms, with wide variation (SD = 28.5). Permanent labor is the dominant employment type (mean = 79.5%), with temporary labor used sparingly (6.2%). These patterns align with semicommercial systems characterized by mixed family-commercial labor and limited mechanization. However, the lack of detailed sociodemographic indicators—such as household size, education level, or gender of the farm manager—limits our ability to explore broader equity or livelihood outcomes, and we acknowledge this as a limitation of the current survey instrument.

Finally, the limited use of recordkeeping systems may constrain informed decisionmaking. Only 30.5% of producers reported using any form of technical records, and just 3.5% used digital software tools. This low adoption of formal recordkeeping could hinder long-term planning, traceability, and the uptake of sustainable management practices. Collectively, these descriptive insights suggest that farmers operate in complex, diversified systems where technical, economic, and informational constraints intersect—justifying the inclusion of multiple farm and household-level variables in the empirical analysis.



6

WHAT SHAPES SILVOPASTORAL AND REGENERATIVE LIVESTOCK ADOPTION? EVIDENCE FROM CHILE

Felipe Bravo-Peña, Homa Taheri
and Claus Köbrich

Abstract

This paper studies the adoption of silvopastoral systems (SPS) and regenerative livestock approaches (RLA) in southern Chile, where cattle farming is central to rural livelihoods. We use original representative survey data for 383 beef and dual-purpose producers in three regions that account for two-thirds of the national herd to estimate associations between adoption decisions and structural, socioeconomic, institutional, attitudinal, and perceptual variables. We find that SPS and RLA have distinct adopter profiles: RLA adoption is associated with larger herd size, higher stocking rates, and higher formal education (college and postgraduate); SPS adoption correlates with smaller farms, environmental motivations such as greenhouse gas mitigation, and limited access to conventional machinery and inputs. Gender interacts significantly with technical assistance: although women are more likely to adopt SPS and less likely to adopt RLA, the pattern is reversed when advisory support is available. Environmental perceptions also play a role: beliefs that RLA improves soil fertility and that SPS reduces greenhouse gas emissions are influential factors. After controlling for observed variables, we find no residual association between SPS and RLA adoption, indicating that each practice responds to unique motivations and conditions. Such heterogeneity implies that a one-size-fits-all policy is unlikely to be effective. Targeted, evidence-based policies—such as soil health monitoring, carbon-linked incentives, and payments for ecosystem services—are needed to encourage adoption.

Introduction

In the livestock sector, climate change and environmental degradation pose major challenges that demand transformative responses. Livestock production accounts for approximately 14.5% of global greenhouse gas emissions and contributes to deforestation and biodiversity loss (Li & Jiang, 2021; Rojas-Downing et al., 2017). At the same time, climate change adversely affects animal health, productivity, and reproductive performance, threatening the sustainability and resilience of livestock systems (Bernabucci, 2019). Mitigation and adaptation efforts increasingly focus on sustainable livestock practices. Mixed crop-livestock systems, for example, can reduce deforestation by 76 million hectares over 30 years (Weindl et al., 2015), and improved management boosts productivity with fewer environmental harms (Melo et al., 2021). Strategies such as improved feed quality, genetic selection, and animal health management also enhance resilience under climatic stress (Paul et al., 2020; Schader et al., 2015). Integrated approaches can deliver synergies by lowering emissions and enhancing ecosystem services (Notenbaert et al., 2021).

Two approaches—regenerative livestock approaches (RLA) and silvopastoral systems (SPS)—have attracted growing attention. RLA comprises adaptive grazing practices centered on high-density, short-duration grazing followed by extended pasture recovery periods (Bravo-Peña et al., 2025). It has been shown to enhance soil carbon sequestration (Santos et al., 2024), reduce greenhouse gas emissions (GHGs), and improve ecosystem functioning and animal welfare (Pinheiro Machado, 2016; Pinheiro-Machado et al., 2021). SPS integrates trees, forage, and livestock in a single production unit; it contributes to carbon sequestration, promotes biodiversity, and improves soil fertility while also increasing production flexibility and diversifying farm income (Yadav et al., 2019).

Despite their benefits, empirical research on the adoption of RLA and SPS is limited. Nearly two decades ago, Prokopy et al., (2008) noted that most studies on the adoption of sustainable practices focused on cropping systems rather than livestock, a trend that continues today. For example, Arslan (2020) highlighted a significant bias toward agronomic practices in adoption studies across Africa, with only 2% addressing livestock. Evidence on RLA and SPS adoption is even scarcer.

This study aims to help fill this gap by examining structural, socioeconomic, institutional, and perceptual factors associated with the adoption of RLA and SPS in Chile, using data from a representative sample of livestock producers in three regions that account for two-thirds of the national herd. It is among the first econometric studies on RLA adoption and one of the few on SPS (as distinct from broader agroforestry) in Latin American cattle systems. Our findings contribute not only to Chile's climate goals and rural development agenda but also to broader global efforts to advance the sustainability of the livestock sector in regions facing similar environmental and socioeconomic challenges.

The remainder of the paper is organized as follows.

Section 6.1.
Literature review

Section 6.2
Analytical framework

Section 6.3
Data

Sections 6.4
Empirical framework

Section 6.5
Results

Section 6.6
Discussion

Section 6.7
Conclusions

6.1 Literature Review

Although direct research on the adoption of silvopastoral and regenerative livestock systems is limited, related studies on agroforestry, integrated crop-livestock systems, and sustainable livestock offer insights. This section summarizes global empirical evidence on the main barriers to adoption.

Structural factors: Farm and herd size. Evidence suggests that larger farms and herds are more likely to adopt sustainable technologies because they can better absorb initial costs and allocate land for experimentation (Herrera et al., 2023; Hyland et al., 2018; Mujeyi et al., 2022). These trends are consistent across grazing strategies, agroforestry, and integrated crop-livestock systems (Jara-Rojas et al., 2020; Owombo & Idumah, 2017; Perosa et al., 2021).

Economic conditions, labor availability, and resources. Although financial stability facilitates SPS adoption (Apan-Salcedo et al., 2022), context matters: some studies find higher adoption among lower-income producers (Zabala et al., 2022). Labor-intensive practiceslike SPS and RLA are more likely to be adopted when producers have more workers available (Beshir et al., 2022; Hyland et al., 2018). Limited access to machinery and high maintenance costs are also cited as barriers (Vargas-De la Mora et al., 2021).

Sociodemographic variables: Age, gender, and education. Younger farmers tend to be more open to innovation (Gebrezgabher et al., 2015), whereas older ones may not adopt long-term practices with delayed returns (Jara-Rojas et al., 2020). Although evidence for SPS and RLA is scarce, studies on climate-smart agriculture suggest that women-led farms may be more engaged in sustainability (Bravo-Peña, 2025; Mujeyi et al., 2022). The relationship between education and adoption varies by practice. Higher education is often linked to the adoption of technically complex practices, such as measurement of GHGs and circular farming innovations (Fernández-Habas et al., 2022; Herrera et al., 2023). However, contradictory evidence exists (See Gebrezgabher et al., 2015; Ogunlana, 2004).

Networks, technical assistance, training, and knowledge exchange. Membership in producer organizations increases SPS and RLA adoption by reducing uncertainty and enabling collective action (Didier & Brunson, 2004; Zabala et al., 2022). Similarly, membership can enhance the flow of technical information and practical experiences, as observed in agroforestry and strip-farming (Beshir et al., 2022; Ogunlana, 2004). Technical assistance and training generally facilitate adoption (Perosa et al., 2021; Vargas-De la Mora et al., 2021), although conventional extension services are not always effective (de Souza et al., 2021).

Perceptions of benefits and costs. Perceived environmental or productivity gains influence adoption decisions (de Mello Brandão Vinholis et al., 2021). When benefits are unclear or returns delayed, producers may opt out (Abolhassani et al., 2013; Borges, 2015). High upfront costs for SPS (e.g., fencing, trees, labor) are a known deterrent (Abdul-Salam et al., 2022), especially where farmers work under financial constraints (Didier & Brunson, 2004).

Risk, social influences, environmental attitudes, and motivations. Fear of failure, uncertainty, and resistance to change discourage adoption (Calle et al., 2013; Martin et al., 2004; Vargas-De la Mora et al., 2021). Risk-reduction tools such as crop insurance or forward contracts can offset these concerns and raise uptake (Melo et al., 2021). Social norms and peer pressure can either hinder or encourage adoption, depending on prevailing practices (Didier & Brunson, 2004). Environmental awareness—especially knowledge about soil health and climate change—often supports adoption; lack of awareness may limit interest (Herrera et al., 2023; Wang et al., 2020).

6.2 Analytical framework

The work of Griliches (1957) on hybrid seed corn adoption laid the foundation for modeling technology uptake in agriculture. Subsequent studies of farmers' adoption decisions have frequently used limited dependent variable econometric models underpinned by a random utility analytical framework (Olwande et al., 2009; Pindyck & Rubinfeld, 1998; Rahelizatovo & Gillespie, 2004). We use this approach to examine adoption of RLA and SPS. Since this framework is well established in the literature, we only provide a brief sketch here.

Suppose the utility of farmer n from choosing option i, U_{ni}, has an observed component, V_{ni}, and an unobserved one, ϵ_{ni}, such that $U_{ni} = V_{ni} + \epsilon_{ni}$ (Train, 2009). The assumption that ϵ_{ni} follows an independent and identically distributed (IID) extreme value distribution implies a logit discrete choice model (Luce & Suppes, 1965).

We assume that the representative utility of farmers is linear in parameters and takes the form $U_{ni} = \beta' x_{ni} + \epsilon_{ni}$, where x_{ni} is a vector of observed variables relating to sustainable practice i.[1] The model satisfies the independence of irrelevant alternatives (IIA) assumption, meaning that the relative odds of adopting SPS versus RLA depend only on attributes of these two options (Appendix, Section A4.3.6).

Let the sample size be N. Then the probability of person n choosing the alternative that she has actually chosen would be $\prod_i (P_{ni})^{y_{ni}}$, where $y_{ni} = 1$ if person n chooses alternative i, and 0 otherwise, and $P_{ni} = \frac{e^{V_{ni}}}{\sum_{j=1}^{J} e^{V_{nj}}}$ is the choice probability over options.
Assuming that the choices of decisionmakers are independent (something our randomly stratified sampling supports), we can derive the probability that person n chooses the alternative she was actually observed to choose is $L(\beta) = \prod_{n=1}^{N}\prod_{i=1}^{J}(P_{ni})^{y_{ni}}$, where β is a vector

containing the parameters of the model. The log-likelihood function is then $LL(\beta) = \sum_{n=1}^{N} \sum_{i=1}^{J} y_{ni} \, ln(P_{ni})$, and the estimator is the value of β that maximizes this function. For linear-in-parameters utility functions, McFadden (1972) shows that $LL(\beta)$ is globally concave.

6.3 Data

6.3.1 Survey

6.3.1.1 Case study description

Our study focuses on three regions (first-order administrative units) in southern Chile—La Araucanía, Los Ríos, and Los Lagos—where cattle farming is a core economic activity shaped by fragmented production systems. These regions account for about two-thirds of the national herd. According to the Agricultural Census, the area is home to 14,918 cattle farms managing a total of 924,740 head of cattle, with an average farm size of 70 hectares and 62 head per farm (INE, 2022). Grazing is the primary feeding strategy: the study area includes 580,000 hectares of natural grasslands, 427,000 hectares of improved pastures, and 81,000 hectares of forage crops (INE, 2024). Small-scale producers dominate the region—more than half the farms have fewer than 10 head of cattle—but there are some large operations. This fragmentation makes the area a good case for examining the dynamics of pasture-based livestock systems and the potential for implementing sustainable grazing management practices.

6.3.1.2 Sampling strategy

Sampling was based on Chile's Official Livestock Information System (in Spanish, abbreviated SIPEC), a mandatory registry maintained by the Agricultural and Livestock Service (SAG). Because producers must file an updated livestock inventory with SIPEC at least once a year—between 1 August and 30 November— the version we accessed in May 2024 reflects declarations for the second half of 2023. We filtered records to include only beef or dual-purpose cattle farms with at least 10 head of cattle and available contact information. This filtering yielded a sampling universe of 6,767 eligible farms in the three regions.

The sample was stratified by region, herd size, and operator gender, reflecting the structure reported in the latest agricultural census. Poststratification weights were applied to adjust for response bias. We estimated the required sample size using Cochran's formula for finite populations (Cochran, 1977), targeting a 95% confidence level and 5% margin of error. This yielded a target of 382 respondents. Assuming a 15% response rate, we randomly selected 2,569 producers for contact.

6.3.1.3 Data collection

Of the 2,569 selected (equivalent to the estimated 15% response rate), only 1,675 needed to be contacted to reach the expected sample size. . The order of calls was randomized to avoid selection bias. Among the 1,675 contacted, approximately 10% had invalid contact information, and another 10% did not meet the eligibility criteria. The remaining cases did not respond after three attempts and were classified as nonresponsive.. The adjusted response rate was 28.6%, yielding 383 completed interviews. Surveys were conducted by phone between October 28 and December 5, 2024, using Qualtrics software. The questionnaire appears in the Appendix, Section A7.

6.3.2 Variables

6.3.2.1 Dependent variables

We defined three binary dependent variables capturing adoption status: (1) SPS adoption, (2) RLA adoption, and (3) joint adoption of both (Table 1). During the survey, producers received descriptions of each practice and confirmed whether they implemented them. RLA adoption required additional verification of rotational intervals of ≤3 days, based on agronomic criteria from the literature (Kampherbeek et al., 2023; Kanneganti & Kaffka, 1995; Teutscherová et al., 2021).

Table 1. Definition and Coding of Adoption Variables

Variable	Coding	Explanation to interviewee
sps adoption Adoption of silvopastoral systems (SPS)	0 = No; 1 = Yes (adopts SPS, does not adopt RLA)	"This practice integrates livestock farming with tree maintenance in the same space. This practice involves planting trees and shrubs in grazing areas, and allows for harvesting additional products such as wood, firewood, and fruits."
rla adoption Adoption of regenerative livestock approaches (RLA)	0 = No (does not adopt or rotation >3 days); 1 = Yes (adopts, rotation ≤3 days and does not adopt SPS)	"This strategy focuses on applying planned grazing methods. It involves rotating livestock between different pasture areas or paddocks in an organized manner, maintaining a high density of animals for short periods of time, and then allowing time for the pasture to recover. Specific examples of this include so-called planned holistic grazing, multi-paddock adaptive grazing, intensive rotational grazing, regenerative grazing, or Voisin Rational grazing (among others)."
joint adoption Adoption of both SPS and RLA	0 = No (adopts neither or only one); 1 = Yes (adopts both)	NA

6.3.2.2 Control variables

Control variables span six dimensions. (1) Farm characteristics reflect structural and management variables (e.g., production cycle, stocking rate). (2) Demographics include age, gender, and education. (3) Institutional support captures organizational membership, training, and access to advice. (4) Attitudes and behavior measure perceptions of labor and cost intensity, risk preferences, and status quo bias. (5) Social and community dynamics account for peer influence, social norms, and recognition. (6) Environmental perceptions gauge beliefs about climate change, soil fertility, and GHG mitigation. Full definitions and coding appear in Table 2; expected signs and sources are in the Appendix, Section A4, Table A4.

Table 2. **Categories, definitions, and coding, of control variables**

Category	Variable	Definition	Coding
Farm characteristics	*prod cycle*	**Production cycle:** Primary production focus of farm	Breeding-Rearing [0], Breeding-Fattening [1], Breeding [2], Rearing-Fattening [3], Rearing [4], Fattening [5], Complete cycle [6]
	income	**Farm income:** Number of animals traded in past 12 months	Continuous (number of animals sold)
	stratum	**Herd size:** Number of cattle owned by farm (category)	Categorical: 10–24 [1], 25–49 [2], 50–99 [3], 100–249 [4], 250+ [5]
	La Araucania; Los Lagos; Los Ríos	**Region:** Geographic location of farm	Los Lagos, Los Ríos, La Araucanía (dummies)
	stock rate	**Stocking rate:** Farm size (ha) divided by number of animal	Continuous (ha/animal)
Demographics	*educ*	**Educational level:** Highest level of education completed	Elementary or less [1], High School [2], College [3], Graduate [4]
	sex	**Gender:** Biological sex of respondent (recorded by interviewer)	0 = Male, 1 = Female
	age	**Age:** Estimated from national ID number	Continuous (years)
Institutional and social capital	*org*	**Organizational membership** in producer associations or cooperatives	None [0], One or more memberships [1]
	training	**Participation in training/ workshops programs** on livestock or rangeland management in past 12 months.	None [0], Once [1], Twice [2], More than twice [3]
	advisor access	**Access to technical assistance:** Frequency of access	Never [0], Occasionally [1], Frequently [2]
	type assistance	**Type of assistance:** Primary source of technical assistance	Government program [1], Paid professional [2], Input supplier advisor [3], Peer producer [4]
	sps info; rla info	**Access to information (SPS/ RLA)** about SPS or RLA in past12 months	No [0], Yes [1] (for each practice)
Attitudinal and behavioral	*sps labor; rla labor*	**Labor requirements (SPS/ RLA)** for RLA or SPS relative to current practices	Less [0], Same [1], More [2]. (for each)
	machine access	**Access to inputs/machinery:** Ease of access to inputs and machinery	Difficult [0], Moderate [1], Easy [2]

Attitudinal and behavioral	*sps cost; rla cost*	**Cost perception** of implementing RLA or SPS	Low [0], Moderate [1], High [2]
	risk aversion	**Risk preference** based on hypothetical coin-flip scenarios	High risk-seeking [0] to high risk-averse [3]
	status quo	**Belief about status quo:** preferring familiar practices over new ones	Agree [0], Disagree [1]
Social and community influence	*peer influence*	**Peer influence:** Perceived importance of peer opinions	Little [0], Moderate [1], High [2]
	social norm	**Social acceptance:** Perception of social acceptance of SPS and RLA	Not accepted [0], Moderately accepted [1], Widely accepted [2]
	recognition	**Perceived recognition** for implementing sustainable practices.	Recognition of efforts: Little [0] to A lot [2]
Environmental perceptions	*climate change*	**Concern for climate change** effects on livestock production.	Not at all [0] to very concerned [4]
	sps soil; rla soil	**Soil fertility:** Belief that RLA or SPS improves soils.	No [0], Yes [1]
	sps climate; rla climate	**GHG reduction:** Belief that SPS or RLA reduces emissions	No [0], Yes [1]

6.4 Empirical framework

We analyzed the survey data following standard procedures for complex sampling (Lehtonen & Pahkinen, 2004; Levy & Lameshow, 2013), accounting for stratification weights and observation counts per stratum. Our analysis focused on three outcomes: (i) adoption of SPS, (ii) adoption of RLA, and (iii) joint adoption of both. All models were estimated using the same survey-weighted logistic regression framework to ensure comparability:

$$ln\left(\frac{P(y = y_i)}{P(y = y_0)}\right. = b_{i0} + b_{i1} X_{i1} + b_{i2} X_{i2} + b_{i3} X_{i3} + \ldots + b_{ik} X_{ik}$$

where y_i is choice of output i, y_0 is the choice of the base output, and X_{i1} are independent variables.

We began by specifying a comprehensive model that included all variables listed in Table 2, which reflect structural, institutional, and attitudinal dimensions previously linked to adoption behavior in the literature (Section 2). Rather than estimating a single final model up front, we gradually built the specification in stages. We first examined structural variables, such as demographics, production characteristics, and regional factors, before incorporating institutional elements like organizational membership, technical support, and training participation. Once these foundational factors were assessed, we extended the model to account for behavioral traits, including risk preferences, social norms, and status quo bias. Finally, we introduced perceptions specifically tied to the adoption of SPS and RLA, such as expectations of environmental benefits or access to information. This sequential approach allowed us to observe how each block of variables contributed to model performance and interpretability.

Throughout this process, we closely monitored diagnostic indicators. Multicollinearity was assessed using generalized variance inflation factors (GVIFs), which did not reveal problematic correlations among explanatory variables (Appendix A4). We also compared alternative model specifications using information criteria (AIC, BIC) and pseudo-R2 measures such as McFadden's R2, with detailed results reported in the supplementary tables. When theory suggested potential synergies, we explored interaction terms—for example, between status quo bias and risk aversion or between gender and training participation—and retained only those that significantly improved model fit.

As the models evolved, we prioritized parsimony and theoretical coherence. The final specifications represent a balance between statistical significance, predictive accuracy, and the interpretability required for policy insights. In addition to the separate analyses of SPS and RLA adoption, we examined the possibility of joint decision making. We defined a joint adoption indicator—coded as 1 when both SPS and RLA were implemented, and 0 otherwise—and subjected it to the same model-building procedure. To account for potential correlations between the SPS and RLA adoption decisions, we also explored a bivariate modeling framework, explicitly testing the error-correlation structure of the two equations

6.5 Results

6.5.1 Descriptive statistics

We compared demographic, structural, and attitudinal indicators by gender (see Appendix Table S3 for full descriptive statistics). On average, male farmers are slightly older and operate larger farms with larger herds, though differences are modest. In contrast, female farmers report higher stocking rates and animal sales, suggesting more intensive production despite smaller landholdings. Men report better access to machinery. Women receive more technical assistance and participate more in training. Women also express greater concern for climate change and higher risk aversion. Although they perceive higher implementation costs for RLA, their expectations of benefits are similar to those of men.

Regarding social capital, men report stronger peer influence and perceived recognition, possibly reflecting the male-dominated nature of the sector. However, women report slightly more frequent access to information about SPS and RLA.

Adoption patterns show no significant gender difference in SPS or joint adoption, but men are significantly more likely to adopt RLA (38.9% vs. 30.4%). Joint adoption remains low (~12%) for both groups.

6.5.2 Comparative regression results (SPS, RLA, Joint Adoption)

Table 3 presents the main regression results for the adoption of SPS, RLA, and both practices jointly. Estimates are based on survey-weighted logit models. We report average marginal effects, standard errors, and significance levels. Fixed effects for production cycle and region are included in the models but omitted from Table 3 for concise exposition (a version that includes fixed effects is in the Appendix, Table A8). As discussed in Section 7, results should be interpreted as associations rather than causal effects.

Table 3. Association between adoption and farmer characteristics: Average marginal effects

Variable	SPS	RLA	Joint
Age	-0.001*** (0.0003)	0.003*** (0.0003)	0.000*** (0.0002)
Sex (female)	0.163*** (0.010)	-0.279*** (0.022)	-0.117*** (0.012)
Herd size	-0.015*** (0.003)	0.021*** (0.003)	0.015*** (0.002)
Educ: high school	0.018** (0.009)	0.058*** (0.009)	0.023*** (0.006)
Educ: college	-0.029*** (0.010)	0.044*** (0.010)	0.040*** (0.007)
Educ: graduate	-0.087*** (0.019)	0.117*** (0.018)	0.155*** (0.015)
Income (animals sold)	0.000*** (0.00001)	0.000*** (0.00001)	-0.000*** (0.00001)
Stock rate (ha/animal)	-0.017*** (0.002)	0.049*** (0.002)	0.004*** (0.001)
Org (association)	0.002 (0.009)	-0.060*** (0.009)	0.083*** (0.006)
Advisor access	0.034*** (0.005)	0.004 (0.006)	-0.084*** (0.005)
Training	-0.041*** (0.004)	0.072*** (0.004)	0.034*** (0.002)
Status quo (prefers familiar)	-0.021*** (0.007)	0.026*** (0.007)	-0.044*** (0.005)
Peer effect	-0.057*** (0.005)	-0.101*** (0.004)	0.033*** (0.004)
Risk aversion	-0.024*** (0.003)	0.032*** (0.003)	-0.005* (0.002)
Machine access	-0.066*** (0.005)	-0.033*** (0.005)	0.019*** (0.004)
SPS info	0.050*** (0.010)		0.146*** (0.009)
SPS improves soil	-0.036*** (0.008)		0.088*** (0.011)
SPS reduces GHG	0.089*** (0.008)		0.171*** (0.009)
RLA info		-0.090*** (0.009)	-0.007 (0.009)
RLA improves soil		0.218*** (0.018)	0.059*** (0.014)
RLA reduces GHG		-0.041*** (0.008)	-0.098*** (0.007)
Sex × adviser access	-0.219*** (0.010)	0.120*** (0.016)	0.119*** (0.007)
Pseudo-R^2	0.305	0.264	0.338
AIC	407.41	270.38	368.55
BIC	517.95	392.77	479.09
Observations	383	383	383

Notes: *p<0.1; **p<0.05; ***p<0.01. All models include fixed effects for production cycle and region, omitted from this table for space.

6.5.2.1 Common factors associated with adoption of both practices

Our results show that certain factors are associated with the adoption of both SPS and RLA. Secondary education (high school) is consistently and positively associated with all three outcomes: +1.8 pp for SPS, +5.8 pp for RLA, and +2.3 pp for joint adoption (all $p<0.01$), relative to those with only primary education or less. Several factors have similar effects on the adoption of both SPS and RLA but a different effect on joint adoption. Greater sensitivity to peer opinions reduces the likelihood of adopting SPS (–5.7 pp) and RLA (–10.1 pp) but increases joint adoption (+3.3 pp), indicating divergent social dynamics between adopting single versus multiple innovations. Machinery access mirrors this pattern: easier access lowers the probability of adopting SPS (–6.6 pp) and RLA (–3.3 pp) but is positively associated with joint adoption (+1.9 pp). Finally, although farm income—proxied by the number of animals sold—is statistically significant in all three models, its effect size is minimal (<+0.01 pp per additional animal sold) for all models, suggesting it has limited economic significance.

6.5.2.2 Divergent factors between practices

Several factors have different effects on SPS and RLA. Age is statistically significant but substantively weak in explaining adoption patterns; for instance, increasing age from 30 to 60 raises the likelihood of RLA adoption by only +0.09 pp. Gender dynamics are notable: women are more likely to adopt SPS (+16.3 pp) but less likely to adopt RLA (–27.9 pp) and both practices jointly (–11.7 pp). However, these patterns shift with access to technical advice. For women, technical assistance reduces SPS adoption (interaction: –21.9 pp) but increases RLA (+12.0 pp) and joint adoption (+11.9 pp), contrasting with modest average effects among men. Herd size is negatively associated with SPS (–1.5 pp per category increase) but positively associated with RLA (+2.1 pp) and joint adoption (+1.5 pp). Stocking rate shows a similar split: negative for SPS (–1.7 pp) but positive for RLA (+4.9 pp), indicating that more intensive systems align better with RLA uptake. Higher education (college or postgraduate) also drives divergence. College-educated farmers are less likely to adopt SPS (–2.9 pp) but more likely to adopt RLA (+4.4 pp). These effects are amplified at the postgraduate level (–8.7 pp for SPS, +11.7 pp for RLA). For joint adoption, both levels are positively associated (+4.0 pp and +15.5 pp, respectively). Training participation increases RLA (+7.2 pp) and joint adoption (+3.4 pp) but reduces SPS uptake (–4.1 pp). Attitudinal factors also differ. Preference for familiar practices lowers SPS adoption (–2.1 pp) but increases RLA (+2.6 pp). Similarly, higher risk aversion reduces SPS uptake (–2.4 pp) but raises RLA adoption (+3.2 pp).

6.5.2.3 Practice-specific factors

Last, we identified practice-specific factors that affect only a certain practice or set of practices. For SPS, access to information (+5.0 pp) and regular technical advice (+3.4 pp) are positively associated with adoption. Belief in SPS's GHG mitigation benefits strongly predicts uptake (+8.9 pp), whereas belief in soil fertility improvements is negatively associated (–3.6 pp). In the joint adoption model, receiving SPS information (+14.6 pp) and holding positive beliefs about GHG reduction (+17.1 pp) are among the most influential factors. Notably, soil fertility belief shifts from negative (in SPS) to positive in the joint model (+8.8 pp).

For RLA, organizational membership (–6.0 pp) and exposure to RLA-specific information (–9.0 pp) are negatively associated with adoption. In contrast, belief in RLA's soil fertility improvement is the strongest positive predictor (+21.8 pp). Surprisingly, belief in RLA's GHG mitigation is negatively associated (–4.1 pp), possibly reflecting disconnects between climate narratives and producers' experience.

In the joint adoption model, some associations invert relative to the single-practice models. Peer influence (+3.3 pp) and machinery access (+1.9 pp), become positive, access to technical assistance (positive for SPS) now predicts lower joint adoption (–8.4 pp), and organizational membership becomes strongly positive (+8.3 pp).

Additionally, we explored residual interdependence in adoption decisions using a bivariate logit model. The analysis found negligible correlation between SPS and RLA choices—indicating that unobserved joint determinants are minimal. Detailed estimates and diagnostics for this model are presented in the Appendix, Section A4, Table A9.

6.6 Discussion

Our results identify the most salient correlates of SPS and RLA adoption in southern Chile. We focus on variables with average marginal effects above ±5 percentage points, since smaller effects, while statistically significant, may have limited practical relevance.

Distinct practices can show divergent adoption profiles. These patterns are consistent with the diffusion of innovations theory (Rogers, 2003), which posits that the characteristics of an innovation shape its adoption. RLA adoption aligns with traits linked to sustainable intensification—larger herds, higher stocking rates, formal education, interest in soil improvement, and participation in technical training (Campbell & King, 2022; Latawiec et al., 2014; Teutscherová et al., 2021). SPS, by contrast, is more common among smaller-scale producers, who are probably motivated by environmental and diversification goals. These adopters perceive SPS as contributing to GHG mitigation and report less access to machinery—traits associated with multifunctional or agroforestry systems (Nahed-Toral et al., 2013; Pignataro et al., 2016; Smith et al., 2022). These differences reflect broader trends showing that adoption drivers vary across sustainability practices (Ahmed, 2015; Anang et al., 2023; Prokopy et al., 2008). Treating adoption of sustainable livestock practices as homogeneous therefore risks ignoring such distinct dynamics.

Gender differences offer actionable insights for extension services. In line with the literature that has identified gender differences in the adoption of sustainable practices (Bravo-Peña, 2025; Karami & Mansoorabadi, 2008), we find that women are more likely to adopt SPS but less likely to adopt RLA. However, if women have access to technical assistance, this pattern reverses. For SPS, the interaction between being female and receiving technical advice is strongly negative, suggesting that advisers may emphasize RLA because it aligns with productivity metrics, which are frequently used to evaluate the results or efficiency of public policies (DIPRES, 2018; Landini et al., 2017; Wright et al., 2025). For women without such support, SPS appears more feasible, given women's roles in income diversification and household subsistence strategies (Cubbage et al., 2012; Nahed-Toral et al., 2013).

Education is an important filter for complexity. University-level education is positively associated with RLA and joint adoption but negatively linked to the SPS. This pattern does not necessarily imply that more educated farmers have stronger preferences for RLA. Rather, it suggests that RLA presents higher cognitive and technical barriers to entry, which university education helps to lower. This aligns with prior research showing that education enhances the ability to adopt complex technologies and practices (López-Maciel et al., 2025; Maini et al., 2021; Ruzzante et al., 2021). In contrast, a less complicated practice, like SPS, may appear more accessible to farmers with less formal education.

Environmental perceptions play a relevant role as predictors of adoption. The belief that RLA improves soil fertility is the strongest predictor across all models, highlighting its relevance for forage productivity, resilience, and perceived returns (Barrowclough et al., 2016; Leddin et al., 2023; Rosa-Schleich et al., 2024). In contrast, SPS adoption is more closely linked to collective environmental benefits, particularly GHG mitigation. The semipermanent nature of SPS may heighten perceptions of irreversibility and risk, which helps explain why risk aversion and preference for the status quo are negatively associated with SPS adoption but positively related to RLA uptake. This pattern aligns with insights from the agroforestry literature, which suggest that the structural permanence of SPS can increase its perceived riskiness (Gebremedhin et al., 2023).

Peer effect shapes adoption patterns in contrasting ways. Peer influence reduces the likelihood of adopting SPS or RLA separately but increases the probability of joint adoption. This likely reflects the social context: in conservative settings, peers may reinforce traditional practices, whereas in more progressive contexts, they may support innovation (Ball et al., 2020; Muhammad et al., 2019). Similarly, access to machinery negatively correlates with separate SPS or RLA adoption but has a weakly positive correlation with joint adoption. This supports the idea that producers with limited access to mechanization may turn to agroecological alternatives that require fewer inputs (Gliessman, 2002). RLA, for example, can reduce dependence on tillage and fertilizers by enhancing soil functions through managed grazing (Bravo-Peña et al., 2025).

Limitations. Despite careful design, our study has several limitations. First, although SIPEC is the most comprehensive and official registry of cattle farms in Chile, it may not fully reflect recent changes in herd composition or farm activity at the time of sampling. Second, reliance on producers to report adoption introduces potential misclassification, particularly for RLA, given its technical complexity. Although definitions were provided during the survey, accurate identification depended on respondents' understanding. To address inconsistencies, we applied a post hoc correction, requiring rotational grazing intervals of less than four days, aligning with agronomic standards. However, this operational correction may still imperfectly reflect actual behavior. Third, our cross-sectional and observational empirical design limits causal inference. Although we control for multiple covariates and test for robustness, unobserved variables—such as latent attitudes or market dynamics—may bias estimates. Findings should thus be interpreted as correlations. Finally, our binary models do not capture variation in adoption intensity. Future research could apply Tobit or double-hurdle models (Cragg, 1971; Tobin, 1958) or explore hybrid choice models incorporating latent constructs (Abou-Zeid & Ben-Akiva, 2024), enabling richer behavioral insight.

6.7 Conclusions

Adoption profiles for SPS and RLA are distinct. RLA uptake is associated with larger herd sizes, higher stocking rates, and advanced formal education, indicating an orientation toward sustainable intensification. In contrast, SPS adopters tend to be smaller-scale producers who are motivated by environmental goals, like GHG mitigation, and have limited reliance on conventional machinery. These contrasting profiles highlight the need for differentiated extension strategies: RLA promotion should emphasize technical training and soil health outcomes, and SPS outreach should focus on ecosystem services and income diversification.

Second, gender and technical assistance have complex associations. Women without technical support favor SPS, but with access to advice, their adoption patterns shift toward RLA. Although causality cannot be confirmed, these dynamics suggest that current extension programs may privilege intensive practices like RLA, inadvertently sidelining SPS, which may align better with women's roles in income diversification and household security (Cubbage et al., 2012; Landini et al., 2017). Extension systems should therefore be gender-responsive and offer guidance tailored to producers' objectives and contexts.

Third, although we cannot rule out the possibility of reverse causality (adoption affect perceptions), our results suggest that environmental perceptions and technical capital may help shape adoption decisions. Perceived benefits, such as improved soil fertility in the case of RLA and reduced GHG emissions for SPS, are strongly associated with adoption. Higher formal education significantly increases the likelihood of adopting technically complex RLA, whereas targeted training programs could help less-educated producers overcome perceived barriers. To the extent that perceptions drive adoption, extension campaigns should move beyond generic "sustainability" messages and deliver clear, concrete information tailored to producers' educational backgrounds and information channels—for example, "RLA increases soil organic matter by X percent in Y years, producing Z benefits," or "SPS captures X tons of CO_2 per hectare."

Finally, our results suggest that policymakers should not assume natural synergies between these practices. Bivariate analysis shows no significant residual association between SPS and RLA adoption, supporting separate modeling and policy design for each. Further, given that RLA adoption is strongly driven by producers' belief in measurable soil fertility gains, public extension programs should prioritize on-farm soil health monitoring—such as subsidized soil audits, user-friendly cost-benefit calculators, and carbon measurement services—especially for smaller farms. For SPS, extension programs can leverage the perceived benefits of GHG mitigation by piloting carbon-linked incentives and simplified GHG verification schemes. These efforts could be reinforced through Chile's new Biodiversity and Protected Areas Law (SBAP), which establishes a legal framework for payments for ecosystem services (PES). By compensating producers who conserve or restore native vegetation through systems like SPS, PES contracts could serve as a strategic financial tool to promote sustainable land management.

Future research could prioritize longitudinal designs to capture adoption intensity over time. Moving toward causal inference will require instrumental variables or natural experiments. In Chile, subsidies from the National Institute for Agricultural Development (INDAP) or eligibility for the incentive system of the Agro-Environmental Sustainability of Agricultural Soils (SIRSD-S program) may serve as credible instruments. Further, field-based cost-benefit analyses are needed to inform producers' risk perceptions and support broader adoption. Gender-focused qualitative studies can also deepen understanding of structural barriers for women. Extending this research to other Latin American contexts would enable assessment of scalability and institutional relevance across diverse agroecological settings.

Acknowledgments

We thank Dr. Emiliano López-Barrera (Texas A&M University) and Dr. Allen Blackman, as well as the IDB Scientific Committee, for their valuable feedback throughout the study. We are also grateful to the Chilean Agriculture and Livestock Service (SAG) and the National Institute for Agricultural Development (INDAP) for facilitating access to participating producers. We extend our sincere appreciation to the ranchers who participated in the survey for their time and insights.

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Appendix

A1. Data description and preliminary analysis

Table A1. A1. Comparison of sample and population characteristics

Characteristic	Sample (%)		Population (%)		Difference (%)
Gender	Female	20.62%	Female	19.55%	1.07%
	Male	77.80%	Male	79.72%	1.92%
Stratum	Stratum 1	45.6%	Stratum 1	41.5%	4.1%
	Stratum 2	21.1%	Stratum 2	23.9%	2.8%
	Stratum 3	13.3%	Stratum 3	14.9%	1.6%
	Stratum 4	9.1%	Stratum 4	10.5%	1.4%
	Stratum 5	10.7%	Stratum 5	9.1%	1.6%
Region	Region 1	24.02%	Region 1	25.97%	1.95%
	Region 2	52.48%	Region 2	50.95	1.53%
	Region 3	23.49%	Region 3	23.06%	0.43%

Adjustment using sampling weights. Given the minor discrepancies observed, particularly in educational levels, we apply sampling weights to adjust for under- or overrepresentation of groups in our sample. We calculated weights using the inverse probability of selection for each stratum, using the population proportions from the agricultural census.

Application of sampling weights. We incorporated the sampling weights into the multivariate logit model estimation to ensure that the results are representative of the population. The weighted analysis accounts for the differences in the probability of selection and corrects for any potential biases due to over- or under-sampling of specific groups.

Incorporation into empirical analysis. All descriptive statistics and regression analyses presented in the following sections are weighted using the sampling weights derived from the population data. This approach enhances the validity of our findings and ensures that they are generalizable to the broader population of livestock farmers in the study regions.

A2. Preparation of variables for modeling

Data cleaning. RLA is a function of frequency of rotation. A subset of the survey respondents reported their rotation in terms like every "1 to 7" days, "2 to 4" days, or " it depends on the season." We coded the values for these intervals by the average of the numbers (4 and 3, respectively), and we coded "depends on the season" as missing values.

Missing values. Two categories of variables have missing values, categorical and numerical. For variables created based on responses to conditional questions, the surveyor asked follow-up questions based on earlier answers. Missing values indicate that the respondent did not have a chance to reply to the follow-up questions, since they were not presented. To fill the missing values for these variables, we artificially created an extra option of "no opinion" [0] and used that. We took these variables as categorical, to prevent any negative consequences of this data manipulation on the analysis. These variables are type_assistance, rla_labor, sps_labor, sps_cost, rla_cost, rla_expectation, and sps_expectation.

The second category is based on responses to unconditional questions: age, educ, farm_size, income, social_norm, rla_soil, sps_soil, rla_climate, sps_climate, risk_aversion and stock_rate. Here, missing values indicate lack of response from the participants. We used regression on all other variables without missing values to mutate these missing values, which then enter the models as numerical regressors. We used the following variables for imputing the missing values: region, sex, org, training, climate_change, rla_expectation, sps_expectation, machine_access, advisor_access, type_assistance, status_quo, peer_effect, recognition, adoption_sps, adoption_rla, rla_labor, sps_labor, sps_cost, rla_cost, adoption_nominal, prod_cycle, rla_info ans sps_info.

Variables educ, social_norm, rla_soil, sps_soil, rla_climate, sps_climate and risk_aversion in this group were dummy or categorical by nature. To preserve their nature, we used half-way thresholds for creating categories from continuous values in these variables.[2] We filled in missing values for variable num_animal (number of cattle) by the most frequent observation in the data (mode of variable), number 10.

[2] The variable farm_size did not enter the regressions because the variable stock_rate represents both. We therefore did not do this conversion for these two variables.

Table A2. Approach to variables with missing values

Variable	Missing values	Method of filling missing values	Type of variable
Age	17	Regression mutation	Numerical
Education (educ)	4	Regression mutation	Numerical
Farm size (farm_size)	1	Regression mutation	Numerical
Number of animals (num_animal)	2	Mode of observations	Numerical
Income (income)	5	Regression mutation	Numerical
Social norm (social_norm)	4	Regression mutation	Numerical
Effect of RLA adoption on soil fertility (rla_soil)	1	Regression mutation	Numerical
Effect of SPS adoption on soil fertility (sps_soil)	1	Regression mutation	Numerical
Effect of RLA adoption on GHG emissions (rla_climate)	4	Regression mutation	Numerical
Effect of SPS adoption on GHG emissions (sps_climate)	4	Regression mutation	Numerical
Risk aversion (risk_aversion)	14	Regression mutation	Numerical
Stock rate (stock_rate)	4	Regression mutation	
Type of technical assistance (type_assistance)	143	Create option for “no technical support” that takes value of 0	Categorical
Long-term expectation about economic benefit of RLA (rla_expectation)	17	Create option for “no opinion” that takes value of 0	Categorical
Long-term expectation about economic benefit of SPS (sps_expectation)	231	Create option for “no opinion” that takes value of 0	Categorical
Number of laborers needed to implement RLA (rla_labor)	17	Create option for “no opinion” that takes value of 0	Categorical
Number of laborers needed to implement SPS (sps_labor)	231	Create option for “no opinion” that takes value of 0	Categorical
Cost of implementing RLA (rla_cost) Cost of implementing SPS (sps_cost)	29	Create option for “no opinion” that takes value of 0	Categorical
Cost of implementing RLA (rla_cost) Cost of implementing SPS (sps_cost)	151	Create option for “no opinion” that takes value of 0	Categorical

Sex. Participants reported their gender in one of three categories: male, female, or legal (corporate). However, because of the very low number of observations in the "legal" category (6 out of 383), we coded the variable to include only two values: male and female. For legal entities, we assigned the sex of the legal representative.

Educ. The response of participants who preferred not to answer the question about education was coded as 99. We marked these observations as missing and instead calculated an estimated value for their education using regression mutation.

Two variables, rla_satisfaction and sps_satisfaction, capture the experience of livestock growers who have already chosen an approach and, as a result, are not descriptive of the decision of farmers to adopt the technology. We therefore exclude them from the model.

Some farmers believed they were practicing RLA, but given the frequency of their rotation, their implementation was not effective. To capture this, we defined a dummy variable adoption_rla that takes the value of 1 for those who both reported implementing RLA and rotate livestock at most every 3 days (1 for those who rotate more frequently), otherwise 0.

A.3. Descriptive statistics, by gender

Table A3 reports weighted means and proportions for demographic, structural, institutional, attitudinal, and adoption-related variables, disaggregated by gender. The table also includes design-based p-values testing for differences between male and female respondents. These statistics provide context for interpreting the gender-specific patterns identified in the regression models and support the argument that women and men face different structural conditions and informational environments.

In particular, the table highlights gendered disparities in access to machinery, access to advisers, and training, as well as in perceptions of the labor and cost burdens associated with SPS and RLA. Differences in peer influence, recognition, and climate-related attitudes further suggest socially embedded dimensions of adoption decisions. Adoption rates are presented for each practice and their combination, offering a descriptive benchmark for the multivariate analyses.

Table A3. Summary statistics of variables, by gender

Variable	Description	Male (304)	Female (79)	P-value
Demographics				
Age	Years	54.86	54.19	0.034**
Education	Category	2.14	2.16	0.338
Farm characteristics				
Farm size	Hectares	92.88	80.75	0.014**
Herd size	Category	141.11	122.95	0.057*
Stocking rate	Index	1.78	2.00	0.000***
Farm income	Number of sold animals	109.44	125.68	0.087*
Machine access	Scale	0.77	0.57	0.000***
Production cycle	Categorical	3.35	3.42	0.157
Institutional and social capital				
Membership in an org	Scale	0.27	0.22	0.000***
Training attendance	Scale	0.50	0.64	0.000***
Adviser access	Scale	0.78	1.04	0.000***
Type of assistance	Categorical	0.91	0.99	0.000***
Access to information about RLA	Scale	0.20	0.27	0.000***
Access to information about SPS	Scale	0.08	0.11	0.000***
Social norm	Scale	1.01	1.01	0.117
Peer effect	Scale	1.27	1.12	0.000***
Recognition	Scale	1.01	0.91	0.000***
Attitudinal and behavioral characteristics				
Climate change concern	Scale	2.86	3.19	0.000***
Risk aversion	Scale	1.51	1.71	0.000***
Belief about status quo	Categorical	0.52	0.58	0.000***
SPS expectation	Scale	1.02	1.07	0.106
RLA expectation	Scale	2.64	2.67	0.080**
Attitude toward RLA	Scale	0.87	0.83	0.000***
Perception about RLA labor	Scale	2.17	2.06	0.000***
Perception about SPS labor	Scale	0.82	0.77	0.049**
Perception about cost of RLA	Scale	2.16	2.35	0.000***
Perception about cost of SPS	Scale	1.32	1.35	0.275
Perception about impact of RLA on soil fertility	Scale	0.93	0.91	0.000***
Perception about impact of SPS on soil fertility	Scale	0.82	0.87	0.000***
Perception about impact of RLA on GHG emissions	Scale	0.69	0.75	0.000***
Perception about impact of SPS on GHG emissions	Scale	0.68	0.78	0.000***
Adoption rates				
SPS adoption	%	30.40	31.76	0.170
RLA adoption	%	38.88	30.43	0.000***
Joint adoption	%	12.03	12.53	0.482

Note: All means and proportions in this table are calculated using the survey design (stratification, clustering) and the corresponding sample weights. Standard errors and p-values are derived from design-based variance estimators.

A4. Choice of variables to be modeled

Information about the relationship between the independent and dependent variables was derived from the literature and is summarized in Table A4.

Table A4. Hypotheses and related literature

Independent variable	Hypothesis	Theory
Herd size	Positive	Larger herds often reflect sufficient resources and operational scale to justify innovative investments (Hyland et al., 2018; Jara-Rojas et al., 2020).
Farm size	Positive	Larger landholdings typically permit greater capacity to allocate space for new technologies, absorb up-front costs, and experiment with complex practices (Mujeyi et al., 2022a; Perosa et al., 2021a). Farm size has been positively associated with adoption of agroforestry, Integrated crop livestock systems (ICLS), improved grazing, and other sustainable systems (Herrera et al., 2023a; Hyland et al., 2018; Owombo & Idumah, 2017).
Production state	No clear directional expectation due to lack of evidence	No specific empirical evidence links production stage or life-cycle phase of farm to SPS or RLA adoption.
Farm income[3]	Predominantly positive, but potentially ambiguous in specific contexts expectation due to lack of evidence	Higher income generally eases financial constraints of adopting resource-intensive practices (Mujeyi et al., 2022a; Boz, 2016). Nonetheless, studies also report contrasting cases where lower-income farms adopted silvopastoral systems under certain support schemes (Zabala et al., 2022). Overall, stable or higher income is likely to facilitate investments in new technologies.
Access to machinery	Positive	Readily available inputs, financing, and markets reduce transaction and information costs, thus facilitating technology uptake (Mujeyi et al., 2022b; Vargas-De la Mora et al., 2021).
Age	Negative	Younger farmers often exhibit more openness to novel techniques; older farmers can be more risk averse or hesitant about long-term projects (Gebrezgabher et al., 2015; Jara-Rojas et al., 2020; Perosa et al., 2021a). Some studies, however, find no significant effect (Zabala et al., 2022).
Sex	Female positive	Research on climate-smart agriculture, conservation agriculture, and similar innovations has shown that women-led households may adopt such practices more intensively and more frequently (Mujeyi et al., 2022b; Turinawe et al., 2015).

[3] We exclusively work with the income originating from cattle growing. So in case we do not specify it is a farm income, the reader should assume it is income solely from cattle growing activities.

Education	Ambiguous, with tendencies toward positive effect when specialized training is involved	Higher formal education may improve comprehension of complex practices, yet several studies document mixed or insignificant effects (Gebrezgabher et al., 2015; Ogunlana, 2004b). Specialized training, rather than general formal education, has sometimes proven more influential (Fernández-Habas et al., 2022; Herrera et al., 2023b).
Organization	Positive	Participation in producer associations or networks fosters information sharing, risk reduction, and collective learning, which can enhance adoption (Didier & Brunson, 2004; Ogunlana, 2004b; Vargas-De la Mora et al., 2021).
Training	Positive effect, contingent on training quality and relevance	Effective capacity building and continuous support are central to implementing resource-intensive or knowledge-intensive practices (Martin et al., 2004; Vargas-De la Mora et al., 2021). Even so, certain studies observe limited influence of specific training formats (de Mello Brandão Vinholis et al., 2021).
advisor_ access	Positive	Frequent engagement with extension services or advisory support can bolster adoption by reducing informational gaps (Mujeyi et al., 2022a), although results are not universally consistent (de Souza et al., 2021)
rla_ expectation	Positive	Producers' perceptions of economic and environmental advantages correlate strongly with technology uptake (Borges, 2015; de Mello Brandão Vinholis et al., 2021). Limited awareness or visibility of short-term returns often hinders adoption.
sps_ expectation	Positive	Same as above.
rla_cost	Negative	High initial expenditures for infrastructure, tree planting, or machinery—if viewed as prohibitive—deter adoption (Abdul-Salam et al., 2022; Hyland et al., 2018). Conversely, favorable cost perceptions can encourage investment in sustainable practices. Sustainable systems often require additional labor inputs for management, tree care, or maintenance (Beshir et al., 2022; Martin et al., 2004). Perceptions that labor is scarce or costly can discourage adoption.
sps_cost	Negative	Same as above
risk_aversion	Negative	Farmers who are highly risk averse may be deterred by uncertainties related to system performance, market fluctuations, and implementation challenges (Martin et al., 2004; Vargas-De la Mora et al., 2021).
recognition	Positive	Conformance with local norms and cultural preferences can enhance adoption; conversely, disapproval or conflicting practices in community undermine uptake (Calle et al., 2009; Didier & Brunson, 2004).
peer_effect	Whether it is positive or negative sign, depends on whether peers are supportive	Observing successful experiences among peers can reduce uncertainty, whereas skepticism within social networks may impede adoption (Borges, 2015; Perosa et al., 2021b).
climate_ change	Positive	Producers prioritizing ecological preservation are more inclined to adopt systems that offer environmental benefits. Limited awareness of these gains can inhibit uptake (Wang et al., 2020).
climate_ effect	Positive	Farmers convinced that their actions have meaningful environmental ramifications exhibit greater propensity to adopt ecologically oriented approaches (Herrera et al., 2023a; Wang et al., 2020).
soil_effect	Positive	Same as above.

A4.1. SPS model[4]

Model specification and variable construction

The analysis begins with the construction of a detailed data set incorporating demographic, economic, institutional, and perceptual variables. Categorical variables such as education, production cycle type, and type of technical assistance were coded into dummy variables to facilitate inclusion in the logistic models. Specifically, education was recoded into four categories (≤8 years, High school, College, Graduate"), production cycle into six categories with Breeding-rearing as the reference, and technical assistance into four dummies with No technical support as the base. Additionally, regional dummies were created for Los Lagos and Los Ríos, with La Araucanía serving as the reference group. Finally, we applied the stratification parameter, weights, and finite population corrections to adjust for the sampling design.

Sequential model specification

The modeling process follows a hierarchical approach, where each model incrementally adds new blocks of theoretically justified variables.

- **Model 1** focuses on structural factors, incorporating age, sex, education, income (measured as animals sold), stock rate (ha/animal), region, and production cycle (with dummies for specific categories).
- **Model 2** extends this baseline by adding institutional factors: organizational membership, access to advisers, technical assistance types, and training.
- **Model 3** further includes attitudinal factors such as concerns about climate change, preference for the status quo, social norms, peer effects, recognition, risk aversion, and access to machinery.
- **Model 4** integrates perceptions specific to SPS, including the availability of information, perceived effects on soil quality, climate benefits, labor requirements, and costs.
- **Model 5** is specified to address potential endogeneity by excluding sps_labor and sps_cost. This model balances explanatory breadth and robustness.

[4] We followed the same variable selection process for SPS, RLA, and joint adoption and ended up with a "parsimonious" model for each. Then, we analyzed the differences and tested a model using the same variables across all three to ensure the coefficients were robust. All steps we took for the SPS were repeated for the others as a robustness check, which helped eliminate several variables. We present the analysis for SPS only.

Table A5 reports the estimated coefficients, standard errors, and significance levels for each variable across models 1–5. This progressive inclusion strategy allows for assessing the marginal contributions of different groups of variables to the explanatory power of the models.

Table A5. Regression results: SPS adoption (models 1–5)

	Dependent variable: adoption_sps				
	(1)	(2)	(3)	(4)	(5)
Age	-0.004*** (0.002)	-0.006*** (0.002)	-0.006*** (0.002)	-0.037*** (0.003)	-0.003 (0.002)
Sex (female)	0.016 (0.050)	0.067 (0.051)	0.072 (0.052)	0.009 (0.110)	-0.071 (0.055)
Herd size (category)	0.016 (0.019)	-0.005 (0.020)	-0.007 (0.021)	0.041 (0.041)	0.031 (0.021)
Educ: high school	0.311*** (0.051)	0.292*** (0.053)	0.261*** (0.055)	0.598*** (0.112)	0.375*** (0.056)
Educ: college	0.071 (0.057)	0.089 (0.060)	0.115* (0.062)	0.491*** (0.112)	0.148** (0.062)
Educ: graduate	0.717*** (0.096)	0.688*** (0.098)	0.765*** (0.104)	0.753*** (0.189)	0.895*** (0.110)
Income (animals sold)	0.0003*** (0.0001)	0.0004*** (0.0001)	0.0004*** (0.0001)	-0.001*** (0.0001)	0.0003*** (0.0001)
Stock rate (ha/animal)	-0.076*** (0.010)	-0.070*** (0.011)	-0.068*** (0.011)	-0.075*** (0.026)	-0.061*** (0.011)
Los Lagos	0.596*** (0.052)	0.608*** (0.055)	0.561*** (0.055)	1.304*** (0.108)	0.564*** (0.055)
Los Ríos	0.420*** (0.062)	0.493*** (0.063)	0.397*** (0.064)	0.907*** (0.151)	0.349*** (0.066)
PC: Breeding–fattening	0.266** (0.109)	0.228** (0.111)	0.256** (0.111)	0.327 (0.239)	0.245** (0.110)
PC: Breeding	-0.659*** (0.076)	-0.714*** (0.074)	-0.696*** (0.075)	-0.732*** (0.185)	-0.426*** (0.071)
PC: Rearing–fattening	-0.207** (0.100)	-0.258*** (0.097)	-0.204** (0.100)	1.254*** (0.205)	-0.106 (0.099)
PC: Rearing	-0.684*** (0.109)	-0.834*** (0.113)	-0.909*** (0.115)	-2.405*** (0.264)	-0.903*** (0.113)
PC: Fattening	-0.130 (0.087)	-0.267*** (0.086)	-0.248*** (0.088)	1.255*** (0.196)	-0.065 (0.087)
PC: Complete cycle	0.575*** (0.078)	0.532*** (0.077)	0.558*** (0.079)	1.825*** (0.163)	0.669*** (0.075)
Org (association)		0.431*** (0.048)	0.431*** (0.049)	0.880*** (0.077)	0.422*** (0.052)
Adviser access		-0.320*** (0.054)	-0.303*** (0.055)	0.474*** (0.120)	-0.472*** (0.059)

Table A5. Regression results: SPS adoption (models 1–5)

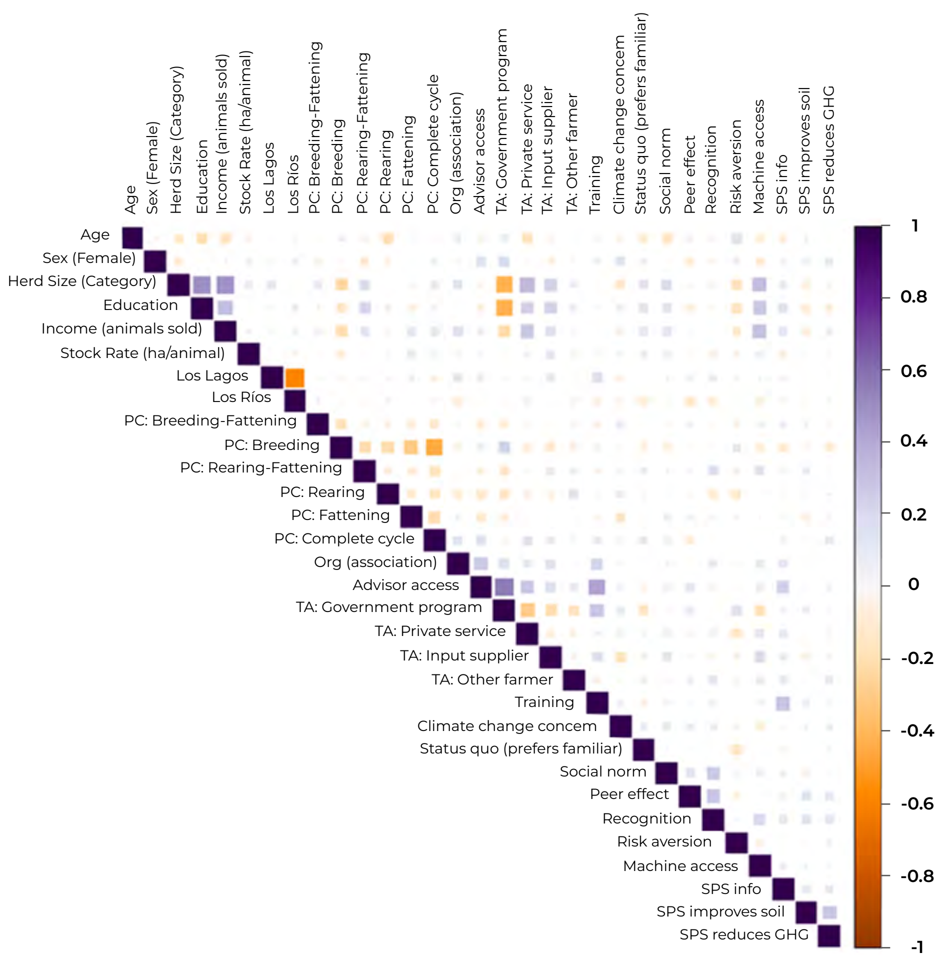
	Dependent variable: adoption_sps				
	(1)	(2)	(3)	(4)	(5)
TA: Government program		0.100 (0.091)	0.072 (0.092)	-0.474** (0.222)	0.257*** (0.096)
TA: Private service		0.118 (0.107)	0.060 (0.109)	-1.686*** (0.232)	0.111 (0.113)
TA: Input supplier		-0.240** (0.120)	-0.227* (0.121)	-1.333*** (0.226)	-0.134 (0.126)
TA: Other farmer		0.664*** (0.111)	0.772*** (0.117)	-1.109*** (0.278)	0.589*** (0.125)
Training		0.169*** (0.021)	0.165*** (0.022)	-0.288*** (0.059)	0.070*** (0.024)
Climate change concern			0.001 (0.018)	0.175*** (0.035)	0.014 (0.019)
Status quo (prefers familiar)			-0.295*** (0.042)	-0.611*** (0.089)	-0.379*** (0.044)
Social norm			0.113*** (0.034)	0.492*** (0.061)	0.144*** (0.036)
Peer effect			-0.084*** (0.029)	0.032 (0.046)	-0.157*** (0.031)
Recognition			0.034 (0.029)	-0.148** (0.059)	-0.059* (0.032)
Risk aversion			-0.115*** (0.018)	-0.196*** (0.037)	-0.161*** (0.018)
Machine access			-0.150*** (0.031)	-0.037 (0.065)	-0.164*** (0.031)
SPS info				0.464*** (0.166)	1.252*** (0.068)
SPS improves soil				0.638*** (0.123)	0.014 (0.061)
SPS reduces GHG				1.289*** (0.088)	0.998*** (0.051)
sps_labor				2.904*** (0.066)	
sps_cost				1.333*** (0.051)	
Constant	-0.975*** (0.126)	-0.798*** (0.129)	-0.420*** (0.155)	-6.833*** (0.355)	-1.378*** (0.165)
Observations	383	383	383	383	383

Note: *p<0.1; **p<0.05; ***p<0.01. PC = production cycle. TA = type of assistance.

Multicollinearity and correlation diagnostics

Prior to interpretation, we assessed the multicollinearity using generalized variance inflation factors (GVIFs). The results indicate that no variables exceeded the commonly used threshold of scaled GVIF > 5, suggesting acceptable levels of collinearity. Correlation matrices for the variables in Model 5 (Figure A1) reveal no pairs of variables with absolute correlations exceeding 0.7, further supporting the stability of the model estimates. This analysis ensures that the inclusion of multiple predictors, including SPS-specific perceptions, does not compromise the integrity of the estimates because of collinearity.

Figure A1. **Figure A1. Correlation matrix for variables of Model 5.**



Model comparison and fit statistics

We next evaluated the comparative performance of the models using Akaike information criterion (AIC), Bayesian information criterion (BIC), and pseudo-R^2. As shown in Table A6 (from sps_logit_models_1to6_combined.html), the complete Model 4 exhibits an unusually high pseudo-R^2 (0.702) but also raises concerns of overfitting and endogeneity because of the inclusion of sps_labor and sps_cost. Model 5 offers a more balanced specification with a pseudo-R^2 of 0.13, AIC of 476.86, and BIC of 607.14, indicating a reasonable trade-off between explanatory power and model parsimony.

Table A6. Model statistics (AIC, BIC, pseudo-R^2)

	Model 1	Model 2	Model 3	Model 4 (complete)	Model 5 (no cost and labor)
AIC	472.83	484.91	495.58	213.85	480.19
BIC	535.99	583.61	621.92	359.93	618.37
Pseudo-R2	0.067	0.079	0.086	0.704	0.131

Model selection and parsimonious specification

A final model incorporating selected interactions was estimated, resulting in enhanced model fit (pseudo-R^2 of 0.16, AIC of 472.56, BIC of 622.59), as reported in Table A7. Subsequently, an automated stepwise selection procedure (stepAIC) was applied to refine the model by retaining statistically and substantively significant variables. This procedure yielded a compact model with reduced complexity and comparable explanatory power. Additionally, we specified a parsimonious model manually by removing variables with limited theoretical justification or statistical support, such as production cycle (PC): fattening, type of assistance (TA): private service, recognition, and income:training. This parsimonious model (Model 4 in Table A7) achieved an AIC of 459.4, BIC of 577.85, and pseudo-R^2 of 0.153, indicating superior balance between fit and simplicity.

Table A7. Regression results including interaction terms

	Dependent variable: adoption_sps			
	Model 5	With interactions	Stepwise	Parsimony
	(1)	(2)	(3)	(4)
Age	-0.003 (0.002)	-0.005*** (0.002)	-0.005*** (0.002)	-0.005*** (0.002)
Sex (female)	-0.071 (0.055)	0.312*** (0.067)	0.318*** (0.066)	0.329*** (0.066)
Herd size (category)	0.031 (0.021)	0.059*** (0.023)		
Educ: high school	0.375*** (0.056)	0.382*** (0.058)	0.400*** (0.058)	0.301*** (0.056)
Educ: college	0.148** (0.062)	0.088 (0.063)	0.145** (0.061)	0.062 (0.060)
Educ: graduate	0.895*** (0.110)	0.958*** (0.115)	1.011*** (0.113)	0.795*** (0.103)
Income (animals sold)	0.0003*** (0.0001)	0.0003*** (0.0001)	0.0004*** (0.0001)	0.0004*** (0.0001)
Stock rate (ha/animal)	-0.061*** (0.011)	-0.055*** (0.013)	-0.054*** (0.013)	-0.057*** (0.012)
Los Lagos	0.564*** (0.055)	0.622*** (0.056)	0.615*** (0.055)	0.594*** (0.055)
Los Ríos	0.349*** (0.066)	0.303*** (0.067)	0.296*** (0.067)	0.332*** (0.065)
PC: Breeding–fattening	0.245** (0.110)	0.399*** (0.115)	0.413*** (0.115)	0.323*** (0.097)
PC: Breeding	-0.426*** (0.071)	-0.224*** (0.072)	-0.245*** (0.073)	
PC: rearing–fattening	-0.106 (0.099)	0.209** (0.101)	0.215** (0.101)	-0.292*** (0.054)
PC: Rearing	-0.903*** (0.113)	-0.952*** (0.113)	-0.958*** (0.112)	-1.033*** (0.098)
PC: Fattening	-0.065 (0.087)	0.038 (0.091)	0.008 (0.091)	
PC: Complete cycle	0.669*** (0.075)	0.791*** (0.077)	0.779*** (0.077)	0.708*** (0.057)
Org (association)	0.422*** (0.052)	-0.072 (0.107)	-0.024 (0.108)	0.017 (0.105)

	Dependent variable: adoption_sps			
	Model 5	With interactions	Stepwise	Parsimony
	(1)	(2)	(3)	(4)
Adviser access	-0.472*** (0.059)	-0.649*** (0.064)	--0.654*** (0.064)	-0.435*** (0.034)
TA: Government program	0.257*** (0.096)	0.549*** (0.102)	0.533*** (0.101)	
TA: Private service	0.111 (0.113)	0.109 (0.120)	0.151 (0.121)	
TA: Input supplier	-0.134 (0.126)	-0.197 (0.136)	-0.193 (0.137)	
TA: Other farmer	0.589*** (0.125)	0.759*** (0.133)	0.776*** (0.132)	0.523*** (0.111)
Training	0.070*** (0.024)	0.073** (0.030)	0.074** (0.030)	0.152*** (0.027)
Climate change concern	0.014 (0.019)	0.047** (0.020)		
Status quo (prefers familiar)	-0.379*** (0.044)	-1.139*** (0.074)	-1.101*** (0.073)	-1.069*** (0.070)
Social norm	0.144*** (0.036)	0.165*** (0.037)	0.184*** (0.037)	0.171*** (0.035)
Peer effect	-0.157*** (0.031)	-0.288*** (0.036)	-0.280*** (0.036)	-0.273*** (0.035)
Recognition	-0.059* (0.032)	-0.166*** (0.033)	-0.163*** (0.033)	-0.129*** (0.032)
Risk aversion	-0.161*** (0.018)	-0.395*** (0.025)	-0.393*** (0.025)	-0.371*** (0.024)
Machine access	-0.164*** (0.031)	-0.168*** (0.033)	-0.163*** (0.033)	-0.166*** (0.033)
SPS info	1.252*** (0.068)	1.272*** (0.069)	1.259*** (0.069)	1.180*** (0.068)
SPS improves soil	0.014 (0.061)	-0.024 (0.065)		
SPS reduces GHG	0.998*** (0.051)	1.129*** (0.054)	1.115*** (0.054)	1.074*** (0.053)
status_quo:risk_aversion		0.481*** (0.038)	0.468*** (0.037)	0.456*** (0.036)

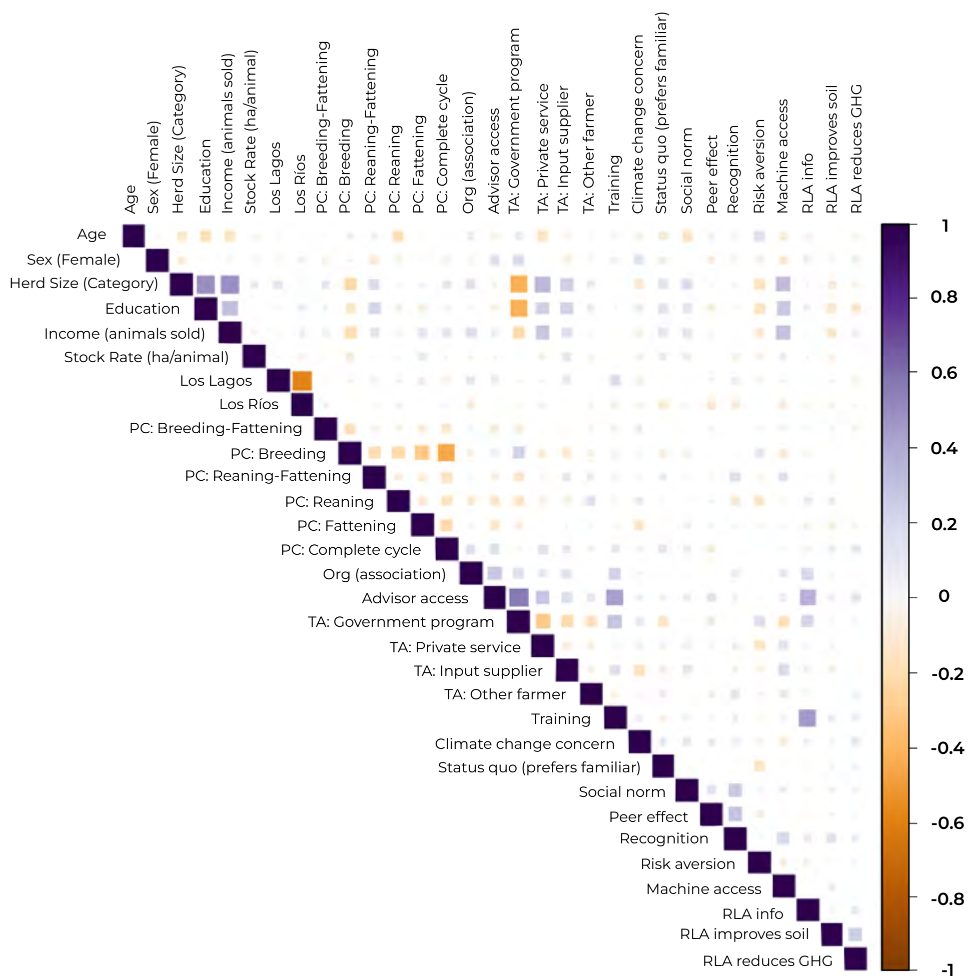
	Dependent variable: adoption_sps			
	Model 5	With interactions	Stepwise	Parsimony
	(1)	(2)	(3)	(4)
sex:org		-1.159*** (0.140)	-1.192*** (0.139)	-1.233*** (0.137)
org:peer_effect		0.598*** (0.068)	0.586*** (0.068)	0.543*** (0.066)
sex:training		-0.435*** (0.054)	-0.426*** (0.054)	-0.365*** (0.052)
income:training		0.001*** (0.0001)	0.001*** (0.0001)	
Constant	-1.378*** (0.165)	-1.075*** (0.175)	-0.877*** (0.159)	-0.692*** (0.147)
Pseudo-R^2	0.13	0.161	0.16	0.153
AIC	478.8	474.36	468.67	459.97
BIC	613.03	628.33	610.8	578.42
Observations	383	383	383	383

Note: *p<0.1; **p<0.05; ***p<0.01. PC = production cycle. TA = type of assistance.*p<0.1;

A4.2. RLA model

The correlation matrix of variables for the RLA model is as below[5], which again, shows low correlations among variables:

Figure A2. Correlation matrix for variables of Model 5 in RLA specification.



[5] As explained in footnote 3, we followed the same variable selection process for SPS, RLA, and joint adoption, and ended up with a “parsimonious” model for each. Then, we analyzed the differences and tested a model using the same variables across all three to ensure the coefficients were robust. So, all steps we took for the SPS were repeated for the others as a robustness check, which helped eliminate several variables. We present the analysis for SPS only.

A4.3. Final variable selection rationale and criteria

This section outlines the rationale, technical criteria, and empirical evidence guiding the refinement and final selection of independent variables in the logit models analyzing the adoption of productive practices—specifically SPS, RLA, and joint adoption. The primary objective was to ensure cross-model comparability, statistical robustness, and policy relevance, while minimizing overfitting, noise, and estimation instability.

A4.3.1. Retained variables

The following variables were included uniformly across the three models:

- Age. Producer's age demonstrated stable sign and significance ($p < 0.01$) across all models (SPS, RLA, and joint adoption).
- Sex (Female). A dummy indicating female household head, significant and negative in RLA ($p < 0.01$), was retained for consistency, despite lower significance in other models.
- Herd size. Although positive in RLA and negative in SPS (both p < 0.01–0.05), it provides scale-relevant policy insight. Included in the joint model despite exclusion under stepwise selection.
- Organizational membership. A dummy for association membership was significant in RLA and joint adoption ($p < 0.01$), and retained for exploratory purposes in SPS despite frequent insignificance.
- Education dummies (High school, College, Graduate). All three were statistically stable (p < 0.05–0.01) with consistent positive effects across models.
- Income (animal sales). Positive and significant ($p < 0.01$) in SPS and RLA; retained for its economic interpretability in the joint model.
- Stocking rate (ha/animal). Negative in SPS and positive in RLA (both $p < 0.01$); included in the joint model to assess its role as a production pressure proxy.

- Regional dummies (Los Lagos, Los Ríos). Significant in all models ($p < 0.01$), capturing critical spatial heterogeneity.

- Production regime categories). Six dummies (Breeding–fattening, Breeding, Rearing–fattening, Rearing, Fattening, Complete cycle) were significant ($p < 0.01$) across models. Complete cycle, though nonsignificant in joint adoption, was retained for categorical completeness and as a reference for integrated producers.

- Adviser access. A negative and significant predictor in SPS and RLA ($p < 0.01$), and also significant in joint adoption, indicating the role of institutional learning.

- TA (Private service). Significant across all models ($p < 0.01$); other TA subtypes were dropped because of collinearity and extreme coefficients.

- Training. Practical training was significant across models ($p < 0.01$), with a negative sign in SPS and positive in RLA and joint models—suggesting differentiated effects by technology type.

- Status quo orientation. A negative and significant predictor ($p < 0.01$) in all models, reflecting resistance to innovation based on traditionalist attitudes.

- Peer effect. A negative and significant influence ($p < 0.01$) across models, capturing social pressure in adoption decisions.

- Risk aversion. Positively associated with adoption in all models ($p < 0.01$), indicating that higher risk aversion may drive adoption of certain technologies or bundles.

- Machinery access. Negative in SPS and RLA, positive in joint adoption (all $p < 0.01$); included to assess capital access disparities.

A4.3.2. Dropped variables

- Technical assistance subtypes (GovProgram, InputSupplier, OtherFarmer). Removed because of extreme coefficients (e.g., “OtherFarmer”), category sparsity, and high intercorrelation. The aggregate Access to assistance variable was preferred for parsimony and clarity.

- Social norms and recognition. Dropped because of instability and weak cross-model significance, offering limited explanatory value and increasing overfitting risk.

- Climate change concern. Excluded for consistent statistical insignificance and limited theoretical relevance in explaining adoption behavior within this context.

A4.3.3. Model-specific variables

Perception and knowledge variables specific to particular technologies (e.g., RLA_info, SPS_info, RLA_improves_soil, SPS_reduces_GHG) were excluded from the common model set. These variables will be included only in targeted regressions where conceptually appropriate.

A4.3.4. Selection of interaction terms

Interaction terms were selected based primarily on their consistent improvement of model fit—as measured by positive changes in pseudo-R^2—across all three adoption models (SPS, RLA, and joint adoption) and their theoretical coherence within each context. Among the candidate interactions, sex × adviser_access stood out for its consistent and meaningful contribution to model performance: it increased pseudo-R^2 by 0.027 in SPS, 0.005 in RLA, and 0.015 in the joint model. This interaction captures a theoretically plausible effect—namely, that the combination of being a female household head and having access to technical advice exerts a differential but consistently positive influence on adoption decisions.

In contrast, although the interaction status_quo × risk_aversion also improved model fit across all three specifications, its contribution in SPS and RLA was marginal (ΔPseudo-$R^2 < 0.005$). Therefore, sex × adviser_access was prioritized as the most robust cross-model interaction.

To avoid overfitting and specification overload, only sex × adviser_access was included in the final models. Optionally, status_quo × risk_aversion may be considered as a secondary interaction in the joint adoption model, where its contribution is more substantial. By requiring a consistent positive effect on pseudo-R^2 and a stable sign across models, we ensured that the inclusion of interaction terms enhances explanatory power without introducing noise or multicollinearity. In particular, sex × adviser_access captures a policy-relevant mechanism—gender-based disparities in access to technical assistance—while improving model fit in a uniform and interpretable manner.

A4.3.5. Comparative regression results (SPS, RLA, joint adoption), full table

Table A8 reports average marginal effects (AMEs) from survey-weighted logistic regressions predicting the adoption of SPS, RLA, and both jointly. All models control for production region and cycle. Results are correlational, not causal.

Table A8. Average marginal effects (AME) of best models, by dependent variable

Variable	AME SPS	AME RLA	AME joint
Age	-0.001* * * (0.0003)	-0.001* * * (0.0003)	0.000* * * (0.0002)
Sex (female)	0.163* * * (0.010)	0.163* * * (0.010)	-0.117* * * (0.012)
Herd size (category)	-0.015* * * (0.003)	-0.015* * * (0.003)	0.015* * * (0.002)
Educ: high school	0.018* * (0.009)	0.018* * (0.009)	0.023* * * (0.006)
Educ: college	-0.029* * * (0.010)	-0.029* * * (0.010)	0.040* * * (0.007)
Educ: graduate	-0.087* * * (0.019)	-0.087* * * (0.019)	0.155* * * (0.015)
Income (animals sold)	0.000* * * (0.00001)	0.000* * * (0.00001)	-0.000* * * (0.00001)
Stock rate (ha/animal)	-0.017* * * (0.002)	-0.017* * * (0.002)	0.004* * * (0.001)
Los Lagos	0.068* * * (0.008)	0.068* * * (0.008)	0.031* * * (0.008)
Los Ríos	-0.035* * * (0.010)	-0.035* * * (0.010)	0.093* * * (0.008)
PC: Breeding–fattening	0.187* * * (0.020)	0.187* * * (0.020)	-0.050* * * (0.012)
PC: Breeding	0.024 (0.016)	0.024 (0.016)	-0.035* * * (0.010)
PC: Rearing–fattening	0.120* * * (0.022)	0.120* * * (0.022)	-0.042* * * (0.012)
PC: Complete cycle	0.167* * * (0.017)	0.167* * * (0.017)	0.017* (0.010)
Org (association)	0.002 (0.009)	0.002 (0.009)	0.083* * * (0.006)

Variable	AME SPS	AME RLA	AME joint
Adviser access	0.034* * * (0.005)	0.004 (0.006)	-0.084* * * (0.005)
Training	-0.041* * * (0.004)	0.072* * * (0.004)	0.034* * * (0.002)
Status quo (prefers familiar)	-0.021* * * (0.007)	0.026* * * (0.007)	-0.044* * * (0.005)
Peer effect	-0.057* * * (0.005)	-0.101* * * (0.004)	0.033* * * (0.004)
Risk aversion	-0.024* * * (0.003)	0.032* * * (0.003)	-0.005* (0.002)
Machinery access	-0.066* * * (0.005)	-0.033* * * (0.005)	0.019* * * (0.004)
SPS info	0.050* * * (0.010)		0.146* * * (0.009)
SPS improves soil	-0.036* * * (0.008)		0.088* * * (0.011)
SPS reduces GHG	0.089* * * (0.008)		0.171* * * (0.009)
RLA info		-0.090* * * (0.009)	-0.007 (0.009)
RLA improves soil		0.218* * * (0.018)	0.059* * * (0.014)
RLA reduces GHG		-0.041* * * (0.008)	-0.098* * * (0.007)
Sex × adviser access	-0.219* * * (0.010)	0.120* * * (0.016)	0.119* * * (0.007)
Pseudo-R^2	0.305	0.264	0.338
AIC	407.41	270.38	368.55
BIC	517.95	392.77	479.09
Observations	383	383	383

A4.3.6. Bivariate analysis

To examine whether unobserved factors jointly influence the adoption of SPS and RLA, we estimated a bivariate logit model that allows for correlated error terms between the two decisions. This specification complements the separate univariate models by testing whether latent or unmeasured factors omitted from the main regressions systematically affect both adoption outcomes. Table A9 presents the full set of estimated coefficients.

The only parameter in the residual association equation—the intercept—has an estimated log-odds of 0.0133 ($p = 0.842$), corresponding to an odds ratio of approximately 1.01, effectively equal to 1. Consistently, when Pearson residuals are extracted from the independent logit models for SPS and RLA and their correlation is computed, the result is $r = 0.0132$ ($p = 0.7966$; 95% CI [–0.0871, 0.1133]). This confirms the absence of significant unobserved covariation between the two adoption decisions beyond what is captured by the covariates included in the model.

The goodness-of-fit indicators for the bivariate model yielded a pseudo-R^2 of 0.16, AIC = 14651.96, and BIC = 14876.99. These values indicate performance comparable to that of the separate univariate logit models (AIC ≈ 407 for SPS alone, 270 for RLA alone), without notable improvements in classification rates or area under the curve for either SPS or RLA. Therefore, for purposes of prediction or interpretation of marginal effects, the separate logit specifications—or even a simple dummy variable for joint adoption—are functionally equivalent to the bivariate model, with no loss of information.

Table A9. Full set of coefficients for bivariate adoption model SPS–RLA

Variable	Coef.	Std. Error	Signif.
(Intercept):1	(Intercept):1	-0.24	***
(Intercept):2	(Intercept):2	-0.26	***
(Intercept):3	(Intercept):3	-0.07	
age:1	age:1	0	
age:2	age:2	0	***
sex:1	sex:1	-0.12	***
sex:2	sex:2	-0.16	***
stratum:1	stratum:1	-0.03	
stratum:2	stratum:2	-0.03	***
factor(educ)High School:1	factor(educ)High School:1	-0.08	***
factor(educ)High School:2	factor(educ)High School:2	-0.08	***
factor(educ)College:1	factor(educ)College:1	-0.09	
factor(educ)College:2	factor(educ)College:2	-0.09	***
factor(educ)Graduate:1	factor(educ)Graduate:1	-0.15	***
factor(educ)Graduate:2	factor(educ)Graduate:2	-0.16	***
income:1	income:1	0	***
income:2	income:2	0	
stock_rate:1	stock_rate:1	-0.02	***
stock_rate:2	stock_rate:2	-0.02	***
Los_Lagos:1	Los_Lagos:1	-0.08	***
Los_Lagos:2	Los_Lagos:2	-0.08	***
Los_Rios:1	Los_Rios:1	-0.09	***
Los_Rios:2	Los_Rios:2	-0.09	***
pc_Breeding_Fattening:1	pc_Breeding_Fattening:1	-0.17	
pc_Breeding_Fattening:2	pc_Breeding_Fattening:2	-0.18	***
pc_Breeding:1	pc_Breeding:1	-0.12	**
pc_Breeding:2	pc_Breeding:2	-0.13	**
pc_Rearing:1	pc_Rearing:1	-0.16	***
pc_Rearing:2	pc_Rearing:2	-0.17	
pc_Rearing_Fattening:1	pc_Rearing_Fattening:1	-0.16	
pc_Rearing_Fattening:2	pc_Rearing_Fattening:2	-0.17	
pc_Fattening:1	pc_Fattening:1	-0.14	
pc_Fattening:2	pc_Fattening:2	-0.15	
pc_Complete_Cycle:1	pc_Complete_Cycle:1	-0.12	***
pc_Complete_Cycle:2	pc_Complete_Cycle:2	-0.14	
org:1	org:1	-0.07	***
org:2	org:2	-0.07	
advisor_access:1	advisor_access:1	-0.05	***
advisor_access:2	advisor_access:2	-0.05	***
training:1	training:1	-0.03	
training:2	training:2	-0.03	***
status_quo:1	status_quo:1	-0.06	***
status_quo:2	status_quo:2	-0.06	
peer_effect:1	peer_effect:1	-0.04	**
peer_effect:2	peer_effect:2	-0.04	***
risk_aversion:1	risk_aversion:1	-0.02	***
risk_aversion:2	risk_aversion:2	-0.03	***
machine_access:1	machine_access:1	-0.04	***
machine_access:2	machine_access:2	-0.04	
sps_info:1	sps_info:1	-0.1	***
sps_info:2	sps_info:2	-0.11	*
sps_soil:1	sps_soil:1	-0.09	
sps_soil:2	sps_soil:2	-0.09	***
sps_climate:1	sps_climate:1	-0.07	***
sps_climate:2	sps_climate:2	-0.07	*
sex_advisor_access:1	sex_advisor_access:1	-0.1	***
sex_advisor_access:2	sex_advisor_access:2	-0.12	***
LogLik	LogLik		
AIC	AIC		
BIC	BIC		
Pseudo-R2	Pseudo-R2		

Table A9. **Full set of coefficients for bivariate adoption model SPS–RLA**

Variable	Coef.	Std. Error	Signif.
(Intercept):1	(Intercept):1	-0.24	***
(Intercept):2	(Intercept):2	-0.26	***
(Intercept):3	(Intercept):3	-0.07	
age:1	age:1	0	
age:2	age:2	0	***
sex:1	sex:1	-0.12	***
sex:2	sex:2	-0.16	***
stratum:1	stratum:1	-0.03	
stratum:2	stratum:2	-0.03	***
factor(educ)High School:1	factor(educ)High School:1	-0.08	***
factor(educ)High School:2	factor(educ)High School:2	-0.08	***
factor(educ)College:1	factor(educ)College:1	-0.09	
factor(educ)College:2	factor(educ)College:2	-0.09	***
factor(educ)Graduate:1	factor(educ)Graduate:1	-0.15	***
factor(educ)Graduate:2	factor(educ)Graduate:2	-0.16	***
income:1	income:1	0	***
income:2	income:2	0	
stock_rate:1	stock_rate:1	-0.02	***
stock_rate:2	stock_rate:2	-0.02	***
Los_Lagos:1	Los_Lagos:1	-0.08	***
Los_Lagos:2	Los_Lagos:2	-0.08	***
Los_Rios:1	Los_Rios:1	-0.09	***
Los_Rios:2	Los_Rios:2	-0.09	***
pc_Breeding_Fattening:1	pc_Breeding_Fattening:1	-0.17	
pc_Breeding_Fattening:2	pc_Breeding_Fattening:2	-0.18	***
pc_Breeding:1	pc_Breeding:1	-0.12	**
pc_Breeding:2	pc_Breeding:2	-0.13	**
pc_Rearing:1	pc_Rearing:1	-0.16	***
pc_Rearing:2	pc_Rearing:2	-0.17	
pc_Rearing_Fattening:1	pc_Rearing_Fattening:1	-0.16	
pc_Rearing_Fattening:2	pc_Rearing_Fattening:2	-0.17	
pc_Fattening:1	pc_Fattening:1	-0.14	
pc_Fattening:2	pc_Fattening:2	-0.15	
pc_Complete_Cycle:1	pc_Complete_Cycle:1	-0.12	***
pc_Complete_Cycle:2	pc_Complete_Cycle:2	-0.14	
org:1	org:1	-0.07	***
org:2	org:2	-0.07	
advisor_access:1	advisor_access:1	-0.05	***
advisor_access:2	advisor_access:2	-0.05	***
training:1	training:1	-0.03	
training:2	training:2	-0.03	***
status_quo:1	status_quo:1	-0.06	***
status_quo:2	status_quo:2	-0.06	
peer_effect:1	peer_effect:1	-0.04	**
peer_effect:2	peer_effect:2	-0.04	***
risk_aversion:1	risk_aversion:1	-0.02	***
risk_aversion:2	risk_aversion:2	-0.03	***
machine_access:1	machine_access:1	-0.04	***
machine_access:2	machine_access:2	-0.04	
sps_info:1	sps_info:1	-0.1	***
sps_info:2	sps_info:2	-0.11	*
sps_soil:1	sps_soil:1	-0.09	
sps_soil:2	sps_soil:2	-0.09	***
sps_climate:1	sps_climate:1	-0.07	***
sps_climate:2	sps_climate:2	-0.07	*
sex_advisor_access:1	sex_advisor_access:1	-0.1	***
sex_advisor_access:2	sex_advisor_access:2	-0.12	***
LogLik	LogLik		
AIC	AIC		
BIC	BIC		
Pseudo-R2	Pseudo-R2		

A5. Survey analysis[6]

Primary sampling units in this analysis are the observations. Given the five strata defined in this study, we used sample weights defined as the inverse probability of selection from each stratum. We also applied finite population correction (FPC) to account for the reduction in variance that occurs when sampling without replacement from a finite population versus sampling with replacement from the same population.[7] We calculated the FPC for each stratum using this formula:

$$FPC_h = \sqrt{\frac{N_h - n_h}{N_h - 1}}$$

where h is stratum h, n_h is the number of elements in the sample of stratum h, and N_h is the number of elements in the population of stratum h. We used Taylor linearized method to estimate the variance.

[6] Reference: https://stats.oarc.ucla.edu/stata/seminars/svy-stata-intro/

[7] StataCorp. (2021). svyset — Declare survey design for dataset. In Stata Survey Data Reference Manual: Release 17 (pp. 10). Stata Press. https://www.stata.com/manuals/svysvyset.pdf

A6. Benchmark full models

A7. Survey questionnaire

7.1. Survey invitation

We are conducting a study to learn more about how cattle producers make decisions regarding their production. You have been selected from the SAG database to participate in this survey.

I would like to remind you that participation is completely voluntary. You may decide not to answer any question, or end the interview at any time, without giving any explanation or consequences of any kind.

Your information will be treated with absolute confidentiality. Your personal data will not be associated with your responses, so they remain anonymous.

The information collected will be used to prepare a report with recommendations and will be shared with the scientific community, and will help us better understand what factors facilitate or hinder the adoption of certain livestock practices.

With this information, would you like to participate in the survey? If you have any questions or need more time to decide, please feel free to let me know.

[If accepted, thank them again and proceed with the survey.]

- Give consent → Continue
- Do not give consent → Thank you and end the survey.

7.2. Survey description of practices

Now, I would like to talk about the use of certain practices in your livestock production.

I will briefly describe two livestock management approaches to ensure we have the same understanding. If you are already familiar with these practices, please let me know.

The first approach is called "Improved Pasture Management." This strategy focuses on implementing planned grazing methods. It involves rotating livestock between different grazing areas or paddocks in an organized manner, maintaining a high animal density for short periods of time, and then allowing time for the pasture to recover. Some specific examples include holistic planned grazing, multi-paddock adaptive grazing, intensive rotational grazing, regenerative grazing, or Voisin rational grazing (among others).

The second approach refers to "Silvopastoral Systems," which integrate livestock farming with tree maintenance in the same space. This practice involves planting trees and shrubs in grazing areas and allows you to harvest additional products such as timber, firewood, and fruits.

Do you have any questions about this? (Clarify as needed)

7.3. Verification of stratification information

(Classification must be carried out by the interviewer before starting the survey)

a. Region

- Los Lagos
- Los Ríos
- La Araucanía

b. Sex

- Male
- Female

Introduction: Thank you very much for your willingness to participate in this survey. Your collaboration is very valuable to us.

7.4. Variables and corresponding questions

Variable	Explanation	Options in EN	Options	Options in EN
StartDate	start date			
EndDate	end date			
Status	response type			
IPAddress	IP address			
Progress	progress			
Duration (in seconds)	Duration (in seconds)			
Finished	Finished			
RecordedDate	Recorded Date			
ResponseId	Response ID			
RecipientLastName	Recipient Last Name			
RecipientFirstName	Recipient First Name			
RecipientEmail	Recipient Email			
ExternalReference	External Data Reference			
LocationLatitude	Location Latitude			
LocationLongitude	Location Longitude			
DistributionChannel	Distribution Channel			
UserLanguage	User Language			
Q_RecaptchaScore	Q_RecaptchaScore			
encuestador	Identificación del encuestador o encuestadora.	Identification of the interviewer.		
ID	Ingrese ID productor (según planilla de contactos)	Enter producer ID (according to contact sheet)		
Q2	Certifico que he leido el consentimiento, y el productor ha aceptado participar	I certify that I have read the consent, and the producer has agreed to participate		
ECONOMIC AND PRODUCTIVE CHARACTERIZATION				
To begin, I would like to ask you a few questions about your livestock activity.				

Variable	Explanation	Options in EN	Options	Options in EN
ECONOMIC AND PRODUCTIVE CHARACTERIZATION To begin, I would like to ask you a few questions about your livestock activity.				
Q1- educ	¿Cuál es el nivel más alto de educación que ha completado?	What is the highest level of education you have completed?	- Sin educación formal [0] - Educación básica o preparatoria (1° a 8° básico) [1] - Educación media o humanidades (1° a 4° medio) [2] - Educación Superior (técnico o universitaria) [3] - Educación de postgrado (magíster, doctorado) [4] - Prefiero no responder. [99]	- No formal education [0] - Basic or preparatory education (1st to 8th grade) [1] - Secondary education or humanities (1st to 4th year of high school) [2] - Higher education (technical or university) [3] - Postgraduate education (master's, doctorate) [4] I prefer not to answer. [99]
Q2- type_ production	¿En qué parte del ciclo de producción de carne bovina se enfoca? (Si aplica, puede marcar más de una)	What part of the beef production cycle do you focus on? (If applicable, you may check more than one)	- Cría (producción de terneros) [1] - Recría [2] - Engorda (crecimiento y engorda de terneros) [3] - Ciclo Completo (desde la cría hasta la engorda) [4]	- Breeding (production of calves) [1] - Rearing [2] - Fattening (growth and fattening of calves) [3] - Complete cycle (from breeding to fattening) [4]
Q3- farm_size	¿Cuántas hectáreas tiene destinadas exclusivamente al manejo de sus bovinos? Si no sabe el número exacto, una estimación cercana está bien.	How many hectares do you have dedicated exclusively to the management of your cattle? If you do not know the exact number, a close estimate is fine.		
Q4- num_ animal	¿Cuántos bovinos de carne tiene actualmente en su explotación? Si no sabe el número exacto, una estimación cercana está bien	How many beef cattle do you currently have on your farm? If you don't know the exact number, a close estimate is fine.		
Q5- income	¿Cuántos animales comercializó en los últimos 12 meses? Si no recuerda con precisión, una estimación cercana está bien	How many animals did you trade in the last 12 months? If you don't remember precisely, a close estimate is fine.		

Variable	Explanation	Options in EN	Options	Options in EN
Q6- org	¿Es usted miembro de alguna asociación, cooperativa o grupo de productores ganaderos?	Are you a member of any association, cooperative or group of livestock producers?	- No [0] - Si, una vez [1] - Si, dos veces [2] - Si, más de dos veces [3]	- No [0] - Yes, once [1] - Yes, twice [2] - Yes, more than twice [3]
Q7- training	En los últimos 12 meses, ¿ha participado en algún taller, capacitación o programa de desarrollo relacionado con la producción ganadera o el manejo de pastizales?	In the last 12 months, have you participated in any workshops, training or development programs related to livestock production or rangeland management?	- No [0] - Si, una vez [1] - Si, dos veces [2] - Si, más de dos veces [3]	- No [0] - Yes, once [1] - Yes, twice [2] - Yes, more than twice [3]
Q8- climate_change	¿Cuánto le preocupan los posibles efectos del cambio climático en su producción ganadera?	How concerned are you about the potential effects of climate change on your livestock production?	- Nada [0] - Poco [1] - Algo [2] - Bastante [3] - Mucho [4]	- Nothing [0] - A little [1] - Somewhat [2] - Quite a bit [3] - A lot [4]

Now, I would like to talk about using some practices in your livestock production.

USE OF TECHNOLOGIES

I will briefly describe two livestock management techniques to make sure we have the same understanding. If you are already familiar with these practices, please let me know.

The first approach is called “Improved Range Management.” This strategy focuses on applying planned grazing methods. It involves rotating livestock between different pasture areas or paddocks in an organized manner, maintaining a high density of animals for short periods of time, and then allowing time for the pasture to recover. Specific examples include so-called planned holistic grazing, multi-paddock adaptive grazing, intensive rotational grazing, regenerative grazing, or Voisin Rational grazing (among others).

The second approach refers to "Silvopastoral Systems", which integrate livestock farming with tree maintenance in the same space. This practice involves planting trees and shrubs in grazing areas, and allows for harvesting additional products such as wood, firewood, and fruits.

Do you have any questions about this? (Please clarify as necessary)

Q9- Adoption	¿Utiliza alguno de estos enfoques de prácticas en su explotación ganadera? (Seleccione todas las que apliquen)	Do you use any of these practice approaches on your livestock farm? (Select all that apply)	- Sistemas Mejorados de Manejo de Pastizales (SMMP) [1] - Sistemas Silvopastoriles (SSP) [2] - Ninguna [0]	- Improved Grassland Management Systems (IGMS) [1] - Silvopastoral Systems (SPS) [2] - None [0]

Variable	Explanation	Options in EN	Options	Options in EN
Q10- rotate	Si realiza pastoreo ¿Cada cuántos días rota a sus animales? - Selected Choice	If you are grazing, how often do you rotate your animals? - Selected Choice	-Más de una vez al día [3] -Todos los días [2] -Cada ___ días [1] -No realizo rotación / Pastoreo [0]	-More than once a day [3] -Every day [2] -Every ___ days [1] -I do not rotate / graze [0]
Q10- rotate_1_ TEXT	Si realiza pastoreo ¿Cada cuántos días rota a sus animales? - Cada___ días - Text	If you do grazing, how often do you rotate your animals? - Every___ days - Text		
Q11- comparerotate	¿Cómo cree que serían los resultados productivos al implementar estas prácticas en comparación a sus prácticas actuales??	How do you think the productive results would be by implementing these practices compared to your current practices?	- Peores que con mis prácticas actuales - Igual que con mis prácticas actuales - Mejores que con mis prácticas actuales	- Worse than my current practices - Same as my current practices - Better than my current practices
Q12- expected_ SMMP	¿Qué tan importantes cree que serían los beneficios económicos a largo plazo, luego de implementar estas prácticas? - Manejo Mejorado de Pastizales	How significant do you think the long-term economic benefits would be after implementing these practices? - Improved Grassland Management	- Poco importante [0] - Moderadamente importante [1] - Muy importante [2]	- Not very important [0] - Moderately important [1] - Very important [2]
Q12- expected_ SSP	¿Qué tan importantes cree que serían los beneficios económicos a largo plazo, luego de implementar estas prácticas? - Sistemas Silvopastoriles	How significant do you think the long-term economic benefits would be after implementing these practices? - Silvopastoral Systems	- Poco importante [0] - Moderadamente importante [1] - Muy importante [2]	- Not very important [0] - Moderately important [1] - Very important [2]
Q12- expected_ SMMP	¿Qué tan importantes cree que serán los beneficios económicos a largo plazo, luego de haber implementado estas prácticas? - Manejo Mejorado de Pastizales	How significant do you think the long-term economic benefits will be after implementing these practices? - Improved Grassland Management	- Poco importante [0] - Moderadamente importante [1] - Muy importante [2]	- Not very important [0] - Moderately important [1] - Very important [2]
Q12- expected_ SSP	¿Qué tan importantes cree que serán los beneficios económicos a largo plazo, luego de haber implementado estas prácticas? - Sistemas Silvopastoriles	How significant do you think the long-term economic benefits will be after implementing these practices? - Silvopastoral Systems	- Poco importante [0] - Moderadamente importante [1] - Muy importante [2]	- Not very important [0] - Moderately important [1] - Very important [2]

Variable	Explanation	Options in EN	Options	Options in EN
13-1-satisfaction_SMMP	¿Qué tan satisfecho está con el resultado de la implementación del Manejo Mejorado de Pastizales (MMP)?	How satisfied are you with the results of the implementation of Improved Range Management (MMP)?	- Poco satisfecho [0] - Moderadamente satisfecho [1] - Bastante satisfecho [2]	- Slightly satisfied [0] - Moderately satisfied [1] - Quite satisfied [2]
Q14- labor_smmp	¿Qué tan diferente sería la cantidad de trabajo o dedicación que necesitaría para implementar estas prácticas, en comparación con sus prácticas actuales? - Manejo Mejorado de Pastizales	How different would the amount of work or dedication you would need to implement these practices be compared to your current practices? - Improved Grassland Management	- Menos trabajo [0] - Similar cantidad de trabajo [1] - Más trabajo [2]	- Less work [0] - Similar amount of work [1] - More work [2]
Q14- labor_ss	¿Qué tan diferente sería la cantidad de trabajo o dedicación que necesitaría para implementar estas prácticas, en comparación con sus prácticas actuales? - Sistemas Silvopastoriles	How different would the amount of work or dedication you would need to implement these practices be, compared to your current practices? - Silvopastoral Systems	- Menos trabajo [0] - Similar cantidad de trabajo [1] - Más trabajo [2]	- Less work [0] - Similar amount of work [1] - More work [2]
Q14- labor_smmp	¿Qué tan diferente es la cantidad de trabajo o dedicación que necesita para implementar estas prácticas, en comparación con sus prácticas previas? - Manejo Mejorado de Pastizales	How different is the amount of work or dedication you need to implement these practices, compared to your previous practices? - Improved Grassland Management	- Menos trabajo [0] - Similar cantidad de trabajo [1] - Más trabajo [2]	- Menos trabajo [0] - Similar cantidad de trabajo [1] - Más trabajo [2] - Less work [0] - Similar amount of work [1] - More work [2]
Q15- machine_access	¿Qué tan fácil le resulta acceder a los insumos y la maquinaria necesarios para implementar estas prácticas?	How easy is it for you to access the supplies and machinery needed to implement these practices?	- Fácil [2] - Moderado [1] - Difícil [0]	- Easy [2] - Moderate [1] - Difficult [0]
Q16- cost_SMMP1	En relación a los costos de implementar un Manejo Mejorado de Pastizales (MMP). ¿Cómo cree que serían estos costos?	Regarding the costs of implementing Improved Range Management (IGM), what do you think these costs would be?	- No lo sé [99] - Bajos [0] - Moderados [1] - Altos [2]	- I don't know [99] - Low [0] - Moderate [1] - High [2]

Variable	Explanation	Options in EN	Options	Options in EN
Q16- cost_ SMMP2	En relación a los costos de implementar un Manejo Mejorado de Pastizales (MMP). ¿Cómo fueron estos costos?	Regarding the costs of implementing Improved Range Management (IGM), what were these costs?	- No lo sé [99] - Bajos [0] - Moderados [1] - Altos [2]	- I don't know [99] - Low [0] - Moderate [1] - High [2]
Q17- cost_ SSP1	En relación a los costos de implementar Sistemas Silvopastoriles (SSP). ¿Cómo cree que serían estos costos?	Regarding the costs of implementing Silvopastoral Systems (SSP), what do you think these costs would be?	- No lo sé [99] - Bajos [0] - Moderados [1] - Altos [2]	- I don't know [99] - Low [0] - Moderate [1] - High [2]
Q17- cost_ SSP1	En relación a los costos de implementar Sistemas Silvopastoriles (SSP). ¿Cómo cree que serían estos costos?	Regarding the costs of implementing Silvopastoral Systems (SSP), what do you think these costs would be?	- No lo sé [99] - Bajos [0] - Moderados [1] - Altos [2]	- I don't know [99] - Low [0] - Moderate [1] - High [2]
Q17- cost_ SSP2	En relación a los costos de implementar Sistemas Silvopastoriles (SSP). ¿Cómo fueron estos costos?	Regarding the costs of implementing Silvopastoral Systems (SSP), what were these costs?	- No lo sé [99] - Bajos [0] - Moderados [1] - Altos [2]	- I don't know [99] - Low [0] - Moderate [1] - High [2]
Q18 - info_ access	En los últimos 12 meses, ¿ha recibido información sobre alguna de estas prácticas?	In the last 12 months, have you received information about any of these practices?	- No, sobre ninguna de ellas [0] - Si, sobre el manejo mejorado de pastizales [1] - Si, sobre los sistemas silvopastoriles [2] - Si, sobre ambas [3]	- No, on none of them [0] - Yes, on improved grassland management [1] - Yes, on silvopastoral systems [2] - Yes, on both [3]
Q19- advisor_ access	¿Con qué frecuencia tiene acceso a algún tipo de asistencia técnica para su producción ganadera?	How often do you have access to some type of technical assistance for your livestock production?	- Nunca [0] - Ocasionalmente [1] - Frecuentemente [2]	- Never [0] - Occasionally [1] - Frequently [2]
Q19- type_ assistance	¿De dónde proviene principalmente la asistencia técnica que recibe?	Where does your technical support primarily come from?	- Asociada a un programa gubernamental (INDAP, SAG, otro) [1] - De un profesional/ técnico al que le pago por su servicio [2] - De un profesional/ técnico de la empresa donde obtengo insumos agrícolas [3] - De otro ganadero con conocimientos del tema [4].	- Associated with a government program (INDAP, SAG, other) [1] - From a professional/ technician whom I pay for his/her service [2] - From a professional/ technician from the company where I obtain agricultural supplies [3] - From another rancher with knowledge of the subject [4].

Variable	Explanation	Options in EN	Options	Options in EN
Q20-status_quo	¿Está acuerdo con la siguiente afirmación? "Prefiero estar seguro y usar las prácticas ganaderas que conozco bien, en vez de intentar usar prácticas nuevas"	Do you agree with the following statement? "I prefer to be safe and use the farming practices I know well, rather than trying to use new ones."	- En desacuerdo [1] - De acuerdo [0]	- Disagree [1] - Agree [0]
Q21- social_norm	¿Qué tan aceptadas cree que son estas prácticas (manejo mejorado de pastizales y sistemas silvopastoriles) por los otros ganaderos de su comunidad?	How accepted do you think these practices (improved grassland management and silvopastoral systems) are by other ranchers in your community?	- Poco aceptadas [0] - Moderadamente aceptadas [1] - Muy aceptadas [2]	- Little accepted [0] - Moderately accepted [1] - Highly accepted [2]
Q22- peer_effect	¿Qué tan importante es la opinión de otros productores que conoce, a la hora de decidir si utiliza estas nuevas prácticas en su predio?	How important is the opinion of other producers you know when deciding whether to use these new practices on your farm?	- Poco importante [0] - Moderadamente importante [1] - Muy importante [2]	- Not very important [0] - Moderately important [1] - Very important [2]
Q23-recognition	¿Cree que las personas valoran y reconocen el esfuerzo por implementar estas prácticas sostenibles?	Do you think people value and recognize the effort to implement these sustainable practices?	- Poco [0] - Medianamente [1] - Mucho [2]	- Little [0] - Moderately [1] - A lot [2]
Q24-impact_smmp	¿Cree que estas prácticas de pastoreo mejorado y los sistemas silvopastoriles realmente mejoran la fertilidad del suelo?	Do you think that these improved grazing practices and silvopastoral systems really improve soil fertility?	- Si, ambas [1] - Sólo el pastoreo mejorado [2] - Sólo los sistemas silvopastoriles [3] - No, ninguno [0]	- Yes, both [1] - Only improved grazing [2] - Only silvopastoral systems [3] - No, neither [0]
Q25-impact_ssp	¿Cree que estas prácticas de pastoreo mejorado y los sistemas silvopastoriles realmente ayudan a reducir los gases contaminantes que causan el cambio climático?	Do you think that these improved grazing practices and silvopastoral systems really help to reduce the polluting gases that cause climate change?	- Si, ambas [1] - Sólo el pastoreo mejorado [2] - Sólo los sistemas silvopastoriles [3] - No, ninguno [0]	- Yes, both [1] - Only improved grazing [2] - Only silvopastoral systems [3] - No, neither [0]
Let's end this survey with a little imaginary game, to understand how comfortable you are with taking risks. Imagine that you can choose between the following bets, which involve flipping a coin. If you guess the result (heads or tails), you receive an amount of money, if you guess wrong, you receive a smaller amount. I remind you that this is just an imaginary exercise and does not involve real money.				

Variable	Explanation	Options in EN	Options	Options in EN
26. risk_ aversion	Le explicaré cuatro opciones y usted me dice cuál preferiría jugar. Las opciones son:	I will explain four options to you and you tell me which one you would prefer to play. The options are:	- Opción A. Si acierta, recibe $40.000, si falla, recibe $40.000 (Siempre obtiene $40.000.-	- Option A. If you guess correctly, you receive $40 USD; if you guess incorrectly, you receive $40 USD (You always get $40 USD regardless of the result) [3] - Option B. If you guess correctly, you receive $60 USD; if you guess incorrectly, you receive $20 USD. [2] - Option C: If you guess correctly, you receive $80 USD; if you guess incorrectly, you receive $10 USD. [1] - Option D: If you guess correctly, you win $100 USD; if you guess incorrectly, you receive nothing. (All or nothing) [0]

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