Scotland's Rural College

Examining Factors for the Adoption of Silvopastoral Agroforestry in the Colombian Amazon

Alvarado-Sandino, Carlos; Barnes, AP; Sepulveda, IS; Garratt, Michael P.D; Thompson, Jill; Escobar, Maria-Paula

Published in:
Scientific Reports

DOI:
10.1038/s41598-023-39038-0

First published: 28/07/2023

Document Version
Peer reviewed version

Citation for pulished version (APA):
Alvarado-Sandino, C., Barnes, AP., Sepulveda, IS., Garratt, M. P. D., Thompson, J., & Escobar, M.-P. (2023). Examining Factors for the Adoption of Silvopastoral Agroforestry in the Colombian Amazon. *Scientific Reports*, *13*(1), Article 12252. Advance online publication. https://doi.org/10.1038/s41598-023-39038-0

Transitioning to silvopastoral forestry: testing the common drivers of farmer adoption in the Colombian Amazon

Alvarado Sandino, C.O.[*1,2], Barnes, A,P.[1], Sepúlveda, I.[1], Garratt, Michael P.D.[3,] Thompson, J. [4], Escobar Tello, M. P. [5]

[1] Rural Economy, Environment and Society, SRUC, The Kings Buildings, West Mains Road, Edinburgh, United Kingdom
[2.] University of Edinburgh, Faculty of Geosciences, West Mains Road, United Kingdom
[3] Sustainable Land Management, School of Agriculture, Policy & Development, University of Reading, United Kingdom
[4] UK Centre for Ecology & Hydrology. Bush Estate, Penicuik, United Kingdom
5 Bristol Veterinary School, University of Bristol, Langford House, Bristol, United Kingdom

* main contact: carlos.o.alvarado@protonmail.com

Acknowledgments
We thank the farmers who took the time to respond to our questionnaire. *This study was a component of the BioSmart multidisciplinary project that included a botanical study and social science. This research was funded through the RCUK-CIAT Newton-Caldas Fund Sustainable Tropical Agricultural Systems Programme BBSRC project numbers BB/R022852/1 and BB/S018840/1, and relied upon the CIAT Sustainable Amazonian Landscapes project which is part of the International Climate Initiative (KI). We also thank the University of Bristol for additional funds to complete the paper.*

The authors declare no competing interests

Abstract

Current land use systems in the Amazon largely consist of extensive conventional livestock operations that drive deforestation, degrade soil ecosystems, and tend to be socioeconomically unsustainable. Silvopastoral systems (SPS) have been promoted for decades as an alternative but widespread uptake has yet to be seen. We explore the main drivers and barriers to uptake through a bespoke survey of 172 farms in the Caquetá *region of the Colombian Amazon split equally between adoption and non-adoption.*

Pearson's chi-square tests and logistic regression models are used to analyse the effects of categorical and continuous predictor variables on a binary adoption variable. Results show that knowledge gaps, years of experience in farming, as well as infrastructure issues around poor road access were negatively related to adoption, while perception of SPS benefits, proximity to other SPS farms, training in SPS, and understanding of SPS were positively related to adoption with statistical significance. The most promising intervention strategies involve addressing knowledge gaps via training and specialised extension and improving market access by removing regulatory barriers and strengthening demand for agroforestry products.

Keywords: Colombia; Silvopastoral Systems; Farmer Behaviour

1.0 Introduction

Deforestation and agricultural expansion endanger the functioning of the Amazon ecosystem and the livelihoods and wellbeing of the communities who live from this resource (Leite-Filho *et al.*, 2021). A reinforcing feedback cycle emerges from the coupling of poor physicochemical soil quality with unsustainable ranching that drives further degradation, eventually forcing farmers to abandon their unproductive land in search of native forest to colonise, thus restarting the degradation cycle (Barrett, Valentim and Ii, 2013; Rodriguez *et al.*, 2021; Armenteras *et al.*, 2017). After Brazil, the Colombian province of Caquetá has the highest deforestation rate in the Amazon basin (Olaya-Montes *et al.*, 2021). Silvopastoral systems (SPS) have been found to offer an alternative to conventional ranching systems (Bermeo *et al.*, 2022). Generally, an SPS incorporates perennial trees and shrubs into pastures to mimic some of the ecosystem services provided by native forests while providing more consistent and higher quality forage to livestock (Aynekulu *et al.*, 2020). SPS can also be less detrimental to ecological health by supporting biodiversity, carbon sequestration, and water quality (Calle *et al.*, 2013). From a socio-economic perspective farmers can also benefit from secondary forest products, such as lumber, food, medicines, and marketable fruits (Ollinaho *et al.*, 2021; Pardo Rozo *et al.*, 2022). Moreover, livestock welfare benefits have been found which limit livestock weight loss, sustain milk production during the dry season, increase fecundity, and lead to 28% higher milk production and 157% higher meat production than conventional systems (Zamora *et al.*, 2001; Ibrahim *et al.*, 2006; de Souza Filho *et al.*, 2021; Notenbaert *et al.*, 2021). Hence a number of studies have found that these benefits will lead to increased financial resilience, as costs are reduced (Gil, Siebold and Berger, 2015; Notenbaert *et al.*, 2021; World Bank, 2008).

Despite these benefits, SPS has not been widely adopted in key areas of the agricultural frontier in the Amazon. Conventional livestock systems still dominate the Amazonian foothills of Colombia and 98% of livestock operations use traditional methods (Pardo Rozo *et al.*, 2020; Pardo Rozo *et al.*, 2022). Context dependant factors pervade discussion of limits to adoption of SPS. Since the 2016 peace agreement land has become more accessible, which has led to increases in land speculation, natural resource extraction, and the expansion of the agricultural frontier (Murillo-Sandoval *et al.*, 2020). Accordingly, the conversion of native forest to cattle ranching is often facilitated by non-legal actors and land speculation (Murillo-Sandoval *et al.*, 2020; Del Río Duque *et al.*, 2022).

The purpose of this paper is to provide a detailed examination of drivers for SPS adoption and apply these to the region of Caquetá, which is at the forefront of deforestation within the Colombian Amazon. The paper is structured as follows. A conceptual background is presented which summarises the significant number of drivers explored by past studies on SPS adoption in Latin America as a whole. We then set multiple hypotheses based on these studies and test these through a bespoke survey of farmers within this region with the aim of exploring the barriers. Results are presented with the aim of testing the key drivers for adoption. This is followed by a discussion of the results and implications for interventions to support transition to SPS.

1.2 Conceptual background

There is a substantial and growing literature on SPS adoption barriers in Latin America. Figure 1 summarises these and indicates that at least 28 main factors have been found to influence adoption of SPS. For brevity these are presented within key categories.

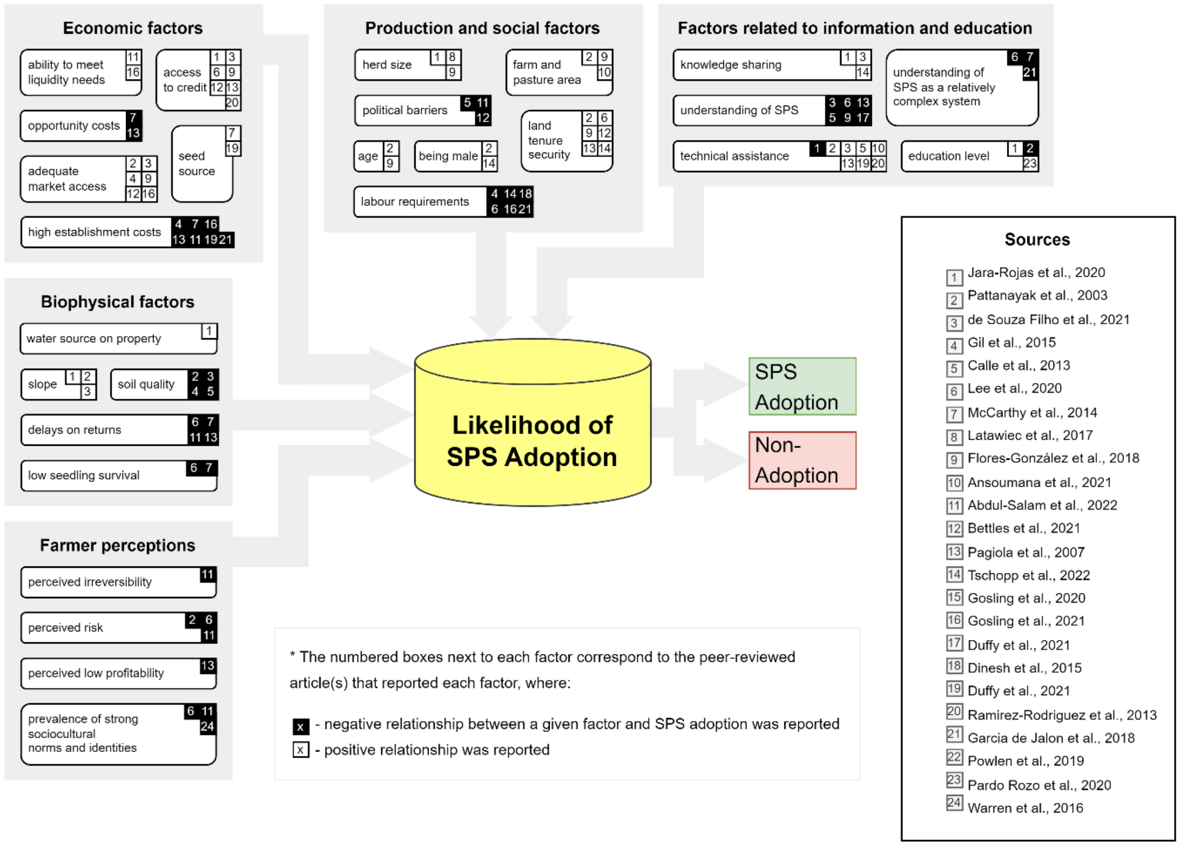

Figure 1. Flow chart of factors determining and inhibiting adoption of SPS We assign the general influence of these factors against the authors, where the colour-coding of the citation numbers indicate a positive or negative relationship with adoption of SPS.

These findings infer a general model of adoption of SPS which cover biophysical, economic and social-cultural and perceptual factors. We aim to test a number of hypotheses around uptake of SPS. These are shown in Table 3 in the results section

2.0 Data and Methods

2.1 Data

Land colonization for cattle ranching is the primary cause of deforestation in Caquetá (Olaya-Montes *et al.*, 2021). This study area (Figure 2) was chosen because SPS present a pragmatic approach to address many of the issues in this region. Almost all farms included in the interviews were in Caquetá; however, to increase the sample size, 19 farmers were interviewed in the adjacent departments of Putumayo (3) and Guaviare (16), which have a similar socioecological context to Caquetá.

Working with the local department of agriculture, structured phone interviews were conducted with farmers across the study area with the aim of collecting an equal sample between adopters and non-adopters across the region. As a result, 172 farms were selected such that 86 (50%) had adopted silvopastoral systems on at least one hectare of land, and the other half had not.

Once completed these data were matched through GPS coordinates to geospatial variables. The spatial variables, which were derived from online sources, were soil type and slope. Soil data was obtained from the website of the Instituto Geografico Agustin Codazzi (IGAC) (IGAC, 2022). Slope data was derived from a global digital elevation model (Watkins, 2022).

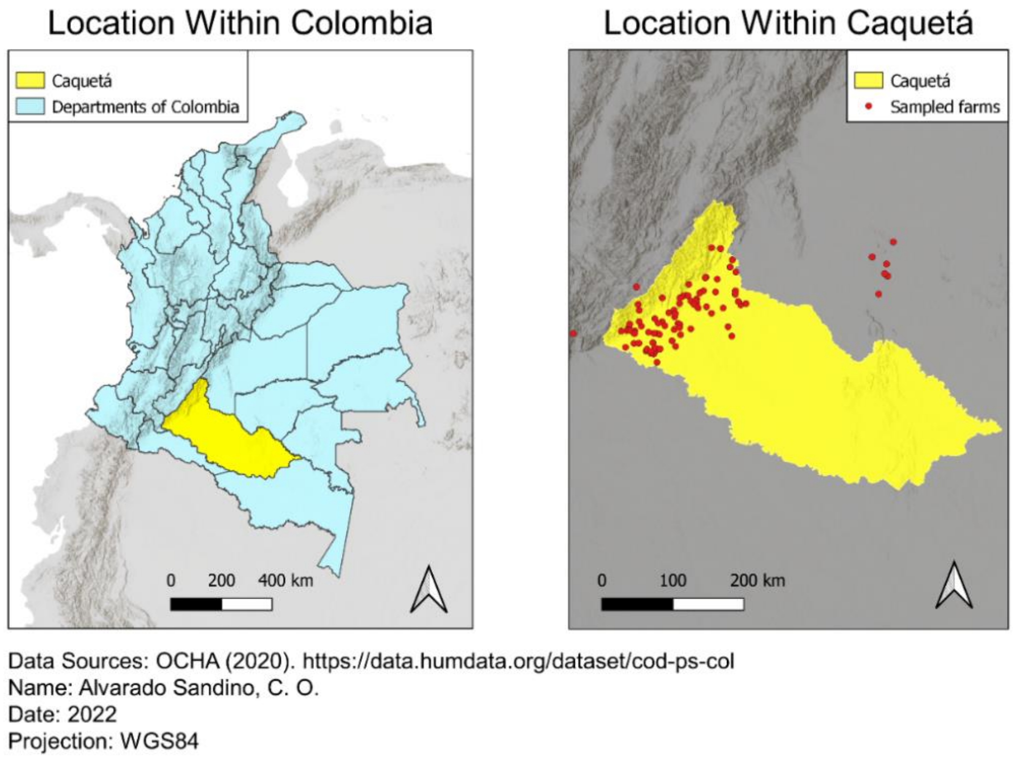

Figure 2. Location of the study area within Colombia and the study locations (farms) within Caquetá (OCHA, 2021)

Table 2 Description of the data with main descriptive statistics

Hypothesis	Mean	*SD*
Biophysical Factors		
slope (in vereda as percentage)	8.858	*(4.200)*
soil type (1=and-oxisol, 2=entisol, 3=ultisol, 4= inceptisol)	3.302	*(0.912)*
Production and Social Factors		
herd size (no)	33.211	*(43.299)*
farm size (ha)	123.737	*(133.251)*
household labour (no)	2.053	*(1.252)*
hired labour (no)	2.196	*(1.285)*
gender (1=female, 2=male)	1.192	*(0.395)*
livestock experience (yrs)	18.735	*(8.047)*
experience at current farm (yrs)	19.616	*(9.293)*
age (1< 50 ,2>= 50)	1.279	*(1.450)*
Economic Factors		
proximity to municipal centre (km)	8.538	*(5.390)*
near to a main road (1=no,2=yes)	1.180	*(1.386)*
proximity to a secondary road (1=no,2=yes)	1.494	*(1.501)*
off-farm job (1=no,2=yes)	1.125	*(0.332)*
Farmer Perceptions		
Perceive the benefits of SPS to:		
profitability (1=no, 2=not sure, 3=yes)	2.337	*(0.604)*
pest reduction (1=no, 2=not sure, 3=yes)	2.157	*(0.790)*
production (1=no, 2=not sure, 3=yes)	2.494	*(0.617)*
product quality (1=no, 2=not sure, 3=yes)	2.488	*(0.626)*
cost savings (1=no, 2=not sure, 3=yes)	2.366	*(0.630)*
milk production (1=no, 2=not sure, 3=yes)	2.378	*(0.623)*
cattle reproduction(1=no, 2=not sure, 3=yes)	2.372	*(0.613)*
Factors Related to Information and Education		
SPS in veredas (1=if vereda has 1 or less, 2=more than 1 SPS).	1.180	*(1.386)*
trained in SPS.(1 = no, 2= yes)	1.715	*(1.453)*
completed secondary school..(1 = no, 2= yes)	1.185	*(1.389)*
farmers who understand SPS, indicated by:		
confidence in SPS(1=no, 2=not sure, 3=yes)	2.238	*(0.849)*
has skills needed for SPS(1=no, 2=not sure, 3=yes)	2.047	*(0.843)*
feeling that SPS are understandable(1=no, 2=not sure, 3=yes)	2.430	*(0.641)*
ability to explain SPS(1=no, 2=not sure, 3=yes)	2.041	*(0.833)*
member of a farmer association.(1=no, 2=yes)	1.345	*(0.477)*

2.2 Data Analysis

We employ the approach of de Souza Filho *et al.*,(2021) where Pearson's chi-square test of independence was the main approach to test the significance of categorical variables and logistic regression for continuous variables (de Souza Filho *et al.*, 2021). The categorical variables fulfilled the requirements of the Pearson's chi-square test, including independence, mutual exclusivity, and expected values of five or more in at least 80% of the contingency table cells (McHugh, 2013). The contingency tables of expected values for each variable (see supplementary material). Seven of the continuous variables fulfilled all the requirements of the logit regression, including, "independence of errors, linearity in the logit for continuous variables, absence of multicollinearity, and lack of strongly influential outliers" (Stoltzfus, 2011), and were analysed in combination. The assumption of absence of multicollinearity was violated by five variables, which, accordingly, were analysed individually.

3.0 Results and Discussion

The results are shown in Table 3 below. We find no significant effect of slope and soil order for these farmers in Caquetá. This is converse to previous studies (Calle *et al.*, 2013; Gil, Siebold and Berger, 2015; Jara-Rojas *et al.*, 2020; de Souza Filho *et al.*, 2021). Slope and soil are expected to be context dependant, and this may be the case here. Moreover, we examined soil order, rather than quality or sand proportion as used in previous studies; hence, this may provide another dimension to understanding how soil influences SPS adoption. Ultisols are especially well-suited to forestry and relatively ill-suited to agriculture due to their acidity, low fertility, and extremely weathered nature (USDA, 1999). This could explain the pattern of higher adoption rates among farmers on Ultisols and provides an agenda for future investigations.

Table 3. Summary of results, strength of effects and p-values for each hypothesis*

Hypothesis	Coef.//Chi^2	SE	p.
Biophysical Factors			
1. Farms in regions with steep slope exhibit higher adoption rates than those in shallow sloping regions.	0.017	0.038	
2. Farms located in veredas* with better soil quality exhibit higher adoption rates than farms in regions with less sandy soils.	7.788		
Production and Social Factors			
3. SPS are more likely to be adopted by farms with larger herds.	-0.007	0.004	
4. SPS are more likely to be adopted by larger farms.	-0.002	0.001	
5. SPS are more likely to be adopted by farms with more available			
(a) household labour	6.501		*
(b) hired labour.	1.756		
7. SPS are more likely to be adopted by male farmers.	4.537		*
Farmers with more years at current farm will adopt SPS	-0.134	0.026	***
Farmers with more livestock experience will adopt SPS	-0.093	0.020	***
SPS are more likely to be adopted by older farmers	1.040		
Economic Factors			
8. SPS are more likely to be adopted by farms with better market access, where market access is proxied by:			
a. better road access	26.851		***
b. proximity to municipal centre	0.064	0.030	*
c. proximity to a main road	0.984		
d. proximity to a secondary road	16.956		***
9. SPS are less likely to be adopted by farmers with off-farm jobs.	0.340		
Farmer Perceptions			
10. SPS are more likely to be adopted by farmers who perceive the benefits of SPS to:			
(a) profitability			
(b) pest reduction	37.919		***
(c) general production	15.475		***
(d) product quality	12.063		**
(e) economic results	58.616		***
(f) milk production	57.463		***
(g) cattle reproduction	58.937		***
Factors Related to Information and Education			
11. SPS are more likely to be adopted by farmers with other SPS-adopters in their vicinity (farmers within veredas where there is at least one other SPS-adopter).	37.816		***
12. SPS are more likely to be adopted by farmers who have been trained in SPS.	4.823		*
13. SPS are more likely to be adopted by farmers who have completed secondary school.	2.947		
14. SPS are more likely to be adopted by farmers who understand SPS, indicated by:			
(a) confidence in SPS	65.856		***
(b) has skills needed for SPS	55.353		***

(c) feeling that SPS are understandable	39.668	***
(d) ability to explain SPS	55.273	***
15. SPS are more likely to be adopted by farmers who are members of a farmer association.	1.957	

*In Colombia, "veredas" are the smallest type of subnational boundary and are spatially equivalent to a sub-municipality or neighbourhood (OCHA, 2020)

Some studies found experience to positively affect adoption, albeit with low or no statistical significance (Pattanayak *et al.*, 2003; Flores-González *et al.*, 2018), we find the converse. Those variables related to experience (years on current farm and livestock experience) showed significant and negative relations with adoption, meaning the increasing experience decreases the likelihood of adoption. This aligns with literature on the role of farming experience which locks farmers into past practices (Barnes *et al.*, 2022; Warren *et al.*, 2016). Ibrahim *et al.* (2006) also reported that traditionality was an inhibitor of SPS in Nicaragua, Costa Rica, and Colombia (Ibrahim *et al.*, 2006). According to systems thinking (Meadows, 2015), paradigms, such as embeddedness in a traditional mindset, are the intervention points in a system that are the most resistant to change but yield greatest results. Therefore, if the negative relationship between experience and SPS adoption in Caquetá is a result of traditional paradigms, addressing these paradigms could generate substantial increases in adoption rates. Despite gender being only weakly significant, this agrees with previous studies who argue that due to gender inequalities women have less access to credit, income, and equipment and therefore a barrier to adoption to SPS (Pattanayak *et al.*, 2003; Theriault *et al.*, 2017; Tschopp *et al.*, 2022). Gumucio *et al.* (2015) found that the roles that women hold in Latin American cattle ranching operations are often discounted; therefore, their contributions to various aspects of cattle management, such as milking, albeit significant, are often overlooked. This pattern has resulted in the relatively lower adoption rates among women observed in the literature.

Access to markets have been found to be important (Pattanayak *et al.*, 2003; Gil *et al.*, 2015; Bettles *et al.*, 2021; de Souza Filho *et al.*, 2021; Gosling *et al.*, 2021) and access to main and secondary roads act as a proxy for this market access. Improving market access by building roads would likely be an effective way to encourage SPS adoption. However, road development is a well-known driver of deforestation in the Amazon and internationally, therefore this approach more likely lead to adverse impacts on forest ecosystems (Barber *et al.*, 2014; Murillo-Sandoval *et al.*, 2020). Perhaps a more important limiter of market access is the lack of local markets resulting from the low population density observed in forest frontier areas, such as Caquetá, that results from the low labour demands of the extensive traditional ranching that dominates these regions (Sloan, 2008; Gosling *et al.*, 2021). SPS can support sustainable and profitable livelihoods in the Colombian Amazon (Taou *et al.*, 2022) therefore, if the other barriers to SPS are dismantled to the point where adoption becomes widespread, the concentration of people seeking SPS-based livelihoods would contribute to increasing population density and the subsequent revitalisation of local markets. Bettles *et al.* (2021) argue that non-state actors have an advantage compared to centralized governmental programs in addressing issues at a highly local scale, for example by helping farmers to overcome regulatory market barriers. Cooperation between state and non-state actors is recommended in order to yield the greatest impact by achieving results at scale and at the community level (Bettles *et al.*, 2021).

All of the seven variables which reflect farmer perceptions exhibited highly significant and positive effects which indicate the importance of perceptions towards the benefits of SPS. These include both economic factors, such as yield and profits, but also pest management and cattle reproduction (Dawson *et al.*, 2011; Bettles *et al.*, 2021). Education, extension specialising in SPS, and community information exchange contributes to the perception of benefits of SPS (Jara-Rojas *et al.*, 2020; Pardo Rozo *et al.*, 2020, Muñoz Ramos *et al.*, 2020; de Souza Filho *et al.*, 2021; Tschopp *et al.*, 2022) and this may be a key intervention route to change attitudes towards SPS within farming.

A significant positive effect on adoption was farmers' proximity to other adopters. We found that farmers in veredas where there are existing silvopastoral farms were more likely to adopt SPS. This is a result of community knowledge sharing, a commonly reported determinant of adoption across Latin America (Jara-Rojas *et al.*, 2020; de Souza Filho *et al.*, 2021; Tschopp *et al.*, 2022). Tschopp *et al.* (2022) found a similar proximity effect in Argentina, where farmers located near other SPS adopters were more likely to adopt, even when other variables, such as market access, were considered sub-optimal. This suggests a strategy for maximization of adoption whereby extension services target as many different veredas as possible, such that SPS dissemination can be achieved via an intra-vereda knowledge exchange to exploit this effect.

Specialised SPS training positively influences adoption. In this study, the effect was positive and statistically significant ($p = 0.043$). Combined with other intervention strategies, the training of farmers in SPS is a promising strategy for increasing adoption rates that is commonly suggested in the literature (Ramírez Rodríguez *et al.*, 2013; Jara-Rojas *et al.*, 2020; Rodrigues *et al.*, 2020; Ansoumana *et al.*, 2021; de Souza Filho *et al.*, 2021; Duffy *et al.*, 2021). Like perception of benefits, the understanding of SPS exhibited strong positive effects on adoption with high significance. Adoption was higher among farmers that either had confidence in their ability to implement SPS, had skills needed for SPS, felt that SPS are understandable, or were able to explain SPS. This finding is closely linked with training, since achieving farmer understanding requires SPS training in some capacity.

Knowledge gaps were the most commonly reported barrier to adoption in the literature, which supports our findings that the absence of knowledge gaps – in other words, the understanding of SPS – is a strong and significant determinant of adoption (Flores-González *et al.*, 2018; Lee *et al.*, 2020; Bettles *et al.*, 2021; de Souza Filho *et al.*, 2021; Duffy *et al.*, 2021; Abdul-Salam *et al.*, 2022). This finding reinforces the need for SPS training programs to reduce knowledge gaps and increase adoption rates, which has well-evidenced positive effects on adoption (Chavan *et al.*, 2015). Both governmental and non-state actors can contribute to closing these knowledge gaps via marketing, workshops on SPS, and specialised extension services (Bettles *et al.*, 2021).

4.0 Conclusions

Colombia in the post-agreement landscape has experienced a range of growth demands but has strong commitments to green growth and, to meeting net zero targets. This should require reducing the intensity of conversion of natural forest to agricultural production. Key to this is supporting and convincing farmers to convert their more traditionally productive, but specialised, activities to engage with silvopastoral approaches. We provide an overall framework of the drivers to uptake in Latin America and an empirical application within a pertinent case study in the Amazonian frontier. However, it is clear that adoption of SPS is context specific and a number of common drivers were not found to be applicable in the Colombian Amazon. This provides some support for locally targeted solutions. Specifically, the role of training and use of peer-to-peer knowledge networks could exploit the strong relationship with positive perceptions held by some of these farmers.

Given the biophysical and socioeconomic context of Caquetá as a ranching-based tropical forest frontier, these results may be applicable in other regions undergoing the same transformations in land use. Since knowledge gaps were the most important barrier to adoption it is recommended that a strong focus be placed on policies and intervention strategies that address information asymmetries, such as specialised extension services and training programs with emphasis on gender equal access. However, there was evidence that, even with sufficient knowledge about SPS, farmers face additional barriers to adoption related to market access. Therefore, efforts must also be taken to bolster markets for agroforestry products and to address barriers to market access.

REFERENCES

Abdul-Salam, Y., Ovando, P. and Roberts, D. (2022) 'Understanding the economic barriers to the adoption of agroforestry: A Real Options analysis', Journal of Environmental Management, 302(October), p. 113955. doi: 10.1016/j.jenvman.2021.113955.

Ainembabazi, J. H. and Mugisha, J. (2014) 'The Role of Farming Experience on the Adoption of Agricultural Technologies: Evidence from Smallholder Farmers in Uganda', Journal of Development Studies, 50(5), pp. 666–679. doi: 10.1080/00220388.2013.874556.

Ansoumana, B. *et al.* (2021) 'Farmers ' perception on the benefits and constraints of Farmer Managed Natural Regeneration and determinants of its adoption in the southern groundnut basin of Senegal', Agroforestry Systems, 14(October). doi: 10.1007/s10457-021-00690-y.

Armenteras, D. *et al.* (2017) 'Deforestation dynamics and drivers in different forest types in Latin America: Three decades of studies (1980–2010)', Global Environmental Change, 46(November 2016), pp. 139–147. doi: 10.1016/j.gloenvcha.2017.09.002.

Aynekulu, E., Suber, M., Van Noordwijk, M., Arango, J., Roshetko, J. M., & Rosenstock, T. S. (2020). Carbon storage potential of silvopastoral systems of Colombia. Land, 9(9), 309.

Barber, C. P. *et al.* (2014) 'Roads, deforestation, and the mitigating effect of protected areas in the Amazon', Biological Conservation, 177(2014), pp. 203–209. doi: 10.1016/j.biocon.2014.07.004.

Barnes, A. P. et al. (2022) 'Farmer intentional pathways for net zero carbon: Exploring the lock-in effects of forestry and renewables', Land Use Policy, 112(October 2021), p. 105861. doi: 10.1016/j.landusepol.2021.105861.

Bermeo, J. P. C., Hincapie, K. L. P., Cherubin, M. R., Morea, F. A. O., & Olaya, A. M. S. (2022). Evaluating soil quality in silvopastoral systems by the Soil Management Assessment Framework (SMAF) in the Colombian Amazon. Revista Ciência Agronômica, 53.

Bettles, J. *et al.* (2021) 'Agroforestry and non-state actors : A review', Forest Policy and Economics, 130(June), pp. 1–11. doi: 10.1016/j.forpol.2021.102538.

Blare, T. *et al.* (2015) 'Is there a choice? Choice experiment to determine the value men and women place on cacao agroforests in coastal Ecuador', International Forestry Review, 17(4), pp. 46–60. doi: 10.1505/146554815816002220.

Calle, Z. *et al.* (2013) 'A Strategy for Scaling-Up Intensive Silvopastoral Systems in Colombia A Strategy for Scaling-Up Intensive Silvopastoral Systems in Colombia', Journal of Sustainable Forestry, 32(September), pp. 677–693. doi: 10.1080/10549811.2013.817338.

Chavan, S. B. *et al.* (2015) 'National Agroforestry Policy in India: A low hanging fruit', Current Science, 108(10), pp. 1826–1834.

Dávalos, L. M. *et al.* (2014) 'Demand for beef is unrelated to pasture expansion in northwestern Amazonia', Biological Conservation, 170, pp. 64–73. doi: 10.1016/j.biocon.2013.12.018.

Dawson, I. K. *et al.* (2011) 'Climate change and tree genetic resource management: Maintaining and enhancing the productivity and value of smallholder tropical agroforestry landscapes. A review', Agroforestry Systems, 81(1), pp. 67–78. doi: 10.1007/s10457-010-9302-2.

Duffy, C. *et al.* (2021) 'Marginal Abatement Cost Curves for Latin American dairy production: A Costa Rica case study', Journal of Cleaner Production, 311(September 2020), p. 127556. doi: 10.1016/j.jclepro.2021.127556.

Duiker, S. W., Flanagan, D. C. and Lal, R. (2001) 'Erodibility and infiltration characteristics of five major soils of southwest Spain', Catena, 45(2), pp. 103–121. doi: 10.1016/S0341-8162(01)00145-X.

Escobar, M. P. *et al.* (2021) BIOSMART Agri-environmental policy , silvopastoral systems , biodiversity , and climate change, Policy Brief No. 60. Cali (Colombia): International Center for Tropical Agriculture (CIAT).

Ferguson, B. G. *et al.* (2013) 'Sustainability of holistic and conventional cattle ranching in the seasonally dry tropics of Chiapas, Mexico', Agricultural Systems, 120, pp. 38–48. doi: 10.1016/j.agsy.2013.05.005.

Flores-González, A. *et al.* (2018) 'Adoption of sustainable cattle production technologies in the Lacandon rainforest , Chiapas , México', International Journal of Agriculture Innovations and Research, 7(2), pp. 159–168.

Foley, J. A. *et al.* (2007) 'Amazonia revealed: Forest degradation and loss of ecosystem goods and services in the Amazon Basin', Frontiers in Ecology and the Environment, 5(1), pp. 25–32. doi: 10.1890/1540-9295(2007)5[25:ARFDAL]2.0.CO;2.

Gil, J. *et al.* (2015) 'Adoption and development of integrated crop-livestock-forestry systems in Mato Grosso, Brazil', Agriculture, Ecosystems and Environment, 199, pp. 394–406. doi: 10.1016/j.agee.2014.10.008.

Gosling, E. *et al.* (2020) 'A goal programming approach to evaluate agroforestry systems in Eastern Panama', Journal of Environmental Management, 261(January), p. 110248. doi: 10.1016/j.jenvman.2020.110248.

Gosling, E. *et al.* (2021) 'Which Socio-economic Conditions Drive the Selection of Agroforestry at the Forest Frontier?', Environmental Management, 67(6), pp. 1119–1136. doi: 10.1007/s00267-021-01439-0.

Gumucio, T. *et al.* (2015) 'Silvopastoral Systems in Latin America : Mitigation Opportunities for Men and Women Livestock Producers', CIAT.

Ibrahim, M. *et al.* (2006) 'Sistemas silvopastoriles como una herramienta para el mejoramiento de la productividad y restauración de la integridad ecológica de paisajes ganaderos Silvopastoral systems as a tool for the improvement of productivity and restoration of the ecological in', Pastos y Forrajes, 29(4), pp. 383–419.

Instituto Geografico Agustin Codazzi (IGAC) (2022) 'Datos Abiertos – Agrología', https://geoportal.igac.gov.co/contenido/datos-abiertos-agrologia

Jara-Rojas, R. *et al.* (2020) 'Factors affecting the adoption of agroforestry practices: Insights from silvopastoral systems of Colombia', Forests, 11(6), pp. 1–15. doi: 10.3390/F11060648.

Latawiec, A. E. *et al.* (2017) 'Improving land management in Brazil: A perspective from producers', Agriculture, Ecosystems and Environment, 240, pp. 276–286. doi: 10.1016/j.agee.2017.01.043.

Lee, S. *et al.* (2020) 'Adoption potentials and barriers of silvopastoral system in Colombia: Case of Cundinamarca region', Cogent Environmental Science, 6(1). doi: 10.1080/23311843.2020.1823632.

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. Nature Communications, 12(1), 1-7.

McCarthy, N. and Brubaker, J. (2014) 'Climate-Smart Agriculture & Resource Tenure in sub-Saharan Africa: a Conceptual Framework', FAO, (September), p. 26. Available at: http://www.fao.org/3/a-i3982e.pdf.

Mchugh, M. L. (2013) 'Lessons in biostatistics The Chi-square test of independence', Lessons in Biostatistics, 23(2), pp. 143–149.

Murillo-Sandoval, P. J. *et al.* (2020) 'The end of gunpoint conservation : forest disturbance after the Colombian peace agreement The end of gunpoint conservation : forest disturbance after the Colombian peace agreement', Environmental Research Letters, 15(March).

Notenbaert, A. M. O. *et al.* (2021) 'Tapping Into the Environmental Co-benefits of Improved Tropical Forages for an Agroecological Transformation of Livestock Production Systems', Frontiers in Sustainable Food Systems, 5, pp. 0–18. doi: 10.3389/fsufs.2021.742842.

Olaya-Montes, A. *et al.* (2021) 'Restoring soil carbon and chemical properties through silvopastoral adoption in the Colombian Amazon region', Land Degradation and Development, 32(13), pp. 3720–3730. doi: 10.1002/ldr.3832.

Ollinaho, O. I. and Kröger, M. (2021) 'Agroforestry transitions : The good , the bad and the ugly', Journal of Rural Studies, 82(January), pp. 210–221. doi: 10.1016/j.jrurstud.2021.01.016.

Pagiola, S. *et al.* (2007) 'Paying for the environmental services of silvopastoral practices in Nicaragua', Ecological Economics, 4. doi: 10.1016/j.ecolecon.2007.04.014.

Pagiola, S., Rios, A. R. and Arcenas, A. (2010) 'Poor Household Participation in Payments for Environmental Services : Lessons from the Silvopastoral Project in Quindío , Colombia', pp. 371–394. doi: 10.1007/s10640-010-9383-4.

Pardo Rozo, Y. Y., Hernández Castorena, O. and Andrade Adaime, M. C. (2022) 'Key Factors of Competitiveness and Sustainability in Livestock Systems of The Andean-Amazonian Piedmont', Mercados y Negocios, 45.

Pardo Rozo, Y. Y., Muñoz Ramos, J. and Velásquez Restrepo, J. E. (2020) 'Tipificación de sistemas agropecuarios en el piedemonte amazónico colombiano Typification of agricultural systems in the Colombian Amazon piedmont', Revista Espacios, 41(47), pp. 213–228. doi: 10.48082/espacios-a20v41n47p16.

Pattanayak, S. K. *et al.* (2003) 'Taking Stock of Agroforestry Adoption Studies', RTI International, 103(3), pp. 239–248. doi: 10.1023/A.

Polanía-Hincapié, K. L. *et al.* (2021) 'Soil physical quality responses to silvopastoral implementation in Colombian Amazon', Geoderma, 386(November 2020). doi: 10.1016/j.geoderma.2020.114900.

Ramírez Rodríguez, J. B. *et al.* (2013) 'Caracterización de los sistemas productivos y percepción de los agricultores sobre agroforestería: caso conformación red silvopastoril', Ingenierías & Amazonia, (6).

Del Río Duque, M. L. *et al.* (2022) 'Understanding systemic land use dynamics in conflict-affected territories : The Understanding systemic land use dynamics in conflict-affected territories : The cases of Cesar and Caquetá', PLoS ONE, 17(May). doi: 10.1371/journal.pone.0269088.

Rodrigues, T. F. *et al.* (2020) 'Ecosystem services provided by armadillos', Biological Reviews, 95(1), pp. 1–21. doi: 10.1111/brv.12551.

Rodriguez, L. *et al.* (2021) 'Agroforestry systems in the Colombian Amazon improve the provision of soil ecosystem services', Applied Soil Ecology, 164(February). doi: 10.1016/j.apsoil.2021.103933.

Silva, A. *et al.* (2019) 'Greenhouse gas emissions in conversion from extensive pasture to other agricultural systems in the Andean region of Colombia', Environment, Development and Sustainability, 21(1), pp. 249–262. doi: 10.1007/s10668-017-0034-6.

Sloan, S. (2008) ‘Reforestation amidst deforestation: Simultaneity and succession’, Global Environmental Change, 18(3), pp. 425–441. doi: 10.1016/j.gloenvcha.2008.04.009.

de Souza Filho, M. H. *et al.* (2021) ‘Determinants of adoption of integrated systems by cattle farmers in the State of Sao Paulo , Brazil’, Agroforestry Systems, 8, pp. 103–117. doi: 10.1007/s10457-020-00565-8.

Stoltzfus, J. C. (2011) ‘Logistic Regression : A Brief Primer’, Academic Emergency Medicine. doi: 10.1111/j.1553-2712.2011.01185.x.

Taou, N. *et al.* (2022) ‘Agroforestry Programs in The Colombian Amazon: Selection, Treatment and Exposure Effects on Deforestation’, NIESR Discussion Ppaer No. 537, (537). Available at: www.niesr.ac.uk.

Theriault, V. *et al.* (2017) ‘How Does Gender Affect Sustainable Intensification of Cereal Production in the West African Sahel ? Evidence from Burkina Faso’, World Development, 92, pp. 177–191. doi: 10.1016/j.worlddev.2016.12.003.

Thomas, G. A. *et al.* (2007) ‘No-tillage and conservation farming practices in grain growing areas of Queensland - A review of 40 years of development’, Australian Journal of Experimental Agriculture, 47(8), pp. 887–898. doi: 10.1071/EA06204.

Tschakert, P., Coomes, O. T. and Potvin, C. (2007) ‘Indigenous livelihoods, slash-and-burn agriculture, and carbon stocks in Eastern Panama’, Ecological Economics, 60(4), pp. 807–820. doi: 10.1016/j.ecolecon.2006.02.001.

Tschopp, M. *et al.* (2022) ‘Adoption of sustainable silvopastoral practices in Argentina’s Gran Chaco: A multilevel approach’, Journal of Arid Environments, 197(October 2021), p. 104657. doi: 10.1016/j.jaridenv.2021.104657.

Ugochukwu, A. I. and Phillips, P. W. B. (2018) ‘Technology Adoption by Agricultural Producers: A Review of the Literature’, Innovation, Technology and Knowledge Management, pp. 361–377. doi: 10.1007/978-3-319-67958-7_17.

USDA (1999) ‘Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys’, United States Department of Agriculture, (436).

Vashisth, T. and Kadyampakeni, D. (2019) Diagnosis and management of nutrient constraints in citrus, Fruit Crops: Diagnosis and Management of Nutrient Constraints. Elsevier Inc. doi: 10.1016/B978-0-12-818732-6.00049-6.

Warren, C. R. *et al.* (2016) ‘Limited adoption of short rotation coppice: The role of farmers’ socio-cultural identity in influencing practice’, Journal of Rural Studies, 45, pp. 175–183. doi: 10.1016/j.jrurstud.2016.03.017.

Watkins (2022) ‘30-Meter SRTM Tile Downloader’ https://dwtkns.com/srtm30m/

World Bank (2008) ‘Implementation and completion and results report on a grant in the amount of SDR 3.7 million equivalent to Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) for the Integrated Silvo Pastoral Approaches to Ecosystem Management Project in Colo’, (November).

Zambrano-Yepes, J., Herrera-Valencia, W. and Motta-Delgado, P. A. (2020) ‘Concentración de los macronutrientes del suelo en áreas de pastoreo del departamento de Caquetá, Amazonia colombiana’, Ciencia & Tecnología Agropecuaria, 21(3), pp. 1–12. doi: 10.21930/rcta.vol21_num3_art:1673.

Zamora, S. *et al.* (2001) ‘Uso de frutos y follaje arbóreo en la alimentación de vacunos en la época seca en Boaco, Nicaragua’, Avances de Investigación, 8(31), pp. 31–38.