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Agroecological transition potential of smallholder avocado systems in the Colombian tropical Andes: an index-based approach

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Summary

The Tropical Andes, one of the most biodiverse and ecologically sensitive regions globally, faces critical sustainability challenges driven by the rapid expansion of high-value crops such as Hass avocado. In northern Tolima, Colombia, smallholder avocado farmers have been systematically exposed to agroecological practices through the 'Tropical Agriculture (AT)' program promoted by the Horticultural Association of Colombia (Asohofrucol), providing a documented context in which to evaluate the degree of agroecological transition. This study applies a Socio-Ecological Systems (SES) framework to quantitatively evaluate the status of agroecological adoption and the socio-ecological factors that facilitate or constrain it among 60 small-scale avocado farmers. We developed two complementary indices: the Socio-Ecological Sustainability Index (SESI, range 0–4), which evaluates sustainability across governance, resource management, production systems, and social interaction dimensions, and the Agroecological Practices Index (API, range 0–1), which evaluates the adoption status of 18 specific AT practices across three domains (Plant Nutrition, Soil Protection, Biodiversity Protection). The API is applied as an evaluative tool—measuring adoption of practices farmers have been trained in—rather than as a prescriptive benchmark. Results show a moderate SESI score of 2.11; governance scored highest (0.63), reflecting secure land tenure for 83% of farmers and high associativity, while the Resource Systems dimension scored lowest (0.39), indicating limited integration of ecosystem services. The average API score of 0.38 reveals highest adoption in Soil Protection (60%) and lowest in Plant Nutrition (24%), with practice-specific barriers linked to input access and technical knowledge. Notably, only 43.3% of farmers intend to continue avocado cultivation, and plantations average 5.2 years of age, indicating that price volatility threatens established productive investments. These findings underscore the need for stable market mechanisms, differentiated technical support, and integrated policies that align smallholder productivity with ecological stewardship in ecologically sensitive Andean landscapes

Keywords

Biodiversity conservation, ecological resilience, sustainable agriculture, land tenure security, Andean agroecosystems.

1. Introduction

1.1. Global and regional context of avocado expansion

The global demand for avocado (*Persea americana* Mill.), a versatile tropical tree species, has surged in recent years, driven by its applications in the food, cosmetics, and oil industries (Mabele and Kiwango, 2023). As the second most traded tropical fruit worldwide (FAO, 2023), global avocado production has grown at an average annual rate of 7% over the past decade, increasing from 4.07 million metric tons (t) in 2011 to 8.69 t in 2021. This expansion has been accompanied by a doubling of cultivated area, from 445,261 hectares to 858,152 hectares during the same period (FAO, 2021). While Mexico remains the dominant global producer, emerging suppliers such as Colombia, Peru, and Kenya have experienced remarkable growth, with annual production increases of 15%, 12%, and 11%, respectively (Rabobank, 2023).

In Colombia, avocado cultivation has expanded significantly, driven by favorable climatic and topographical conditions, particularly in the Tropical Andes. Colombian farmers produce avocados from the Antillean, Guatemalan, and Mexican races, as well as their hybrids. Among the most cultivated varieties are Hass, Lorena, Papelillo, Trinidad, Booth-8, Fuerte, Trapo, Santana, Colinred, and Ettinger (Orjuela et al., 2020). By 2023, the total area dedicated to avocado cultivation in Colombia reached 135,276 hectares, with the Hass variety occupying 69,369 hectares, yielding 564,830 t. Other varieties covered 56,016 hectares, contributing 451,108 t to the national total, while the Papelillo variety, grown on 9,890 hectares, produced an additional 69,828 t. Collectively,

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this positioned Colombia's avocado production at 1,085,766 t in 2023, reflecting its growing importance in domestic and international markets (Ministerio de Agricultura y Desarrollo Rural, 2024).

Within this national context, the department of Tolima has established itself as a strategic contributor to Colombian avocado production. Located in the Tropical Andes, Tolima benefits from optimal agroecological conditions, particularly in its northern region bordering Caldas and Antioquia. By 2023, Tolima accounted for 11.3% of national production and 13.67% of Colombia's total avocado-growing area (Ministerio de Agricultura y Desarrollo Rural, 2024). Specifically, the department produced 123,029 t of avocado across 18,316 hectares, with nearly half of this cultivated area concentrated in the municipalities of Fresno, Casabianca, and Palocabildo. Together, these three municipalities represented 47.17% of Tolima's total avocado output, emphasizing their strategic importance within the regional agricultural landscape (Ministerio de Agricultura y Desarrollo Rural, 2024).

1.2. Sustainability challenges and agroecology in the tropical andes

Despite these promising production trends, avocado cultivation in the Tropical Andes faces significant environmental challenges, including soil degradation, erosion, and water scarcity, which particularly impact small-scale farmers (Suárez, 2024). In highly biodiverse regions like the Andes, where natural resources are limited and ecosystems are ecologically sensitive, sustainable practices are crucial to preserving both the environment and the livelihoods of local farmers. Agroecology has emerged as a strategic framework to address these challenges by promoting sustainable agricultural practices that integrate ecological, social, and economic principles. By emphasizing local knowledge, biodiversity conservation, and reduced reliance on synthetic inputs, agroecology offers a pathway for smallholders to transition toward more resilient farming systems (Altieri and Nicholls, 2012; Cortés et al., 2023; Gliessman, 2021).

However, the implementation of agroecological practices in high-demand crops like avocado is complex, as these systems often rely on intensive methods that can conflict with sustainability goals (Hernández-Aguilera et al., 2022). Furthermore, while agroecological principles are well-theorized, there is a lack of studies that systematically evaluate their adoption in smallholder systems growing high-value crops, particularly in ecologically fragile regions (Altieri et al., 2015; Ibarra et al., 2024).

In regions like northern Tolima, where steep slopes, variable rainfall, and fragile soils heighten the risks of soil degradation and reliance on agrochemicals, agroecology offers an approach that balances socio-economic needs with ecological limitations. In Colombian coffee agroecosystems, for example, practices like shade management, leaf litter conservation, and habitat complexity have shown benefits for biodiversity, particularly for amphibian and reptile populations (Ríos-Orjuela et al., 2024). However, transitioning to agroecological practices remains challenging for small-scale avocado farmers due to limited resources and technical support.

Frameworks such as the socio-ecological systems (SES) approach, which considers governance, land tenure, and community participation, are essential for facilitating these transitions and ensuring the resilience of agroecosystems in the Tropical Andes (Brito et al., 2022; Builes et al., 2024).

The socio-ecological systems (SES) framework offers a comprehensive approach for examining sustainability in interdependent systems like small-scale agriculture in the Tropical Andes. SES emphasizes the interactions among ecological resources, governance structures, and community behaviors, shaping resource use and sustainability outcomes (Ostrom, 2009). By applying the SES framework, this study provides a structured lens to evaluate the multiple dimensions of sustainability in smallholder avocado farming, including land tenure security, resource availability, and socio-economic resilience. The framework has been effectively applied in other tropical and mountainous regions to identify conditions that support or hinder sustainable agricultural practices (Leslie et al., 2015; Berrio-Giraldo et al., 2021), making it a suitable model for assessing agroecological transitions in northern Tolima.

1.3. Agroecological transition context: institutional promotion of at practices in northern Tolima

A critical aspect that frames the analytical approach of this study is the prior and ongoing institutional promotion of agroecological practices in the study region. In northern Tolima, the Horticultural Association of Colombia (Asohofrucol) has actively developed and disseminated a set of sustainable agricultural practices collectively known as 'Tropical Agriculture (AT) practices.' These practices—encompassing biofertilization with mountain microorganisms and bocashi, biological pest management using sulfocalcic broth and Supermagro solution, soil cover through mulching and ground cover crops, polyculture integration, and establishment of biological corridors—are explicitly grounded in agroecological principles. Their promotion began systematically in the region approximately in 2016–2018, coinciding with the rapid expansion of Hass avocado cultivation, through mechanisms including technical assistance workshops, on-farm demonstration plots, subsidized access to bioinputs, and support for Good Agricultural Practices (BPA/GAP) certification processes.

This institutional context is fundamental to understanding the analytical approach adopted in this study. Prior to and during the data collection period (2022–2023), small-scale avocado farmers in northern Tolima had been systematically exposed to AT practices through Asohofrucol's programs. Consequently, the Agroecological Practices Index (API) is applied here as an evaluative tool—assessing the degree to which farmers have adopted practices they have been trained in and exposed to—rather than as a prescriptive benchmark imposing external standards on systems that have never engaged with agroecology. The central research problem of this study is therefore the agroecological transition process itself: the degree of adoption of AT practices, the socio-ecological factors that facilitate or constrain this adoption, and the overall sustainability trajectory of smallholder avocado farming systems in northern Tolima. This framing distinguishes our work from purely normative assessments and grounds the API within a documented institutional transition process

Building on this institutional context, this study pursues two explicit objectives: (1) to evaluate the current status of agro-ecological practice adoption among smallholder avocado farmers in northern Tolima, Colombia, using the SESI and API indices within a Socio-Ecological Systems (SES) framework; and (2) to identify the socio-ecological factors—including governance structures, land tenure, community organization, and market dynamics—that facilitate or constrain the agro-ecological transition in this region. By providing mixed-methods evidence—quantitative, index-based data on adoption status and enabling/limiting conditions, complemented by qualitative findings—this study contributes a replicable methodological framework applicable to other high-value crop systems in ecologically sensitive tropical landscapes, and generates actionable insights for policies that aim to align smallholder productivity with long-term environmental stewardship in the Tropical Andes.

2. Materials and methods

2.1. Study area

This study was conducted in the northern region of Tolima, Colombia, focusing on the avocado-producing municipalities of Fresno and Palocabildo. Located on the eastern slopes of the Central Cordillera in the Tropical Andes, the study area spans coordinates from 5°09'N to 5°10'N latitude and 75°02'W to 74°57'W longitude (Figure 1), with altitudes ranging from 225 to 2,640 m.a.s.l. This elevation gradient encompasses diverse ecological zones, including premontane humid forest, lower montane humid forest, and very humid lower montane forest, with nival zones at the highest elevations. The 297 km² region is characterized by intensive agricultural activity, with key crops such as coffee, avocado, sugarcane, and various fruit trees, as well as pasturelands for livestock. The climate is predominantly temperate and humid, with mean annual temperatures of 20 °C (ranging from 16.5 °C to 23.5 °C) and annual precipitation between 2,600 and 4,300 mm (average 2,941.7 mm), providing optimal conditions for diverse and productive agriculture (CORTOLIMA, 2021).

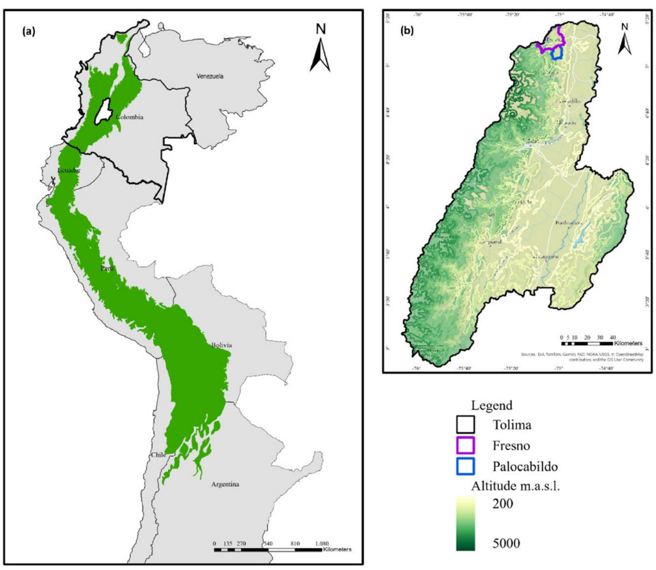

Figure 1. Study area within the Tropical Andes region. (a) Spatial distribution of the Tropical Andes across South America, emphasizing its ecological and geographical extent. (b) Northern Tolima, Colombia, highlighting the municipalities of Fresno and Palocabildo, located within the Tropical Andes

2.2. Study design and variable selection

This study followed a sequential mixed-methods design structured in two phases. In the first (qualitative) phase, 16 semi-structured interviews were conducted with key informants representing farmer organizations, government agencies, commercial actors, and guild organizations. These interviews served to map the structure and dynamics of the socio-ecological system (SES) in the study area and to identify the most relevant variables and indicators for constructing the SESI and API indices. In the second (quantitative) phase, a structured survey instrument was applied to 60 small-scale avocado farmers selected via snowball sampling (see below). Survey data were used to compute SESI and API scores for each farmer. Qualitative data from farmer interviews were integrated during the analysis phase to provide contextual interpretation of quantitative patterns, following a triangulation approach. All data sources were cross-validated to ensure analytical coherence.

The interview protocol consisted of 27 questions, covering multiple aspects of the socio-ecological system, including general information, resource systems and units, actors, production systems, governance, and interactions (Supplementary Material 1). Additionally, an Exponential Discriminative snowball sampling procedure (Robinson, 2014) was employed to select 60 avocado farmers in the study area. Initial contacts (farmer organization leaders, government representatives, and guild organizations) were asked to refer multiple potential participants, who were then screened by the research team to confirm eligibility (active small-scale avocado farmers in Fresno or Palocabildo with at least 1 ha under avocado cultivation). This approach is frequently used in agricultural research to reach specific farming communities that may not be accessible through conventional random sampling (Lustosa-Silva et al., 2023; Robinson, 2014). According to official records from the municipal agricultural technical assistance offices (UMATA) and the Ministerio de Agricultura y Desarrollo Rural (2024), there are an estimated 320–350 registered small-scale avocado producers in these two municipalities. The 60 farmers surveyed thus represent approximately 17–19% of the registered producer population and manage a combined avocado area of approximately 117.6 ha, equivalent to roughly 12–15% of the total estimated avocado-cultivated area in the study municipalities. It should be noted that beginning the snowball chain with organizational leaders likely results in overrepresentation of farmers affiliated with formal associations; consequently, the associativity rates reported in the results should be interpreted with this potential sampling bias in mind.

The semi-structured interviews with farmers explored their socio-economic profiles (age, education level, farm area, and production destination), perceptions of natural resources, and local management practices. These aspects included seed and seedling management, plot preparation and transplanting, agronomic management, pest and disease control, irrigation and drainage, harvesting, post-harvest handling, and infrastructure. Interviews also investigated the presence or absence of agroecological practices related to avocado cultivation, as well as environmental, productive, social, and economic constraints (Supplementary Material 2). All interviews were transcribed and analyzed thematically to identify key patterns and categories. Representative quotes from participants are presented in the results section to illustrate the qualitative findings. Descriptive statistics, including frequencies, percentages, and means, were calculated using R software (version 4.3.1) (R Core Team, 2023).

2.3. Development and implementation of agroecological indices within a socio-ecological systems (SES) framework

The Socio-Ecological Sustainability Index (SESI) was developed to quantitatively characterize the socio-ecological conditions that mediate agroecological practice adoption among smallholder avocado farmers, following a structured approach spanning four dimensions: Resource Systems and Units, Governance, Actors and Production Systems, and Interactions. Rather than measuring transition as a longitudinal process, the SESI captures the systemic enabling and constraining factors that shape the current adoption status of agroecological practices. This approach builds upon established frameworks for composite index construction (Nardo et al., 2008; Leslie et al., 2015; Scherzer et al., 2019), ensuring robustness and comparability across variables.

As outlined in Section 2.4, three normalization methods were applied to standardize variables on a 0-1 scale, facilitating balanced aggregation within the composite index. For continuous indicators, min-max normalization was used; categorical variables were coded based on their relevance to the study; and percentile rank discretization was applied to variables with broad value ranges. These techniques allow for the integration of diverse data types while maintaining comparability (Nardo et al., 2008; Leslie et al., 2015). Additionally, dichotomous variables, such as the presence of conservation zones, were retained in binary format (0 or 1), representing absence or presence within the index's framework.

Each variable within a dimension was assigned a weight based on expert judgment, taking into account its relative significance within the agroecological transition framework (Table 1 lists the variables and their weights). The normalized value $x_{i,j}$ of each variable j within dimension i was then weighted according to its assigned coefficient $w_{i,j}$ to compute a composite score for each dimension (Eq. 1)

$$S_i = \sum_{j=1}^{n_i} w_{i,j}\, x_{i,j} \qquad (1)$$

Where, S_i is the score for dimension i, $w_{i,j}$ represents the weight of variable j within dimension i, $x_{i,j}$ is the normalized

Table 1. Variables and weights for SESI dimension scores.

Dimension	Variable	Code	Weight
Resource Systems (SU)	Number of ecosystem services recognized by farmer	SU1	0.5
	Sufficient water for household and crop needs	SU2	0.25
	Conservation zones within farm	SU3	0.25
Governance (GV)	Type of land tenure declared by farmer	GV1	0.25
	Farm area managed by farmer's family	GV2	0.25
	Annual organization meetings attended by farmer	GV3	0.25
	Perception of organization functionality	GV4	0.25
Productive Systems (SP)	Main economic activities are diversified	SP1	0.125
	Proportion of farm area cultivated in avocado	SP2	0.125
	Household participation in avocado cultivation	SP4	0.125
	Presence of a home garden	SP5	0.125
	Age of avocado farmer	SP6	0.125
	Education level of avocado farmer	SP7	0.125
	Reported productivity in the last year (t/ha)	SP8	0.125
	Certifications held by farmer (BPA, GAP, etc.)	SP9	0.125
Interactions (I)	Perceived negative environmental impact of cultivation	I1	0.333
	Number of sustainable practices implemented	I3	0.333
	Perception of benefits of Tropical Agriculture Practices	I4	0.333

value of variable j within dimension i, n_i denotes the number of variables in dimension i. Each dimension score S_i was calculated to fall within the range of 0 to 1, with higher scores indicating a greater level of agroecological practice adoption in that dimension. This calculation generates a dimension score S_i between 0 and 1, indicating the extent of agroecological practice adoption within each dimension.

The SESI was computed as the sum of the four-dimension scores, each contributing equally to the overall index (Eq. 2)

$$SESI = S_{SU} + S_{GV} + S_{SP} + S_I \tag{2}$$

Where S_{SU}, S_{GV}, S_{SP} *and* S_I are scores for Resource Systems, Governance, Productive Systems, and Interactions, respectively. The SESI score ranges from 0 to 4, serving as an aggregate measure of agroecological transition, where scores closer to 4 indicate a high level of sustainability within the SES framework. The SESI's methodology is informed by established composite index construction approaches (e.g., Nardo et al., 2008), providing a balanced measure of agroecological practices.

Complementarily, a literature review was conducted to identify practices contributing to the agroecological transition. The Agroecological Practices Index (API), developed following the approach of Cortés et al. (2023), quantifies the adoption of agroecological practices by assessing the presence or absence of 18 specific practices across three primary domains: Plant Nutrition, Soil Protection, and Biodiversity Protection (Table 2).

The API provides a straightforward and interpretable measure of management intensity and alignment with agroecological principles. It evaluates each practice group equally, ensuring a balanced assessment of agroecological adoption. The API calculation (Eq. 3) integrates equal contributions from each practice group, offering a comprehensive reflection of agroecological practices across key domains.

$$API = 1/3 \sum_{g=1}^{3} \frac{\sum_{k=1}^{N_g} P_k}{N_g} \tag{3}$$

Where: *API*: Agroecological Practices Index, indicating the overall level of agroecological practice adoption; g is each practice group (1 for Plant Nutrition, 2 for Soil Protection, 3 for Biodiversity Protection); N_g: total number of practices within each group g; P_k denote presence (1) or absence (0) of each practice k within group g.

Table 2 presents the agroecological management practices investigated in avocado crop production in northern Tolima, categorized into three principal domains: Plant Nutrition, Soil Protection, and Biodiversity Protection. These practices were selected for their critical role in promoting sustainability and resilience in agricultural systems.

Table 2. Investigated agroecological management practices in avocado crop production in northern Tolima.

Practice Group	Management Practice
Plant Nutrition (n=7)	Mountain Microorganisms
	Commercial Microorganisms
	Organic amendment (Bocashi)
	Anaerobically fermented liquid biofertilizer (Biol)
	Liquid Humus
	Supermagro Solution*
	Wood ash application for crop production
Soil Protection (n=3)	Ground cover
	Application of mulch under avocado trees
	Polycultures and growing mixtures of different crops together
Biodiversity Protection (n=8)	Native plants
	Ecological Niches
	Establishment of biological corridors
	Use of monitoring traps as an eco-friendly pest management strategy
	Bordeaux Mixture**
	Sulfocalcic broth or sulfur-lime solution
	Neem Extract (*Azadirachta indica)*
	Potassium Soap

Note: *Supermagro is a multi-nutrient liquid biofertilizer composed of zinc sulfate, calcium chloride, magnesium sulfate, manganese sulfate, cobalt sulfate, sodium molybdate, boric acid, hydrated lime, milk, molasses, bone meal, fresh manure, and water (Hermann-Bandera et al., 2023).

**Bordeaux Mixture is a copper-based fungicide widely used against fungal diseases in agricultural systems (Jiang et al., 2020).

2.4. Data transformation and normalization

Eighteen variables, representing the socio-ecological systems (SES) framework were analyzed and grouped into four categories: Resource Systems, Governance, Production Systems, and Interactions (Table 3). For comparability within the composite index, fourteen variables were transformed to a standardized 0-1 scale, while four dichotomous variables retained their original binary coding (0 or 1).

Each transformation method was selected based on variable type and purpose to ensure the uniformity and interpretability of the resulting index values. The applied normalization techniques are detailed below. Min-Max Normalization:

Table 3. Selected variables and applied normalization methods for socio-ecological system analysis in small-scale avocado farming

Dimension	Variable	Code	Initial Scale	Normalization Type	Normalized Scale
Resource Systems and Units (SU)	Number of ecosystem services recognized by the farmer	SU1	Numeric 0 to 12	Min-Max Normalization	0 - 1
	Water availability is sufficient to meet household and crop needs	SU2	0: Not Sufficient 1: Sufficient	Not applicable	0: Not Sufficient 1: Sufficient
	Conservation zones within farm	SU3	0: Does Not Have 1: Has	Not applicable	0: Does Not Have 1: Has
Governance (GV)	Type of land tenure declared by the farmer	GV1	Categorical: Owner, Holder, Tenant, Other NS/NR	Categorical Coding; Importance Coding	1: Owner 0.66: Holder 0.33: Tenant 0: Other NS/NR
	Farm area managed by farmer's family	GV2	Numeric (Min Area: 1 ha; Max: 138 ha)	Percentile Rank Discretization	*
	Annual organization meetings attended by the farmer	GV3	Numeric	Min-Max Normalization	0 - 1
	Perception of organization functionality	GV4	Categorical: Good, Fair, Poor, NS/NR	Categorical Coding; Importance Coding	1: Good 0.66: Fair 0.33: Poor 0: NS/NR
Actors and Production System (SP)	Main economic activities are agricultural and diversified	SP1	Categorical: Avocado_Coffee_Diversified, etc.	Categorical Coding; Importance Coding	1: Avocado_Coffee_ Diversified etc.
	Proportion of farm area cultivated with avocado	SP2	0-100%	Percentile Rank Discretization	*
	Household participation in avocado cultivation	SP3	0-100%	Percentile Rank Discretization	*
	Farmer reports having a home garden	SP4	0: Does Not Have 1: Has	Not applicable	0: Does Not Have 1: Has
	Age of avocado farmer	SP5	Numeric	Percentile Rank Discretization	*
	Education level of avocado farmer	SP6	None, Incomplete Primary, etc.	Categorical Coding; Importance Coding	0: None, 1: Graduate/ Postgraduate
	Yield of the productive system in the last year (t/ha)	SP7	Numeric	Percentile Rank Discretization	*
	Number of certifications reported by farmer (BPA, GAP)	SP8	3 Certifications, 2, 1, or 0	Categorical Coding; Importance Coding	1: 3 Certifications, 0: No Certifications
Interactions (I)	Farmer acknowledges negative impact of cultivation on environment	I1	0: Does Not Recognize 1: Recognizes	Not applicable	0: Does Not Recognize 1: Recognizes
	Number of sustainable practices implemented by farmer	I2	Numeric	Percentile Rank Discretization	*
	Perception of benefits of Tropical Agriculture Practices	I3	Composite: Cost0.25+ Quality0.25+Yield0.25+ Prices0.25	Percentile Rank Discretization	0-1.5

Note: The range score assignment for Indicator 1 was based on calculations using the following percentiles: a range score of 0.50 was assigned to the median value (50th percentile); a score of 1.00 to the maximum value; and a score of 0.00 to the minimum value. The 10th percentile was assigned a range score of 0.10; the 25th percentile a score of 0.25; the 75th percentile a score of 0.75; and the 90th percentile a score of 0.90. Values for each property were matched to their closest percentile.

Applied to continuous variables (e.g., SU1 and GV3), min-max normalization rescales data between 0 (minimum) and 1 (maximum), preserving the relative distances between data points. This approach ensures that continuous variables maintain their intrinsic data relationships within the standardized index, enhancing comparability across diverse data ranges (Nardo et al., 2008; Leslie et al., 2015).

For categorical variables, such as GV1, GV4, SP1, SP6, and SP8, a weighted coding system was implemented, assigning values based on the variable's relevance within the agroecological context. This coding allows each category to be proportionally represented within the index, aligning categorical variable contribution with the study's objectives and preserving analytical fidelity in multi-criteria assessments.

Variables GV2, SP2, SP3, SP5, SP7, I2, and I3, which exhibit wide ranges or non-uniform distributions, were standardized using percentile rank discretization. By assigning percentile ranks, this technique ensures that outliers or high-variance variables do not disproportionately influence the composite index score, a common best practice in multidimensional assessments that require harmonized data inputs for index construction.

3. Results

3.1. Descriptive results: socio-ecological systems (SES) framework

This section provides an analysis of the avocado production system in northern Tolima through the lens of socio-ecological systems (SES). The analysis focuses on four key dimensions: Resource Systems and Units, Governance, Actors and Productive Systems, and Interactions (Figure 2). By combining quantitative data with qualitative insights, we explore the complex dynamics and interdependencies shaping sustainability, governance, and production practices within the region's agroecological transition.

Resource systems and units

Farmers identified an average of 3.47 ecosystem benefits related to nearby natural resources, with variability indicated by a standard deviation of 1.78. The primary benefits cited were water availability for domestic and agricultural use (65%),

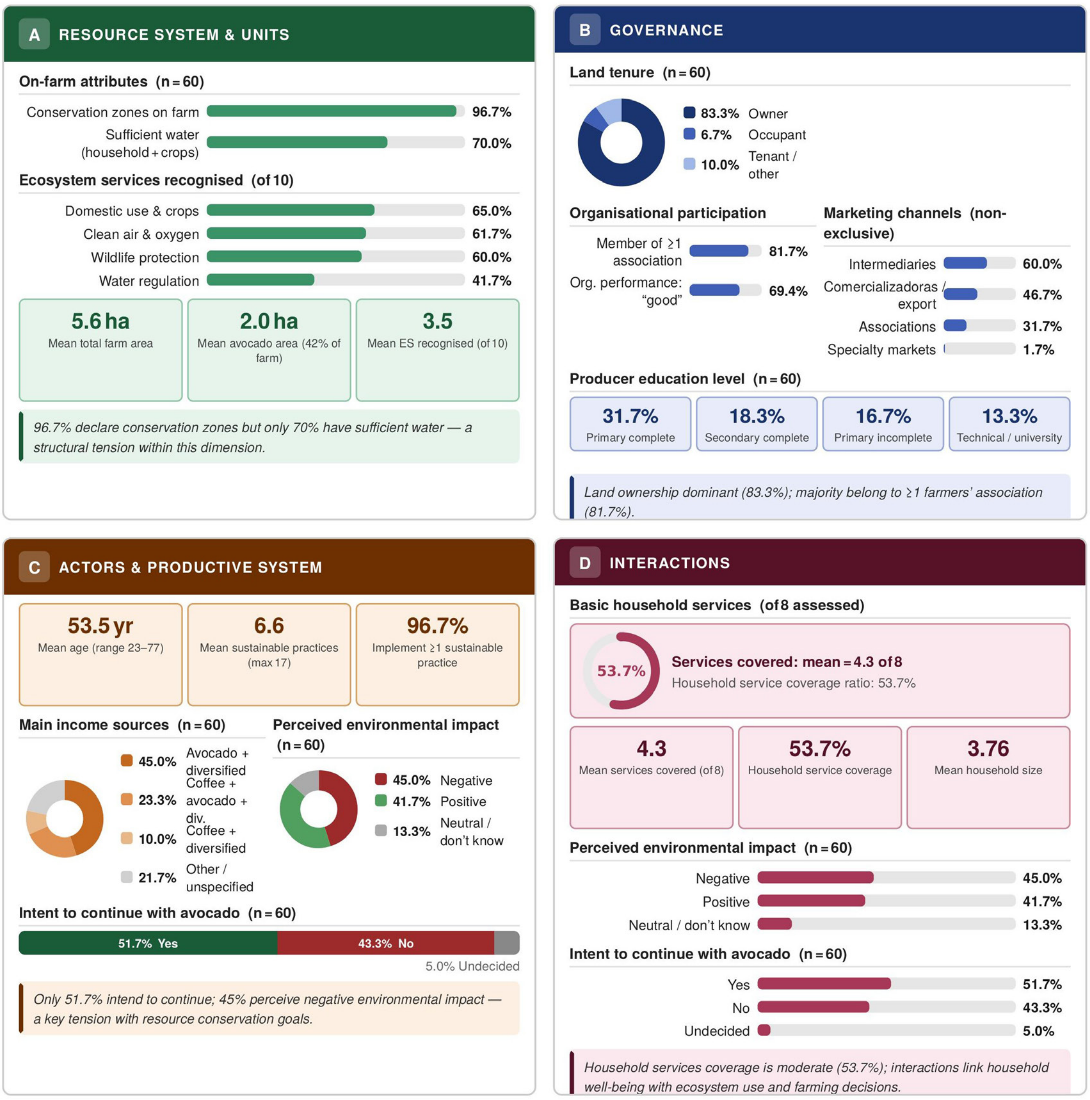

Figure 2. Socio-ecological framework for avocado cultivation in northern Tolima: integration of resources, governance, interactions, and productive system.

clean air and oxygen provision (61.7%), and wildlife protection (60%). Additional, though less frequently recognized, benefits included climate regulation (30%) and landscape enhancement (17%).

Qualitative feedback from interviews revealed nuanced views on resource conservation. A farmer from Fresno noted, “During the rainy seasons, landslides and other issues arise due to deforestation. Forests are not protected, and water sources are vulnerable” (Interview #17, Fresno). This concern aligns with quantitative findings, where 28% of respondents reported insufficient water resources, contrasting with the 70% who found water availability adequate. Notably, 97% of farmers reported maintaining areas on their farms that are not under active cultivation and serve as, or function as, conservation zones. These areas may include riparian buffer strips required by Colombian environmental law, marginal or steep terrain unsuitable for crop production, or patches deliberately maintained for biodiversity purposes. As the survey did not systematically record the primary motivation or legal status of these zones, this finding is reported descriptively without attributing it uniformly to voluntary environmental stewardship. Regardless of origin, these non-cultivated areas likely contribute to habitat connectivity in the Northern Tolima landscape.

Governance structures in northern Tolima are characterized by predominantly small landholdings, with Agricultural Production Units (APUs) averaging 5.56 ha (SD = 4.35; range = 1–25 ha). The predominance of small-scale farms may limit opportunities for scaling production and accessing larger markets. Regarding land tenure, 83.3% of farmers reported formal ownership supported by legal title deeds, while the remaining producers accessed land through possession arrangements (6.7%) or tenant/other arrangements (8.3%), including rental agreements and other informal tenure mechanisms.

In the Colombian context, possessors are individuals who occupy and use land as de facto owners, including cultivating, managing, or renting the property, despite lacking formal legal title or official registration. This condition is based on effective occupation and social recognition rather than formal documentation (Land Restitution Unit – Government of Colombia, 2024). As one farmer explained, “Most are owners; however, we also have possessors and a few who lease” (Interview #25, Palocabildo). Another participant added, “Here, there is a mix of ownership forms, such as sale letters, which are informal and not legally recognized” (Interview #26, Fresno).

Most producers (81.7%) reported participation in at least one agricultural association. Among the organizations mentioned by participants were PALTOLIMA, ASOFRUTOS, and FRUPAL. Producers associated these organizations with activities related to commercialization, technical support, and producer coordination. However, as discussed in Section 2.2, this relatively high participation rate should be interpreted cautiously because the snowball sampling process originated through organizational leaders, potentially overrepresenting producers with formal associative ties relative to the broader smallholder population.

Commercialization patterns indicate that intermediaries were the most frequently used marketing channel (60%), followed by commercial/export companies (46.7%) and producer associations (31.7%), while specialized markets represented a marginal proportion (1.7%). These percentages are not mutually exclusive, as some producers reported using more than one marketing channel simultaneously (Figure 3).

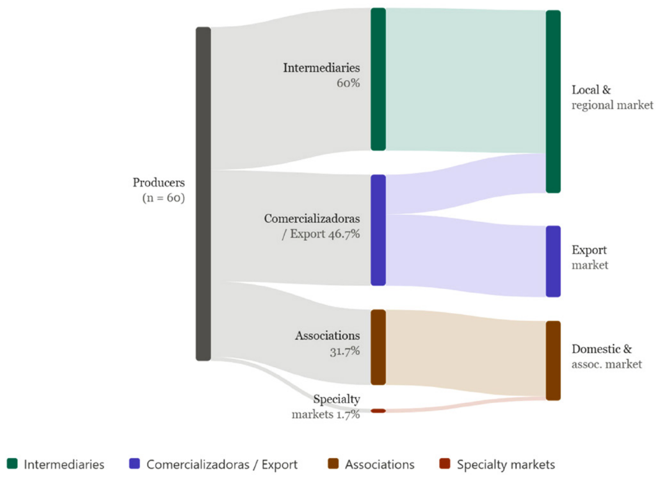

Figure 3. Sankey diagram of avocado marketing channels among smallholder producers in northern Tolima, Colombia. Flow widths are proportional to the percentage of producers using each channel. Percentages are non-mutually exclusive; some producers commercialize through more than one channel simultaneously.

Actors and productive systems

Avocado crop in Tolima predominantly involves diversified systems. For 45% of farmers, avocado is part of a diversified production system, while 23% integrate avocado with coffee, and others with additional crops. On average, 1.96 hectares (SD = 1.24) are dedicated to avocado, representing 42% of total farm area (SD = 33%). Notably, only 43.3% of farmers plan to continue avocado cultivation, with market volatility and climate variability cited as key challenges. This finding is particularly significant given that avocado plantations in the sample had been established for an average of 5.2 years (SD = 3.1; range: 1–15 years), with 68% of farms having been in production for more than three years. The willingness to abandon an established, multi-year perennial crop investment underscores the severity of economic pressures and constitutes a strong indicator of production system vulnerability rather than the mere discontinuation of short-term experiments. A farmer highlighted, “The market lacks fair prices for small farmers. Prices vary significantly” (Interview #17, Fresno), reflecting economic uncertainties that affect avocado farming viability.

Household composition varied across the sample (household members are defined as all individuals sharing the same dwelling and resources, including children and elderly members regardless of participation in farming). The average household size was 3.76 members. A descriptive comparison shows that smaller households (fewer than

4 members) reported a higher rate of household participation in agriculture (75.36%) compared to larger households (more than 6 members, 42.86%). While no formal statistical test was performed to evaluate this difference, the pattern may partly reflect the presence of children or elderly dependents in larger households, or adults pursuing non-agricultural employment. This observation warrants further investigation with appropriate inferential methods.

Interactions

Sustainable agricultural practices, commonly known in the region as "Tropical Agriculture (AT) practices," are based on agroecological principles and have been developed and promoted under this designation by the Horticultural Association of Colombia (Asohofrucol). Asohofrucol has actively disseminated these practices among avocado farmers, resulting in widespread implementation among the small-scale farmers included in this study, with 97% of them adopting at least one AT practice. Among the most widely adopted practices are soil protection through ground cover (71.6%) and biodiversity conservation via biological corridors (45%). Biofertilizers, such as mountain microorganisms (25%) and bocashi (13%), are applied to improve soil health, while biostimulant broths like Supermagro and sulfocalcic solutions support crop resilience and pest control. According to one farmer from Palocabildo, "With biopesticides, I've seen improvements in plant health and yields" (Interview #22, Palocabildo), aligning with survey data that shows 63% of respondents experienced cost reductions and 62% observed improved fruit quality through the use of these sustainable practices.

Despite these advances, 45% of farmers perceived negative environmental impacts linked to agrochemical use in avocado production. One farmer emphasized this concern: "High insecticide and herbicide use is one of the most critical issues for Fresno" (Interview #18, Fresno). These insights reveal an ongoing tension between the need for productivity and environmental sustainability.

3.2. Agroecological indices within the socio-ecological systems (SES) framework

The Socio-Ecological Sustainability Index (SESI) was calculated across four dimensions: Interactions, Actors and Production System, Governance, and Resource Systems and Units. The average SESI score was 2.11 (±0.38) on a 0–4 scale, reflecting moderate agroecological adoption and variability among avocado farms (range: 1.31–2.89). Figure 3, shows a detailed breakdown of these scores across the four dimensions, highlighting areas of strength and opportunities for improvement.

Resource Systems and Units (SU) this dimension received the lowest score (0.39), indicating limited integration of natural resources into sustainable practices (see Figure 3). Conservation zones within farms scored the lowest (0.06), highlighting weak biodiversity management. It is important to note that this low SU3 dimension score does not contradict the finding that 97% of farmers report maintaining non-cultivated areas

Figure 4. Average scores of dimensions and variables for the socio-ecological sustainability index (SESI) in avocado farms in northern Tolima, calculated across four socio-ecological dimensions: interactions, actors and production system, governance, and resource systems and units.

on their farms. The SU3 sub-indicator (binary: presence/absence of conservation zones) scores high individually; however, within the composite SESI, it is averaged with SU1 (ecosystem services recognized: mean normalized score = 0.29) and SU2 (water sufficiency: 28% of farmers score 0), which substantially reduces the overall SU dimension average. Furthermore, as discussed in Section 3.1, the reported conservation zones may include legally mandated riparian buffer strips or marginal terrain rather than actively managed biodiversity areas, which is reflected in the overall low SU dimension score. Water sufficiency for household and crop needs scored slightly higher (0.16), but recognition of ecosystem services by farmers remained low (0.18). These findings suggest a pressing need to improve resource use practices and strengthen biodiversity conservation.

Governance (GV) recorded the highest average score (0.63), reflecting strong institutional support and secure land tenure systems (see Figure 3). Land tenure security achieved the highest score (0.22), supporting sustainable investments. Farmers' perceptions of organizational functionality were moderately positive (0.17), but attendance at organizational meetings (0.10) and family management of farm areas (0.14) scored lower, suggesting opportunities to enhance participation and collaboration in governance structures.

The Actors and Production System (SP) dimension scored an average of 0.59. Economic diversification was the strongest variable (0.11), highlighting farmers' efforts to maintain multiple income sources (see Figure 3). However, low scores in certifications (0.06), productivity (0.06), and household participation in avocado cultivation (0.05) indicate gaps in technical capacity and family involvement. Addressing these challenges could improve productivity and foster stronger engagement in agroecological practices.

The Interactions (I) dimension scored 0.51, reflecting moderate engagement in environmentally and socially supportive practices (see Figure 3). Implementation of sustainable practices scored slightly better (0.20), but perception of benefits of tropical agricultural practices (0.17) and awareness of environmental impacts of cultivation (0.15) were lower. These results emphasize the need for educational initiatives to enhance farmer awareness and the adoption of sustainable practices.

Governance and economic diversification provide a stable foundation for sustainability (see Figure 4). However, the low scores in resource management, biodiversity conservation, and farmer engagement highlight critical areas for improvement. Enhancing farmer education, promoting certifications, and strengthening resource conservation practices could improve sustainability and resilience in avocado farming systems.

3.3. Agroecological management practices and API in avocado production

The evaluation of agroecological practices among 60 small avocado farmers in northern Tolima yielded an average API score of 0.38 (sd±0.20) on a scale from 0 to 1, reflecting moderate level of adoption of the promoted agroecological practices. The maximum API score recorded was 0.82, indicating that while some farmers demonstrate strong alignment with agroecological practices, most have room for improvement. Notably, all farmers reported adopting at least one practice, emphasizing some level of engagement with agroecological methods. The distribution of average and maximum adoption rates across the three groups of agroecological practices—Plant Nutrition, Soil Protection, and Biodiversity Protection—is summarized in Figure 5.

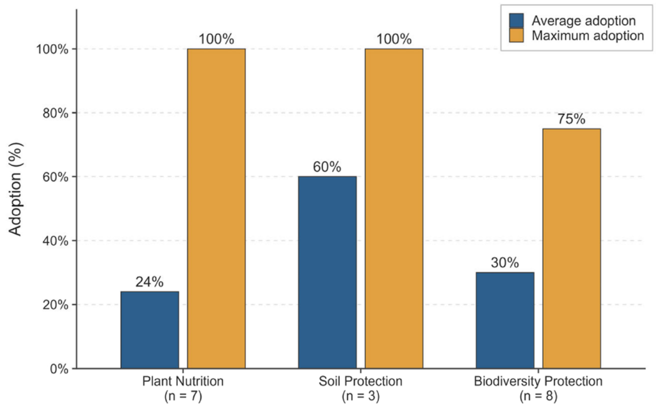

Figure 5. Comparison of average and maximum adoption of agroecological practices by small avocado farmers in northern Tolima.

In the Plant Nutrition group, which included seven practices, farmers implemented an average of 24% of the available practices, equivalent to approximately 1.68 practices per farmer (Figure 6). Among the most widely adopted practices were the use of Supermagro solution, reported by 52% of farmers, and the application of microorganisms, with 25% and 28% of farmers using mountain and commercial microorganisms, respectively. In contrast, practices such as the application of anaerobically fermented liquid biofertilizer (Biol) (15%) and the application of the organic amendment Bocashi (13%) were less commonly adopted, suggesting a need for targeted training and resource support to enhance the uptake of these organic fertilizers.

In Soil Protection, which encompassed three practices, farmers demonstrated the highest average adoption rate, implementing 60% of the available practices, or approximately 1.8 practices per farmer (Figure 5). Ground cover was the most prevalent practice in this category, adopted by 68% of farmers, followed by mulch application (63%). The use of polycultures, while lower, was still notable, with 48% of farmers integrating this approach into their farming systems, reflecting moderate engagement with soil conservation strategies.

For Biodiversity Protection, which included eight practices, the average adoption rate was 30%, corresponding to approximately 2.4 practices per farmer (Figure 5). Sulfocalcic broth emerged as a leading practice in this category, implemented by 50% of farmers, while the establishment of biological corridors (42%) and the planting of native plants (40%) indicated efforts to integrate biodiversity into farming systems. However, other practices, such as the use of Neem extract (5%) and potassium soap (22%), showed much lower adoption

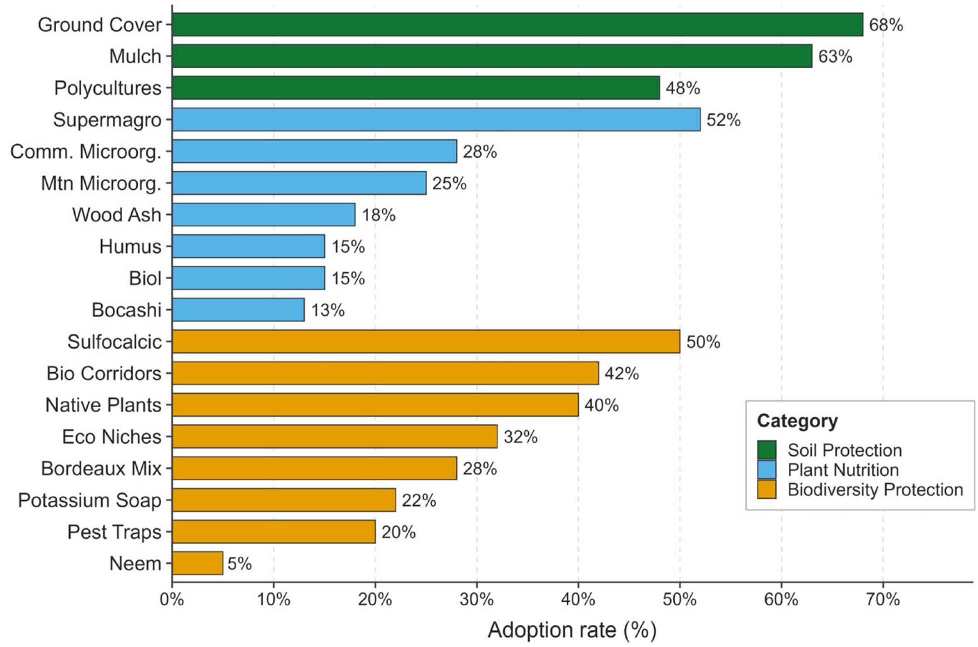

Figure 6. Distribution of agroecological practices adopted by avocado farmers in northern Tolima

rates, suggesting barriers to access or awareness of these ecological pest management strategies.

The data highlight significant variability in the adoption of agroecological practices across categories, with Soil Protection practices showing the highest levels of engagement and Biodiversity Protection practices exhibiting greater potential for improvement. The prevalence of widely adopted practices such as ground cover and Supermagro solution suggests that farmers recognize the immediate benefits of these approaches, while the lower adoption of other practices points to gaps in knowledge, resources, or feasibility.

4. Discussion

This discussion addresses the two study objectives in sequence: (1) the current status of agroecological practice adoption as measured by the SESI and API indices; and (2) the socio-ecological factors that facilitate or constrain the ongoing agroecological transition in northern Tolima. The Socio-Ecological Systems (SES) framework provides the analytical structure for interpreting the interacting governance, resource, production, and social dimensions that shape both adoption outcomes and transition dynamics. Northern Tolima presents a distinctive combination of conditions—high biodiversity, predominantly secure land tenure, active farmer associativity, and significant market volatility—that together define a system in which agroecological promotion has made measurable but uneven progress.

The Socio-Ecological Sustainability Index (SESI) and Agroecological Principles Index (API) developed in this study provide quantitative tools to assess progress toward agroecology in complex, diversified systems like those in Tolima. The SESI, with an average score of 2.11, reflects a moderate level of agroecological transition, highlighting both advancements and challenges across multiple dimensions. Specifically, the Resource Systems and Units dimension scored the lowest (0.39), indicating limited integration of natural resources in productive management. This finding aligns with prior studies in tropical agricultural systems, where farmers often prioritize tangible resources, such as water, over ecosystem services that are less immediately apparent, such as climate regulation (Altieri et al., 2015; Rendón-Sandoval et al., 2021). This undervaluation of ecosystem services underscores an opportunity to strengthen environmental education programs, as suggested in other high-biodiversity systems where agroecological practices enhance resilience to climatic and market disturbances (Tito et al., 2018; Vargas et al., 2019; Tittonell, 2020).

The low SU dimension score warrants interpretive caution regarding the sub-indicator on conservation zones (SU3). While 97% of farmers reported maintaining non-cultivated areas on their farms, the SU dimension score is a composite average of SU3 (conservation zones), SU1 (ecosystem services recognized, mean normalized score 0.29), and SU2 (water sufficiency, with 28% of farmers scoring 0). The low values of SU1 and SU2 pull the composite dimension score downward despite the high SU3 rate. Furthermore, as discussed in Section 3.1, the high SU3 prevalence likely includes legally mandated riparian buffer strips or marginal terrain unsuitable for cultivation, rather than uniformly reflecting active biodiversity management decisions. This distinction has important implications for index design: future iterations of the SESI should consider disaggregating SU3 into voluntarily managed conservation areas versus legally mandated or non-arable zones, to more precisely capture farmers' actual conservation agency and intent.

The Governance dimension achieved the highest SESI score (0.63), driven by secure land tenure and community organization in Tolima. With 83% secure tenure, farmers have a stable foundation that facilitates long-term planning and the adoption of sustainable practices. Furthermore, local associations such as PALTOLIMA, ASOFRUTOS and FRUPAL strengthen this structure, improving access to resources and training while reducing dependency on intermediaries (Rodríguez, 2013; Kumar et al., 2015; Dardonville et al., 2022; Wentink, 2024). Land tenure security and community organization are important factors that support a robust agroecological transition. Farmers with secure land tenure are more likely to invest in sustainable practices, as they can plan for long-term benefits rather than focusing solely on short-term gains. Without security, landholders may hesitate to adopt practices that take years to show positive returns (Richardson, 2018).

Farmers in northern Tolima are increasingly adopting diversified cropping systems, integrating coffee and avocado to enhance resilience against market and climate risks. While coffee has long been a high-value crop in global markets, fluctuating prices and declining profitability for smallholders have led many to transition toward avocado cultivation. This shift aligns with broader trends in the Tropical Andes, where high-value crops like avocado are gaining prominence. Diversification contributes to economic stability and sustainable resource management (Wezel et al., 2020). However, despite its benefits, only 43.3% of farmers in Tolima intend to continue cultivating avocado, citing price instability as a significant barrier. This highlights the urgent need for policies that promote equitable market access and price stabilization to support both coffee and avocado producers in the region.

As Suárez (2024) notes in a study of Salamina (Caldas)—a region with similar tropical characteristics and agricultural dynamics—the transition from a coffee-centered economy to capital- and labor-intensive avocado production has intensified social grievances and widened inequalities within local communities. While the avocado sector has become a critical economic driver, it has also caused environmental disruptions and exposed governance gaps in addressing sustainability and social equity. For Tolima, this underscores the need for integrated policy frameworks that stabilize markets, incentivize sustainable practices, and ensure equitable opportunities for small-scale farmers. Without such measures, the rapid expansion of avocado production risks replicating the same challenges that have historically affected coffee growers, including market volatility and deepening rural inequalities.

Building on these challenges, studies from other Andean regions demonstrate that agroecological practices can enhance sustainability in high-biodiversity systems (Bellon et al., 2015; Rolando et al., 2016), addressing challenges similar to those observed in the Tropical Andes of Colombia. For example, in Peru's Huánuco region, smallholder farmers have adopted agroecological principles to reduce reliance on external inputs and improve climate resilience (Velásquez-Milla et al., 2011; Enthoven & Van Den Broeck, 2023). However, limited market access and financing options continue to hinder their agroecological transition. In Ecuador's Chocó Andino, agroecological initiatives emphasize forest conservation and habitat regeneration through diversified production systems and strong local marketing networks, fostering ecosystem connectivity and sustainable income for local communities (Heredia et al., 2021; Cuesta et al., 2023). Similarly, in Colombia's high Andean dairy systems, silvopastoral practices have improved biodiversity conservation, soil resilience, and productivity, despite the high initial costs and extended adaptation periods required in these mountainous environments (Durana et al., 2023). These examples emphasize the need for continuous support and local market development for agroecological products to advance sustainable agricultural transitions among small avocado farmers in Colombia's Tropical Andes.

The Tropical Andes represent one of the most biodiverse and ecologically fragile regions globally, with fertile but vulnerable soils, steep slopes, and variable climates presenting unique agricultural conditions (Martínez et al., 2011; López-Bedoya et al., 2023). These characteristics offer a favorable environment for agroecology but also bring challenges, such as soil erosion and pressure on water resources. In our study, 70% of farmers reported sufficient access to water, although 28% expressed concerns about future availability, suggesting that strengthening water and soil conservation practices is essential for sustainability in these systems.

The use of biofertilizers and biopesticides, promoted by local organizations, has reduced production costs and improved fruit quality. However, reliance on agrochemicals remains a challenge, with 45% of farmers perceiving negative environmental impacts associated with their use, a common issue in regions undergoing agroecological transition (Altieri & Nicholls, 2012). A promising alternative would be the development of locally adapted bioinputs, as demonstrated by successful research on biofertilizers and biopesticides in Brazil and other Andean contexts (Fischer et al., 2023; Ibañez et al., 2023; Ferreyra-Suarez et al., 2024).

The moderate API score observed among small avocado farmers in northern Tolima highlights both the progress and challenges in adopting the AT practices promoted by Asohofrucol in the study region. Interpreted as a cross-sectional adoption status snapshot—rather than longitudinal evidence of transition—the API score of 0.38 reflects a system in which institutional promotion has achieved meaningful but uneven penetration across practice domains. Similar patterns have been reported by Altieri et al. (2017) who emphasize that resource availability, technical training, and market incentives significantly influence the adoption of agroecological practices. The variability in adoption across categories underscores systemic challenges in promoting lesser-adopted practices such as Biol or Neem extract. These findings align with Nicholls et al. (2017), who noted that the adoption of organic inputs often requires technical assistance to overcome knowledge gaps and financial constraints. The relatively high engagement with practices offering immediate benefits, such as ground cover and Supermagro solution, suggests that practical, low-cost solutions resonate most with farmers, reflecting their need for tangible returns on investment in resource-limited settings. The differential adoption rates across the three API domains are particularly informative about the effectiveness and limitations of the AT promotion program. The Soil Protection domain showed the highest adoption rate (60%), likely because its core practices—ground cover and mulching—overlap with traditional farming knowledge already present in the region and require no purchased inputs. This finding underscores an important methodological nuance: high adoption of practices like mulching or polycultures cannot be attributed solely to the AT program, as these may have pre-dated it. Future research should disentangle program-induced adoption from pre-existing traditional practices, for example through before-after comparisons or by distinguishing farmers enrolled in

AT training from those who were not. In contrast, the low adoption of Plant Nutrition practices (24%)—particularly biofertilizers such as Biol (15%) and Bocashi (13%)—points to real barriers in the AT program's reach: these practices require more elaborate preparation, specific inputs, and sustained technical assistance that have not been equitably distributed across the farming population. Similarly, the moderate adoption of Biodiversity Protection practices (30%) suggests that ecological connectivity measures—such as biological corridors and native plant establishment—are understood but face implementation barriers related to land availability, labour, and perceived short-term economic return. These results suggest that future iterations of the AT program should prioritize differentiated support strategies: consolidating and certifying existing Soil Protection adoption; intensifying technical accompaniment for Plant Nutrition practices through demonstration plots and input subsidies; and developing economic incentives (e.g., premium markets, Payment for Ecosystem Services) that make Biodiversity Protection practices financially attractive for smallholders.

Expanding the adoption of agroecological practices requires targeted interventions that leverage existing successes while addressing the barriers limiting uptake. As Tittonell et al. (2016) and Jiménez et al. (2024) have shown, farmer-to-farmer training and access to subsidized inputs can significantly enhance adoption rates, particularly for practices with demonstrable benefits such as biodiversity conservation and soil fertility management. Jiménez et al. (2024) emphasize that farmers' deep knowledge of their soils, gained through years of interaction, can be effectively integrated into management plans. Linking this local expertise with scientific advances enables the refinement of traditional practices and the adoption of new technologies, optimizing soil management outcomes. Additionally, integrating agroecological practices into broader agricultural policies and local market systems could incentivize adoption by reducing costs and enhancing economic returns for farmers.

This study provides empirical evidence on the applicability of the SES framework for evaluating agroecological adoption in the Tropical Andes, with important methodological limitations that should inform the interpretation of results and guide future research. First, the cross-sectional design does not allow causal inference or longitudinal tracking of the transition process; the API captures adoption status at a single point in time and cannot establish whether observed practices resulted from AT program exposure or pre-existed it. Second, the Exponential Discriminative snowball sampling, initiated through organizational leaders, likely overrepresents farmers with formal associative ties, potentially inflating associativity rates and biasing the sample toward more agroecologically engaged producers. Third, the SU3 sub-indicator (conservation zones) does not distinguish between legally mandated buffer strips, non-arable terrain, and voluntarily managed biodiversity areas, limiting its interpretive value as a measure of active conservation agency. Fourth, while the SESI and API indices offer a structured, reproducible measurement approach, the selection of variables and weighting assumptions reflects contextual judgments that may require adaptation in other production systems or regions. Addressing these limitations in future research—through longitudinal designs, probabilistic sampling frames, disaggregated indicators, and cross-context validation—will strengthen the generalizability and causal interpretability of findings generated by these indices. Notwithstanding these constraints, the framework provides a methodologically transparent and replicable tool for guiding sustainability assessments in complex smallholder agricultural systems, and the findings generate actionable evidence to inform policies that support farmers in their transition toward agroecological practices.

5. Conclusion

This study underscores the potential of the Socio-Ecological Systems (SES) framework as an effective tool for assessing sustainability in small-scale avocado production within the Tropical Andes. By developing and applying the Socio-Ecological Sustainability Index (SESI) and the Agroecological Practices Index (API), we evaluated both the current status of agroecological practice adoption and the broader socio-ecological sustainability of smallholder avocado farming systems in Northern Tolima. The API, applied in the context of an institutionally promoted transition process initiated by Asohofrucol through its Tropical Agriculture (AT) program, provides a snapshot of adoption status rather than a prescriptive normative benchmark. The SESI, in turn, captures the systemic socio-ecological conditions—governance, resource management, community organization, and interactions—that mediate the pace and depth of this transition. The results reveal a moderate adoption of agroecological practices, with substantial progress in governance and land tenure security, but limited integration of resource-based and ecosystem-oriented practices. This indicates both strengths in organizational capacity and governance, and significant gaps in the ecological management of productive resources.

Regarding objective 1 (adoption status), the API results reveal a clearly uneven landscape: Soil Protection practices are well-adopted (60%), likely reflecting a combination of AT program promotion and pre-existing traditional knowledge; Biodiversity Protection remains moderate (30%), constrained by implementation costs and limited economic incentives; and Plant Nutrition practices show the lowest adoption (24%), pointing to specific gaps in input access and technical support for complex biofertilizers. These differentiated adoption rates are a core empirical contribution of this study and should inform future AT program design. Regarding objective 2 (facilitating/constraining factors), secure land tenure and high associativity through organizations such as PALTOLIMA and ASOFRUTOS emerge as the strongest enablers of agroecological adoption, consistent with findings from comparable Andean systems (Bellon et al., 2015; Builes et al., 2024). Conversely, market price volatility—which threatens to undermine established multi-year productive investments, given an average plantation age of 5.2 years—constitutes the most critical systemic constraint. The limited recognition of ecosystem services (low SU1 scores) further suggests that the environmental value proposition of agroecological practices is not yet fully internalized by farmers, representing an important target for future educational and extension efforts.

Comparisons with other high-biodiversity regions in the Andes, such as Huánuco, Chocó Andino, and high Andean silvopastoral systems, confirm that successful agroecological transitions require continuous and differentiated institutional support, stable market access, and financial incentives linked to environmental outcomes.

Future research should: (1) expand SESI and API application to other high-value crop systems in ecologically sensitive tropical regions to assess index robustness and cross-context validity; (2) incorporate longitudinal designs that can distinguish AT program-induced adoption from pre-existing traditional practices, enabling genuine before-after transition measurement; (3) explicitly disaggregate SU3 conservation zones by management motivation and legal status; and (4) investigate the relationship between associativity, market access, and AT practice adoption using regression or causal inference methods to move beyond descriptive characterization. Public policies should prioritize: market stabilization mechanisms for avocado (including price floor instruments or cooperative commercialization models); differentiated technical support targeting Plant Nutrition and Biodiversity Protection practice gaps identified by the API; and the formal recognition of agroecologically managed farms within national certification and Payment for Ecosystem Services frameworks. This study contributes a methodologically novel, empirically grounded, and policy-relevant analysis of agroecological dynamics in the Tropical Andes—one that offers both a replicable index framework and concrete, practice-level evidence for designing more effective institutional programs of agroecological transition support.

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Conflicts of interest

The authors declare that they do not have any conflicts of interest.

Data availability

The data that support the findings of this study are available from the author upon request. Supplementary material is provided at the landing page the DOI points to. Supplementary file 1: interview protocol, Supplementary file 2: semi-structured interview.

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