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Unveiling agroecological transitions in Northern Patagonia: a comparative typology approach

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Introduction: Agroecological transitions are complex, multidimensional processes that require analytical tools capable of capturing contextual and systemic diversity. Typology construction has proven valuable for characterizing the heterogeneity of farming systems and supporting the design of agroecological transformation pathways.

Methods: This study applies a comparative typology approach in the *Comarca Andina del Paralelo 42 (CAP42)*, a mountainous forest region of Northern Patagonia, Argentina. We analyzed 53 small- and medium-scale farms (median area: 13 ha) representing diverse production systems, including fruit and/or vegetable growing, livestock, and mixed farming. The *Tool for Agroecology Performance Evaluation (TAPE)* was used to assess the agroecological transition level of each farm. Data derived from TAPE were analyzed using two complementary multivariate methods: Archetypal Analysis and Reinert's Descending Hierarchical Classification.

Results: Both methods effectively captured meaningful patterns of diversity in the configuration of the Elements of Agroecology, enabling the identification of representative farm types. Archetypal Analysis revealed hybrid or transitional profiles and subtle intra-group variations, while Reinert's classification generated distinct and interpretable clusters. The resulting typology comprised four groups—*Agroecology Keepers*, *Community Pillars*, *Social Weavers*, and *Agroecology Seekers*—reflecting the diversity and socially driven nature of agroecological change in the CAP42 region.

Discussion and Conclusions: This study demonstrates the potential of typology-based approaches to enhance both analytical depth and practical relevance in agroecological research. By combining interpretability and complexity, the proposed methodology provides a robust framework for understanding diverse transition pathways. Further research exploring the main barriers and drivers of change will deepen understanding of the detected patterns and clarify the influence of territorial context on the dynamics of agroecological transitions in Northern Patagonia.

KEYWORDS

agroecology, TAPE, archetypal analysis, Reinert classification, typologies

1 Introduction

The transition to agroecology is increasingly recognized as a key strategy for achieving more sustainable and resilient food systems (Ewert et al., 2023; Titttonell, 2023). By integrating ecological principles into agricultural practices while addressing social and economic dimensions, agroecology offers a holistic approach to enhancing food security, biodiversity conservation and rural livelihoods (Altieri, 1999; Quintero et al., 2023; Titttonell et al., 2021; Wezel et al., 2020). However, the transition process is highly complex and context-dependent, varying significantly across regions, production systems, and socio-political settings (Titttonell, 2019). Understanding how different farming systems progress towards agroecology is essential for designing effective policies and interventions (Barrios et al., 2020). This requires methodological approaches that can not only assess the level of agroecological transition but also classify farming systems into meaningful groups based on their shared characteristics and trajectories (Barrios et al., 2020; Darmaun et al., 2023). Several approaches, tools and frameworks have been developed to measure the level of agroecological transitions and its performance (Geck et al., 2023). Most of them use the 13 Principles or the 10 Elements of Agroecology as reference frameworks at least in one of their steps. However, the methodologies vary in their qualitative or quantitative nature, their main goal (agroecological transition, performance) and the level of analysis integration (field, farm, landscape, food system). A recent comparative evaluation of 14 multiscale and multidimensional assessment methods identified the Tool for Agroecology Performance Evaluation (TAPE) as one of the most robust, meeting four out of five key evaluation criteria, including adaptability to local contexts, stakeholder integration, conceptual clarity, and a participatory approach (Darmaun et al., 2023).

Among them, the Tool for Agroecology Performance Evaluation (TAPE) provides a comprehensive framework that integrates the assessment of agroecological transition and performance at farm/household level with context characterization and participatory analysis and validation of the results at community and territorial

level (Mottet et al., 2020). TAPE was developed as a framework to provide evidence of the contribution of agroecological systems to the UN sustainable development goals and retains some key attributes of 12 pre-existing frameworks (Mottet et al., 2020). While TAPE offers valuable insights into different sustainability dimensions, the step of performance assessment is time-consuming and represent one of the main bottlenecks of TAPE implementation. The TAPE stepwise approach proposes the identification of typologies as an optional step. However, it does not inherently generate typologies of farming systems, neither recommends methodologies for typology's identification. This classification of farms into distinct groups is crucial to reduce the number of farms to be considered for the performance assessment and for identifying common challenges, strengths, and potential pathways for transition. Moreover, developing typologies provides a cost-effective means to capture system diversity and guide more resource-intensive or long-term studies, by identifying representative cases and prioritizing areas for in-depth investigation (Huber et al., 2024).

Multiple approaches exist for constructing typologies, each relying on different theoretical foundations, methodological assumptions and purposes (Bartkowski et al., 2022; Collier et al., 2012; Titttonell et al., 2020). Farm typology analysis has been extensively reported around the world (e.g., Awoke Esheta et al., 2024; Benitez-Altuna et al., 2023; Kumar et al., 2019; Quemada et al., 2020) and integrated in agroecological transition research (e.g., Bagagnan et al., 2024; Teixeira et al., 2018).

Among these approaches, Archetypal Analysis and Reinert's descending hierarchical classification represent alternative methods for typology identification (Álvarez et al., 2019; El Mujtar et al., 2023; Titttonell et al., 2020). Archetypal Analysis is an unsupervised learning method that identifies extreme, idealized profiles (Cutler and Breiman, 1993). These profiles, namely archetypes, represent reference configurations rather than actual observations. Alternatively, Reinert's descending hierarchical classification (Reinert, 1983) identifies independent classes of correlated farm characteristics by iteratively subdividing the most heterogeneous groups into increasingly differentiated ones. While both methods could address the complexity and diversity of agroecological

transitions, Archetypal Analysis, rooted in quantitative approaches, works with continuous multivariate data. In contrast, Reinert's method, originated in the social sciences, works with categorical multivariate data.

Since 2020, when the first version of TAPE was available, more than 30 scientific articles reported its use (e.g., Gomori-Ruben and Reid, 2023; Sciuano et al., 2024; Sokolowski et al., 2023). Among the articles that combined TAPE with farm typologies, most of them used pre-defined typologies such as categories based on the level of transition, farming systems, farm size (e.g., Lucantoni et al., 2023; Verkuil et al., 2024) instead of identified typologies. Identified typologies based on the elements/indices used for the characterization of agroecological transition can be, however, more informative as they can capture the diversity of farm transitions. These typologies are better than pre-defined typologies to identify more homogenous farm groups. Archetypal Analysis has been successfully applied to categorize household-level functional responses (Tuttonell et al., 2020), and its use for typology identification was tested during the development of TAPE (Álvarez et al., 2019). Similarly, the Reinert's method has been successfully applied to derive farm typologies from TAPE data (El Mujtar et al., 2023). However, the use of both methods for the analysis of the same TAPE data has been not yet compared.

The present study focused on the *Comarca Andina del Paralelo 42°* (CAP42) in northern Patagonia, Argentina, a region with a long-standing agroecological history. Since the 1960s, CAP42 has been a pioneering area for agroecology, shaped by a diverse mix of traditional farming knowledge and modern organic agriculture influences (Cabrera et al., 2010; Eyssartier et al., 2011). Thus, the CAP42 serves as an ideal case study for assessing typologies of agroecological transition. The goal of the study was to test the use of Archetypal Analysis and Reinert's descending hierarchical classification for typology identification based on the same TAPE data and to compare their effectiveness in capturing the heterogeneity of agroecological transitions. Additionally, the study contributed to characterize the level of agroecological transition in the CAP42 and establish the effect of socio-ecological context on the agroecological transition.

2 Materials and methods

2.1 Study site

2.2 Characterization of the transition to agroecology

The Andean-North Patagonian Biosphere Reserve, designated by UNESCO in 2007, covers 22,670 km² and includes ecosystems ranging from the humid forests of the Andean Cordillera to the semi-arid Patagonian steppe (UNESCO, 2007). Globally, biosphere reserves under UNESCO's Man and the Biosphere Programme serve as testing sites for interdisciplinary approaches to understanding and managing socio-ecological systems. They

contribute to the development of sustainable agricultural and livestock practices, fostering a balance between human activity, socio-economic development, and environmental conservation (UNESCO, 2022). Within this reserve lies the *Comarca Andina del Paralelo 42°* (CAP42), a 7,550 km² area located in a valley region near the Andes mountains, intersected by the 42nd parallel south. CAP42 is considered a representative socio-ecological system, where agricultural practices are shaped by the interaction between human and natural components (Aiani and Ejarque, 2019; Madariaga and López, 2020). The area is characterized by a heterogeneous cultural and agricultural landscape, where organic, conventional, and traditional farming systems are embedded within a native forest matrix, reflecting the integration of local knowledge (influenced by indigenous and peasant heritage) and external influences (Aloras, 2020). This is a hotspot for agroecological research including the development of certification by Participatory Guarantee System and technological innovations for pest management and soil health (e.g., Chillo et al., 2025; Frank et al., 2025; Mestre et al., 2024). Although farm typologies have been reported for this area (e.g., Basso, 2018; Cardozo, 2014; Cardozo et al., 2022), they were not based on agroecological transition data.

To characterize the transition to agroecology in the CAP42, 53 farms were selected based on the following criteria: (i) geographical location within four pre-defined zones of homogeneous socio-ecological characteristics, (ii) representative production types of the region, (iii) small- and medium-scale agricultural producers transitioning toward more intensive systems, and (iv) active support from the Rural Extension Agency *El Bolsón* (AER El Bolsón) of the National Institute of Agricultural Technology (INTA) (Figure 1). While the sample was not randomly drawn from the total farm population, it was designed to provide a meaningful overview of transition pathways. We acknowledge that this approach may introduce some selection bias towards farms already engaged with extension services, but it ensures that the selected farms are informative and relevant for characterizing ongoing agroecological transitions. At the same time the number of farms assessed was adequate for typology identification based on TAPE data.

In this study, we considered the Step 1 of TAPE, referred to as the Characterization of AgroEcological Transition (CAET). This Step is based on the ten Elements of Agroecology (Barrios et al., 2020) encompassing both farm management and innovation elements—i.e., *Diversity, Resilience, Synergies, Efficiency, and Recycling*—as well as social elements—i.e., *Human and Social Values, Culture and Food Traditions, Circular and Solidarity Economy, Co-Creation and Sharing of Knowledge, and Responsible Governance*. Each element was evaluated using 3 to 4 indices scored on a descriptive (Likert) scale ranging from 0 (least agroecological status) to 4 (most desirable agroecological status). The scores for each element were summed, standardized against the maximum possible score (i.e., the sum of the maximum scores of all indices), and expressed as a percentage. Thus, this scoring yields the percentage of advancement for each Element and an aggregate score (CAET), which represents the overall degree of agroecological

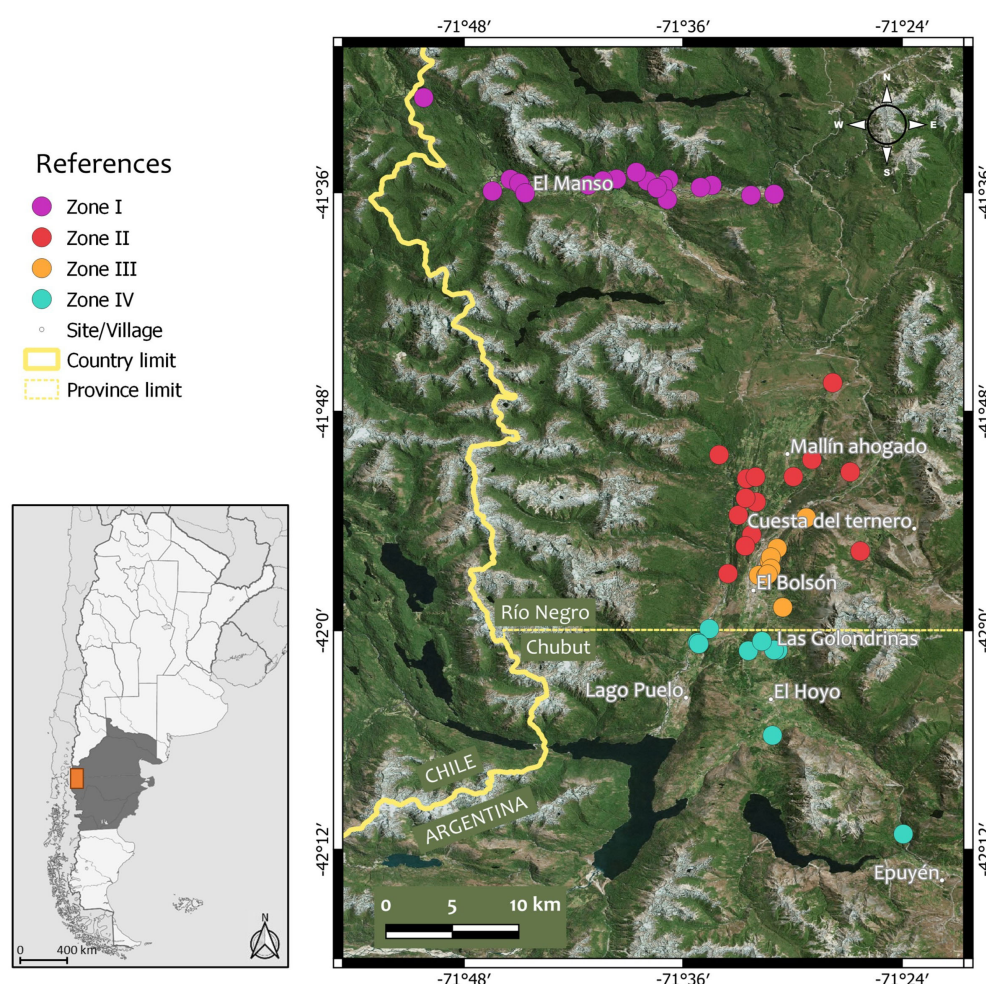


FIGURE 1

Distribution of the 53 farms evaluated throughout the *Comarca Andina del Paralelo 42°*. Zones I, II, III, and IV correspond to four zones of differential socio-ecological characteristics.

transition within the farm (Mottet et al., 2020). The CAET was further disaggregated into two components: farm-CAET, which accounts for the five management and innovation-related elements, and social-CAET, which accounts for the five social-related elements. The complete list of the assessed indices for each Element of Agroecology is provided in the [Supplementary Table S1](#). Scoring was based on the descriptions of the scores of each element provided by Mottet et al. (2020) without modifications. To ensure consistency and minimize enumerator bias, the assessment of the 53 farms was carried out by a single team composed of five members, including researchers and local extension agents. Additionally, contextual information (Step 0 of TAPE) was collected using a matrix of eight variables: farm size, gender and age range of the main decision-maker, farmer's origin, production objectives, economic resources, production type, and farm location within the CAP42. The modalities of each categorical variable of context data are detailed in [Table 1](#).

2.3 Typology identification

Data collected from Step 1 was used to identify agroecology transition typologies (TAPE Step 1 *bis*) based on classification methods.

We used Archetypal Analysis to identify extreme configurations of the ten Elements of Agroecology within CAP42, representing farms as combinations of archetypes. Cases with higher degree of similarity to archetypes are considered *archetypoids*. We considered a predefined 0.8 threshold for archetypoids assignment. Due to methodological constraints—specifically, the need for an approximately square data matrix—the analysis was performed using the disaggregated set of 36 agroecological indices rather than the aggregated values at the Element level. This choice ensured a more balanced matrix dimension relative to the 53 farm observations. The analysis was conducted in R (v 4.3.1) using the 'stepArchetypes' function (parameters $k = 3:5$ and $nrep = 1000$) from the 'archetypes' R package (Eugster and Leisch, 2009).

TABLE 1 TAPE step 0, definitions of the modalities for each context variable.

Variable	Modalities
Zone	I (El Manso) II (Mallín ahogado, Cuesta del ternero) III (El Bolsón) IV (Las Golondrinas, Lago Puelo, El Hoyo, Epuyén)
Production type	Horticulture Fruit Fruit-horticulture Livestock Mixed
Farm size	< 25 ha 25–250 ha > 250 ha
Production objectives	Profit driven (PD) Self-sufficiency and profit (SSP) Lifestyle (LS)
Economic resources	High Medium Medium-Low Low NA (when the production objective is LS)
Gender of the main decision-maker	Female Male Both
Age range of the main decision-maker	Young adult (Y) Adult medium age (A) Elderly (E) Y–A Y–E A–E
Origin of the main decision-maker	Rural Urban

Among the models tested, the four-archetype model was selected based on its ability to delineate an acceptable number of groups from 53 observations (Sharma, 2003) and its capacity to capture the observed diversity in the region.

On the other hand, Reinert's descending hierarchical classification was applied to a matrix of categorized scores for the ten Elements of Agroecology, following the classification proposed by Lucantoni et al. (2022b) for the CAET score: conventional (average score < 40), conventional with sustainability elements (40–50), initial transition (50–60), advanced transition to agroecology (60–70), and fully agroecological farms (> 70). In the matrix, each Element of Agroecology corresponded to a categorical variable and categorized scores corresponded to the modalities of each variable. Hierarchical clustering was performed based on chi-square distances, with the algorithm sequentially between segments, with the algorithm sequentially to maximize inter-class variance. Farm assignments to these classes were subsequently assessed using the chi-square test to evaluate the associations with context variables (TAPE Step 0, Table 1). The analysis was conducted in IRaMuTeQ (version 0.7 alpha 2, <http://www.iramuteq.org/>) using default settings.

2.4 Soil properties variation among agroecological typologies

To evaluate whether the farm typologies identified also captured meaningful biophysical variation, we examined their relationship with soil properties. Such analysis provides an empirical test of the typological classification, as typologies are intended not only to describe diversity but also to reduce analytical complexity by grouping representative cases for further assessment. To assess the relationship between typologies and soil properties, we used the soil physicochemical dataset compiled by (Trinco et al., 2024), which includes information from farms within the CAP42. This dataset integrates data from three sources: (i) the INTA AER El Bolsón database, (ii) peer-reviewed scientific publications, and (iii) unpublished data from our research group (e.g., Basso (2018) and ongoing PhD theses). To ensure comparability across samples, minimize missing data, and maximize coverage across the identified typologies, we selected soil samples taken from the 0–30 cm depth layer and retained the following variables: soil organic matter (SOM), pH, electrical conductivity (EC), bulk density (BD), phosphorus (P), potassium (K), and nitrogen (N). Soil properties were assessed by external services over the period 2018–2022. Soil pH and electrical conductivity (EC) were determined by soil suspension in water at a 1:2.5 soil-to-water ratio (Sparks et al., 1996). Soil organic matter (SOM) was estimated using the Walkley–Black wet oxidation method (Walkley and Black, 1934). Total nitrogen (N) was determined by the Kjeldahl method (Bremner, 1960), and available phosphorus (P) was measured following the Olsen extraction procedure (Olsen et al., 1954). Bulk density (BD) was determined using the core method on undisturbed soil samples (Blake and Hartge, 1986). Exchangeable potassium (K) was extracted with ammonium acetate (1 N) and measured via flame photometry (Helmke and Sparks, 1996). A subset of 47 soil samples from nine farms was retained, corresponding to those farms for which complete, and quality-controlled laboratory data were available. These nine farms included representatives of all typology groups identified. The soil samples come from actively managed plots, including annual crops, fruit orchards (predominantly berry plantations), horticultural plots, and pastures, thereby reflecting the main land uses across the studied farms. We acknowledge that soil data were not available for all 53 farms, which constrains the spatial scope of inference, but it was useful for an empirical test of the typology identification.

2.5 Statistical analysis

All analyses described below were conducted in R (v 4.3.3) (R Core Team, 2020; RStudio Team, 2015). To evaluate the effect of context variables (Table 1) on the level of agroecological transition (CAET, farm-CAET, and social-CAET), linear models were fitted, treating each variable as a fixed factor. Models were constructed using the 'lm' function from base R, incorporating eight context variables: zone, production type, farm size, production objectives, availability of economic resources, and the gender, age range, and origin of the main decision-maker(s). The best-fitting model for

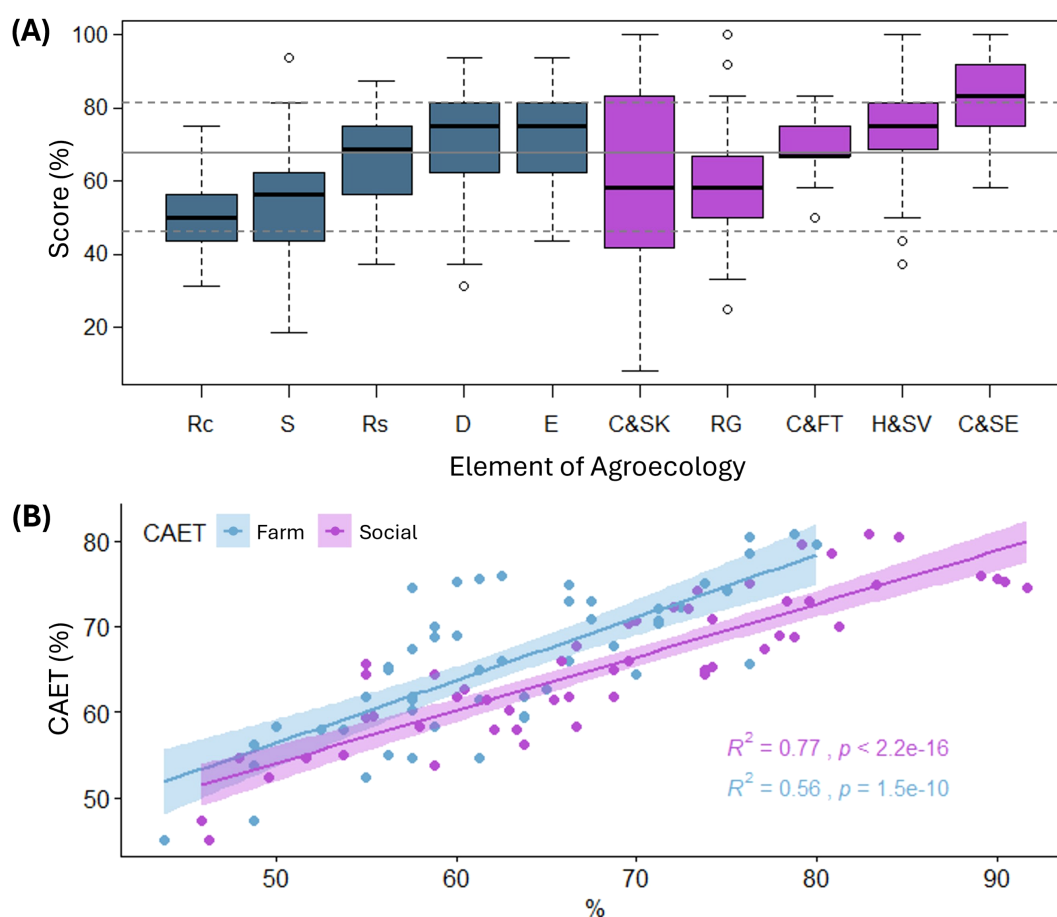


FIGURE 2

(A) Percentage of progress for each Element of Agroecology across 53 farms in the *Comarca Andina del Paralelo 42°*. Elements related to management aspects: Recycling (Rc), Synergies (S), Resilience (Rs), Diversity (D), and Efficiency (E). Elements related to social aspects: Co-Creation and Sharing of Knowledge (C&SK), Responsible Governance (RG), Culture and Food Traditions (C&FT), Human and Social Values (H&SV), and Circular and Solidarity Economy (C&SE). The solid grey line indicates the mean CAET score, and the dashed grey lines indicate its minimum and maximum values. (B) Correlation of the CAET score (mean of the ten Elements of Agroecology) with its subcomponents: farm-CAET (management-related elements) and social-CAET (social-related elements).

each CAET metric (global, farm, and social) was selected based on Akaike's Information Criterion (AIC) using the 'step' function from the 'stats' R package (R Core Team, 2020). To assess the association between the two typologies—by Archetypal Analysis and Reinert's descending hierarchical classification—, a weighted contingency matrix was constructed by summing the membership values to each archetype across farms grouped by Reinert's group. The resulting matrix represented the cumulative weight of archetypal membership within each Reinert's group. A chi-squared test with Monte Carlo simulation (99,999 permutations) was applied to this matrix using the 'chisq.test' function from base R to evaluate the independence between the two classification systems.

To facilitate the comparison of soil characteristics across the different farm types identified in the typology, all variables were normalized to a 0–1 scale. For each farm type, we calculated the mean value of each soil variable based on the corresponding subset of samples (ranging from 4 to 21), with data drawn from two to three farms per type. To visualize differences between farm types we generated radar charts.

3 Results

3.1 Characterization of the agroecological transition in CAP42

The 53 farms assessed in the *Comarca Andina del Paralelo 42°* (CAP42) exhibited variability in their scores across the different elements (Figure 2). Recycling had the lowest average score, whereas Circular and Solidarity Economy had the highest (Figure 2A). The Co-Creation and Sharing of Knowledge element showed the greatest dispersion, followed by Synergies (Figure 2A). Overall, the farms presented a relatively advanced stage of agroecological transition, with an average CAET index of 66%, ranging from 45% to 81% (Figure 2A). Based on the classification proposed by Lucantoni et al. (2022b), 32% of the farms were classified as agroecological (CAET > 70%), 40% were in transition to agroecology (CAET between 60–70%), 24% were in the initial transition stage (CAET between 50–60%), and only 4% were conventional with elements of sustainability (CAET between 40–60%). No conventional farms

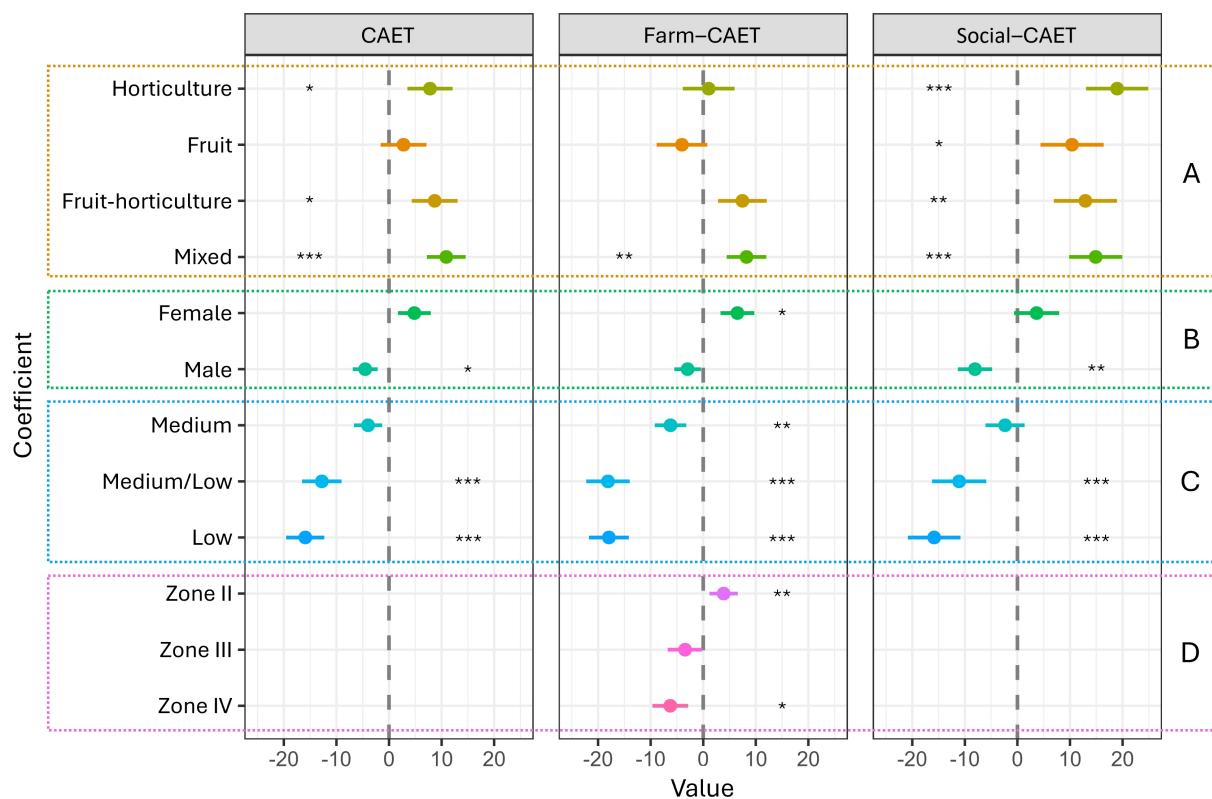


FIGURE 3

Estimated coefficients of the linear model for CAET, farm-CAET and social-CAET. Asterisks indicate model coefficients that were statistically significant (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$). (A) Type of production, reference level *Livestock*; (B) Gender of main decision-maker(s), reference level *Both*; (C) Availability of economic resources, reference level *High*; (D) Geographical area, reference level *Zone I*. CAET-intercept: 65.2; farm-CAET-intercept: 67.8; social-CAET-intercept: 63.6.

(CAET < 40%) or agroecological “lighthouses” (CAET > 90%) were identified.

The average score for elements related to farm management and innovation aspects (farm-CAET) was 63% (44–80%), while for elements associated with social aspects (social-CAET), it was 69% (46–92%). A stronger correlation was observed between CAET and social-CAET than with farm-CAET (Figure 2B).

Of the eight context variables analyzed, only three—production type, gender of the main decision-makers, and availability of economic resources—had a significant effect on CAET, farm-CAET, and social-CAET. Additionally, the geographical area (zone) where the farm is located was identified as a significant factor for farm-CAET (Figure 3, Supplementary Figure S1). Overall, farms engaged in horticultural, fruit, fruit-horticultural, and mixed production exhibited higher levels of agroecological transition compared to those focused on livestock production. Likewise, transition levels were lower on farms where the main decision-maker was male, compared to those led by females or by both genders. Farms with medium to low economic resource availability also showed lower transition levels than those with high availability (Figure 3). Regarding the effect of zone on farm-CAET, farms in Zone IV exhibited the lowest values of agroecological transition, whereas those in Zone II showed the highest.

3.2 Identification of agroecological typologies

3.2.1 Typology based on numerical scores (archetype analysis)

A scree plot of the residual sum of squares across models with varying numbers of archetypes indicated that four archetypes adequately captured the structure of the data (Supplementary Figure S2). This pattern supports their selection as the most parsimonious representation. Considering this model, the farm scores and the classification proposed by Lucantoni et al. (2022b), Archetype 1 represented agroecological farms with a balanced configuration of the Elements of Agroecology (Figure 4A), with average CAET, farm-CAET, and social-CAET scores of 75%, 76%, and 75%, respectively. Archetype 2 corresponded to agroecological farms with an unbalanced configuration (Figure 4A), characterized by an average lower farm-CAET (60%) compared to social-CAET (86%), and an average CAET of 73%. In this case, social-CAET was primarily driven by the Elements *Co-Creation and Sharing of Knowledge* and *Responsible Governance*. Archetype 3 reflected farms in transition towards agroecology, also with an unbalanced configuration (Figure 4A), but with lower average values than Archetype 2, resulting in scores of 65% (CAET), 59% (farm-CAET), and 70% (social-CAET). Here, social-CAET was mainly

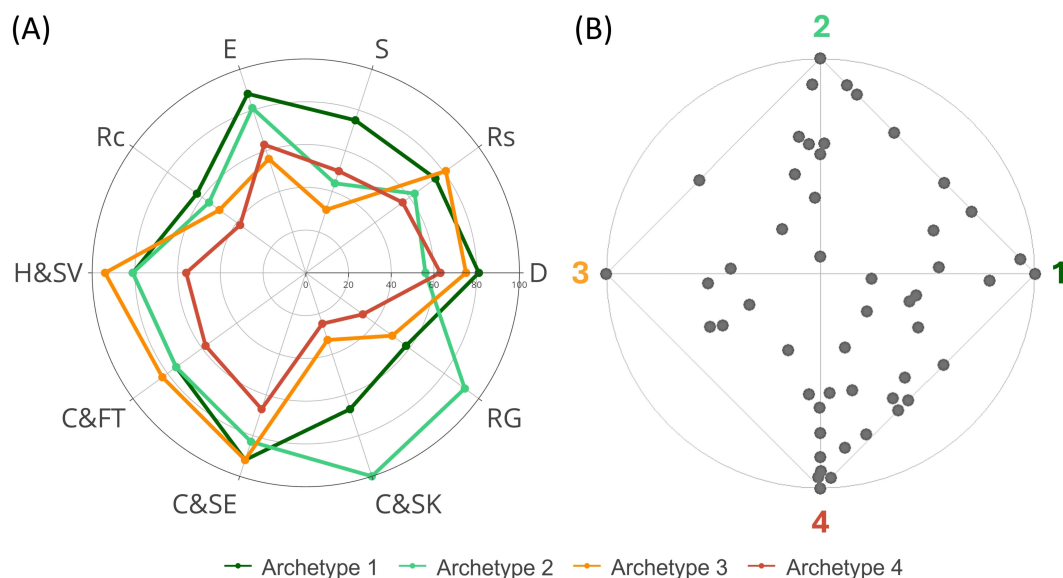


FIGURE 4

(A) Scores of the ten elements of agroecology for the four archetypes. Diversity (D), Resilience (Rs), Synergies (S), Efficiency (E), Recycling (Rc), Human and Social Values (H&SV), Culture and Food Traditions (C&FT), Circular and Solidarity Economy (C&SE), Co-Creation and Sharing of Knowledge (C&SK) and Responsible Governance (RG). (B) Distribution of the 53 farms in the space defined by the four archetypes.

influenced by the elements *Human and Social Values*, *Culture and Food Traditions*, and *Circular and Solidarity Economy*. Finally, Archetype 4 represented farms in an initial stage of transition (Figure 4A), with the lowest average scores across CAET (51%), farm-CAET (54%), and social-CAET (48%). The greatest differences between the four archetypes were observed for the elements *Co-Creation and Sharing of Knowledge* (25–100%), *Responsible Governance* (33–92%), and *Human and Social Values* (56–94%). Three, five, one, and eight farms were classified as archetypoids of archetypes 1, 2, 3, and 4, respectively (Figure 4B), accounting for 32% of the total farms assessed. This low number of archetypes indicates that most CAP42 farms exhibited intermediate configurations of the Elements of Agroecology, suggesting they are best characterized as combinations of archetypal profiles.

3.2.2 Typology based on categorized scores (Reinert's typology)

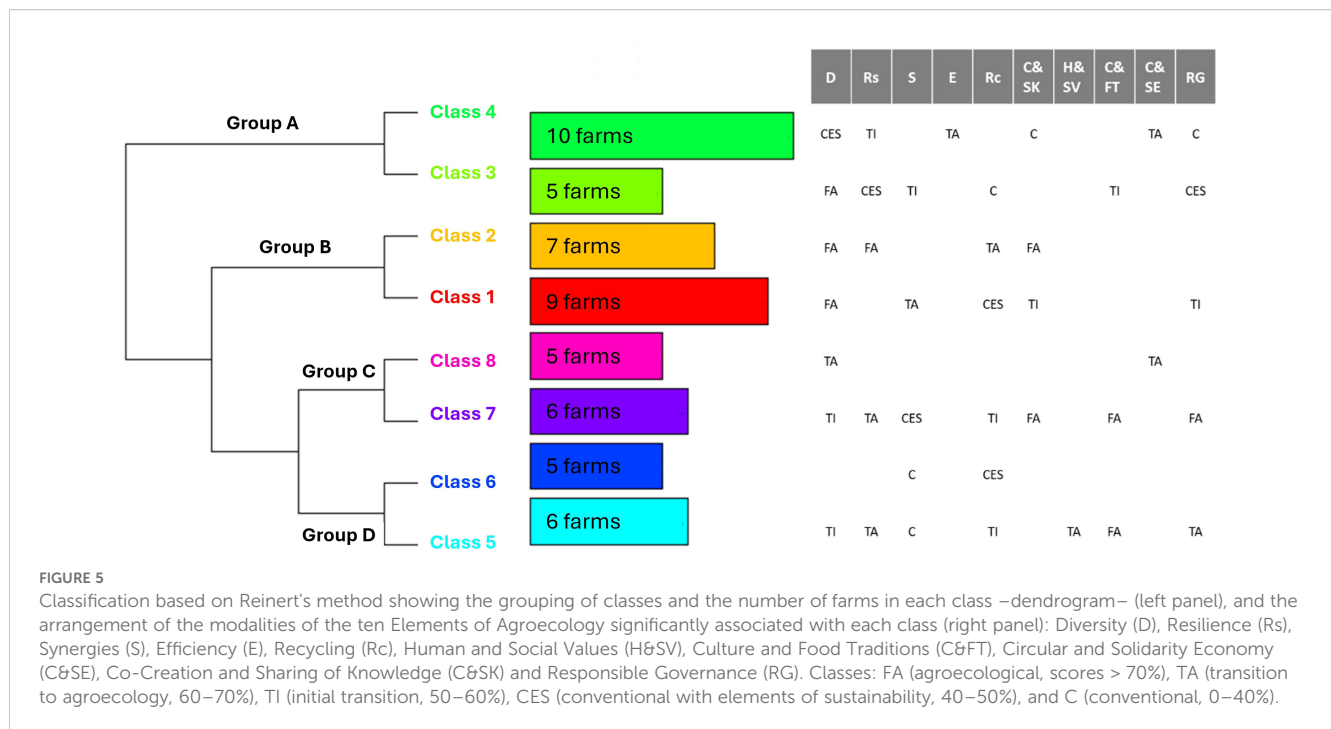
The Reinert's descending hierarchical classification yielded eight distinct classes, which could be grouped into four broader classes based on the structure of the dendrogram (Figure 5). All farms were significantly associated with one of the groups, as confirmed by the Chi-square test, Group A (Classes 3 and 4) included 28% of the farms assessed, Group B (1 and 2) 30%, Group C (7 and 8) 21%, and Group D (5 and 6) 21% (Figure 5). Each class was defined by a specific configuration of agroecological element modalities, reflecting varying degrees and patterns of transition. For instance, Class 1 exhibited a mixed arrangement: 'agroecological' (AE, scores > 70%) for *Diversity*; 'in transition to agroecology' (TA, 60–70%) for *Synergies*; 'initial transition' (TI, 50–60%) for both *Co-creation and Sharing of Knowledge* and

Responsible Governance; and 'conventional with sustainability elements' (CES, 40–50%) for *Recycling*.

Analysis of the farms associated with each class revealed distinct patterns in average CAET, farm-CAET and social-CAET scores (Table 2). Group A correspond to the classes with the lowest CAET scores, indicative of farms in the early stages of agroecological transition (CAET between 50–60%), with relatively balanced farm-CAET and social-CAET values. Within Group B, Class 1 included farms in transition to agroecology (CAET between 60–70%) with a balanced distribution between farm-CAET and social-CAET, while Class 2 represented agroecological farms (CAET > 70%) with a slight predominance of social-CAET over farm-CAET. Group C included both in transition (Class 8) and agroecological farms (Class 7), but both classes displayed a consistent pattern of lower farm-CAET than social-CAET scores, with this difference being most marked in Class 7. In Group D, both classes were also in transition to agroecology, but again exhibited higher social-CAET than farm-CAET scores, with Class 6 showing the greatest difference. Across all groups, the widest differences were observed in the Elements *Co-Creation and Sharing of Knowledge* (33–93%), *Responsible Governance* (43–81%) and *Synergies* (35–65%) (Table 2, Figure 6).

3.3 Comparison of analytical methods

The chi-squared test with Monte Carlo simulation (99,999 replicates) revealed a significant association between the archetypal membership profiles and the Reinert's groups ($\chi^2 = 24.33$, $p = 0.0014$). This indicates a non-random correspondence between the typologies derived from Archetypal Analysis and Reinert's descending hierarchical classification. This



statistical association was further supported by the comparison of the profiles of the ten Elements of Agroecology across classification groups. In both typologies, the CAET indices and the balance between farm–CAET and social–CAET played a central role in shaping their structure. Consequently, the correspondence can be established between the archetypes and Reinert's groups/classes by comparing the average values and relationships of these indicators (Table 3, Figure 7). Both analyses revealed four distinct arrangements of the Elements of Agroecology, capturing the gradient of agroecological transition in CAP42 farms—from initial transition to fully agroecological systems. The comparison between classification methodologies showed strong consistency in farm groupings, although farms in Group D showed the least alignment between methods (Supplementary Table S2, Supplementary Figure S3). These configurations were named to reflect their defining characteristics. *Agroecology Keepers*

(Archetype 1, Group B) denote farms with a balanced and consolidated agroecological profile. *Community Pillars* (Archetype 2, Group C) refer to agroecological farms with high CAET values and a marked emphasis on social elements. *Social Weavers* (Archetype 3, Group D) are farms in transition with mid-level CAET scores and a stronger expression of social dimensions. *Agroecology Seekers* (Archetype 4, Group A) represent farms at the early stages of transition, with the lowest CAET scores but a balanced relationship between farm–CAET and social–CAET.

A comparative overview of the socioeconomic and productive features of the four farm types provides further insight into their structural diversity and transition dynamics (Supplementary Table S3). *Agroecology Keepers* show a balanced participation of rural and urban farmers, with both genders often sharing decision-making roles and managing small- to medium-sized farms with diversified production aimed at self-sufficiency, profitability, or lifestyle goals.

TABLE 2 Average values of CAET (mean of the ten Elements of Agroecology), farm–CAET (management-related elements), social–CAET (social-related elements), and the difference between farm–CAET and social–CAET for each class identified by Reinert's descending hierarchical classification.

Group (n farms)	CAET (group)	Class (n farms)	CAET (class)	farm–CAET (class)	social–CAET (class)	Diff. CAET farm–social
A (15)	57	4 (10)	55	55	55	0
		3 (5)	58	60	57	3
B (16)	73	2 (7)	77	74	79	–5
		1 (9)	68	68	68	0
C (11)	70	8 (5)	66	62	71	–9
		7 (6)	73	62	84	–22
D (11)	65	6 (5)	63	56	70	–14
		5 (6)	67	63	72	–9

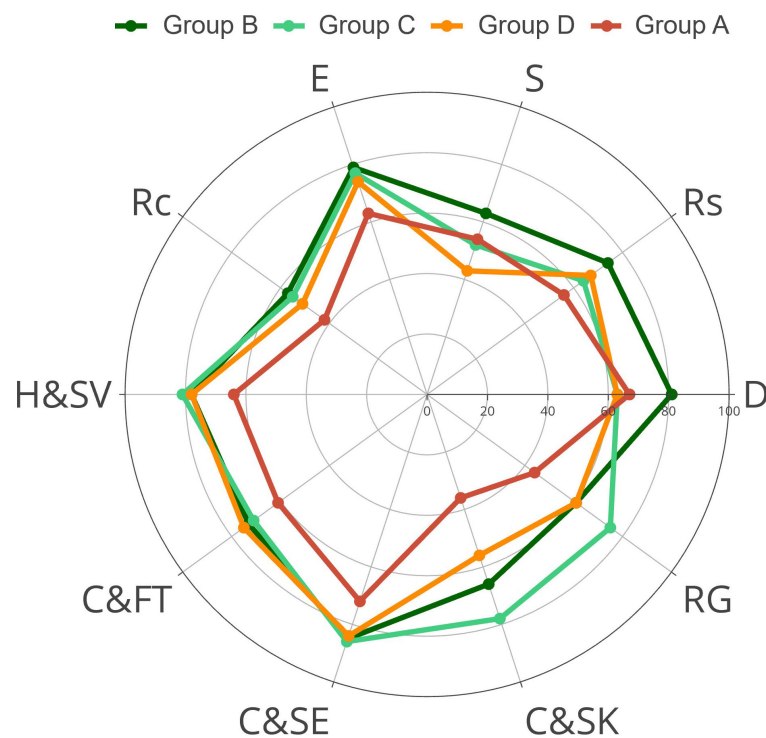


FIGURE 6

Scores of the 10 Elements of Agroecology for Reinert's four groups (average of the farms in each group). Diversity (D), Resilience (Rs), Synergies (S), Efficiency (E), Recycling (Rc), Human and Social Values (H&SV), Culture and Food Traditions (C&FT), Circular and Solidarity Economy (C&SE), Co-Creation and Sharing of Knowledge (C&SK) and Responsible Governance (RG).

Community Pillars encompass medium-scale mixed or horticultural systems managed by rural and urban farmers, typically under male or shared leadership. *Social Weavers* are characterized by a broad age range among decision-makers, predominantly shared management between genders, and medium-sized farms engaged mainly in fruit-horticulture or mixed production. In contrast, *Agroecology Seekers* are mostly rural male farmers operating medium- to large-scale farms with low to medium resource endowment, focused on mixed or livestock-based production systems where self-sufficiency and profit remain central motivations.

3.4 Soil properties variation among agroecological typologies

The comparison between the overall mean values across the complete dataset and the average values associated with each farm

type revealed distinct patterns in soil properties (Figure 8, see Supplementary Table S4 for mean $\pm$ SD values). *Agroecology Keepers* were characterized by consistently higher values across most soil properties, particularly in soil organic matter and total nitrogen, positioning them at the upper end of the observed gradient. In contrast, *Community Pillars* exhibited the lowest values for these indicators, delineating the opposite end of the spectrum. *Agroecology Seekers* also displayed relatively low nutrient levels, though they were distinguished by markedly higher bulk density. *Social Weavers* presented a distinctive profile, defined by the highest electrical conductivity and the lowest bulk density among all groups. For the remaining indicators, *Social Weavers* showed values close to the overall mean. In general, the most notable differences among farm types were observed in soil organic matter, nitrogen, electrical conductivity, and bulk density, whereas variation in phosphorus and potassium were less pronounced. These soil properties patterns aligned more closely

TABLE 3 Relationship between archetypes and Reinert's groups based on their CAET values (mean values of the ten Elements of Agroecology) and the difference between farm-CAET (management-related elements) and social-CAET (social-related elements).

CAET	Relationship farm-CAET/social-CAET	Archetype	Reinert's group (n farms)	Name
High (≥ 73)	Balanced	1	B (16)	Agroecology Keepers
High (≥ 70)	Unbalanced	2	C (11)	Community Pillars
Medium (= 65)	Unbalanced	3	D (11)	Social Weavers
Low (≤ 57)	Balanced	4	A (15)	Agroecology Seekers



FIGURE 7
Comparison of the scores of the 10 elements of agroecology for the four trios formed according to degree of similarity between archetype and Reinert's classes (average of the farms in each class). Diversity (D), Resilience (Rs), Synergies (S), Efficiency (E), Recycling (Rc), Human and Social Values (H&SV), Culture and Food Traditions (C&FT), Circular and Solidarity Economy (C&SE), Co-Creation and Sharing of Knowledge (C&SK), and Responsible Governance (RG).

with Farm-CAET scores than with CAET or social-CAET values, highlighting farm-CAET as a potentially more sensitive indicator of ecological performance related to soil quality across farm types.

4 Discussion

This study validates the use of two classification methods for typology identification based on data from characterization of agroecological transition (Step 1 of TAPE) and reveals that both methods are similarly useful to capture the diversity of agroecological transitions in the region. The study also contributes to the understanding of farming systems in Northern

Patagonia revealing a diverse and complex socio-ecological system, where multiple pathways to socially and ecologically sustainable food and agricultural production coexist.

4.1 Agricultural systems in the Andean Region of the *Comarca Andina del Paralelo 42*

Overall, the CAP42 exhibited a relatively advanced degree of transition towards agroecology compared with other regions in Argentina (Lucantoni et al., 2022a; Sokolowski et al., 2023), and even with other areas of Northern Patagonia beyond CAP42

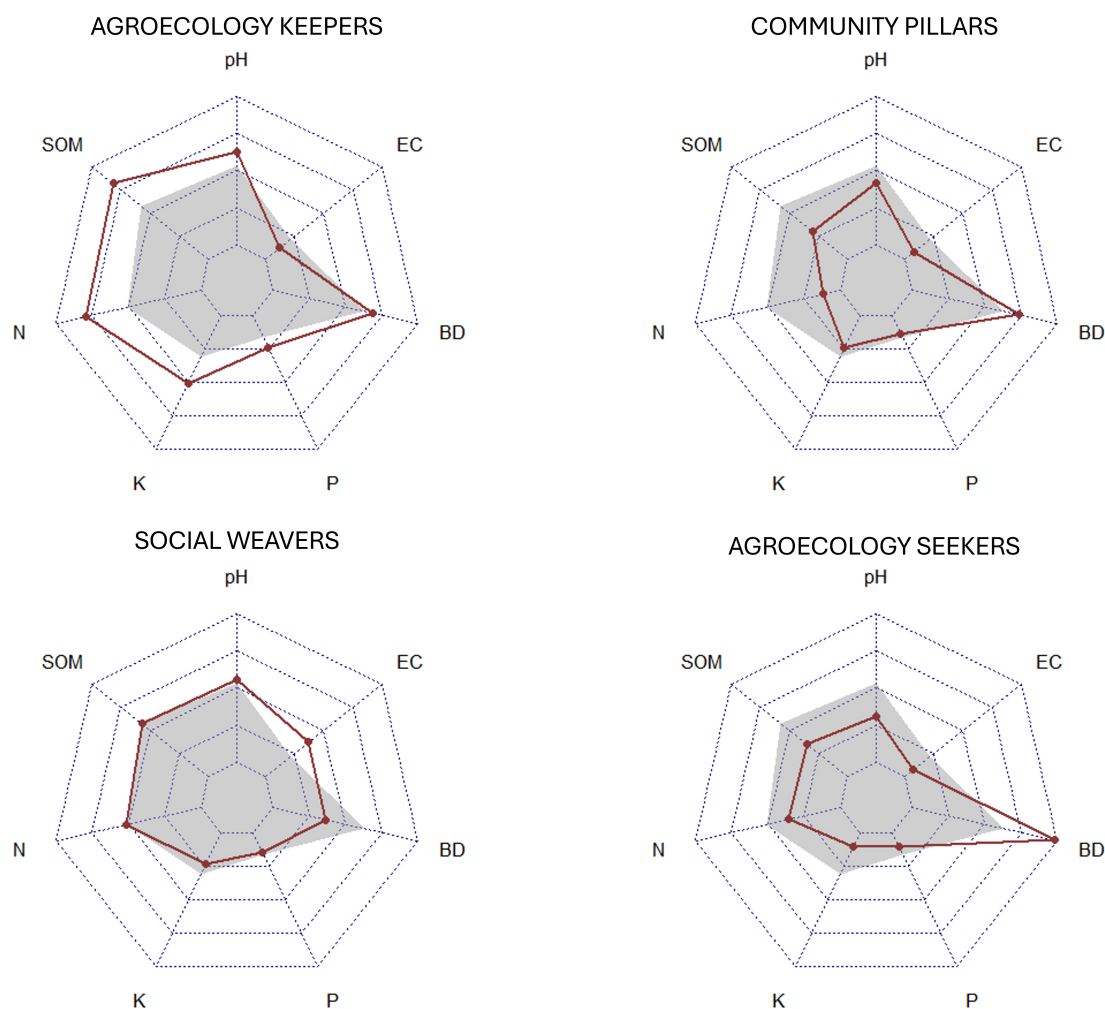


FIGURE 8

Differences in soil properties between farm types. Grey polygons represent the overall mean values across the complete dataset, while colored polygons indicate the average values for each farm type. Soil organic matter (SOM), pH, electrical conductivity (EC), bulk density (BD), phosphorus (P), potassium (K), and nitrogen (N).

(Álvarez et al., 2019; Hara et al., 2019). For instance, Lucantoni et al. (2022a) reported an average CAET value of 49% for the Rosario Metropolitan Area, which is considerably lower than the 66% observed in CAP42. Regarding horticultural systems, the contrast is even more pronounced when compared with the 46% CAET value reported by Sokolowski et al. (2023) in the Florencio Varela green belt. Notably, the exclusively horticultural systems within CAP42 recorded CAET values close to 70% (cf. Figure 3). Such differences may be partially attributed to the productive diversification found in CAP42 systems, the influence of indigenous and peasant heritage, and traditional management practices that align closely with agroecological principles. Additionally, the region is characterized by high levels of natural biodiversity. These factors stand in contrast with the metropolitan green belts of Buenos Aires and Rosario, which have been shaped by decades of intensive production and are embedded within urban areas that collectively accommodate nearly 34% of Argentina's population (Instituto Nacional de Estadística y Censos, 2023). At the global level, CAP42 also ranks among the sites with the most

advanced agroecological transitions, based on comparisons with other TAPE-assessed regions. For example, average CAET values reported in several studies are considerably lower: 40% in Benin and Burkina Faso (Tapsoba et al., 2023), 38% in Côte d'Ivoire (Dosso et al., 2024), and 37% in the Netherlands (Verkuil et al., 2024). Even in countries with more established agroecological movements, such as Colombia and Portugal, reported averages range from 48% to 58% (Barrios Latorre et al., 2023; Horstink et al., 2023). Only a few sites, such as Nicaragua (73%; El Mujtar et al., 2023) and France (69%; Anthonioz, 2022), have shown comparably high or higher levels of agroecological transition.

Typologies derived from the analysis (cf. Table 2, Table 3) suggest that the agroecological transition in CAP42 is primarily driven by improvements in the social and enabling environment, rather than by on-farm innovations. The "movement" dimension within the agroecology triad—science, practice, and movement (Wezel et al., 2009)—appears to play a central role in the region. This pattern is partly informed by the influence of countercultural movements, the cosmovision of *buen vivir* ('good living', a

worldview rooted in harmony with nature and collective well-being), and a view of agriculture as a lifestyle intimately connected to natural cycles (da Silva Araujo, 2021; James et al., 2023). Barrios et al. (2020) proposed that the consumer–market–health nexus, particularly embodied in the *Circular and Solidarity Economy* element, may represent a key entry point for agroecological transitions. Such transitions are often catalyzed by rising consumer demand for diverse, nutritious, and safer food. Meeting this demand typically requires a diversification of supply, supported by diversified farming systems that improve resource use efficiency while reducing dependency on external inputs.

An additional factor supporting this pathway in CAP42 is the prominent role of women as farm decision-makers, which was positively associated with higher degrees of agroecological transition (cf. Figure 2). This relationship was examined while considering several context variables, including production type, farm size, economic resources, geographical zone, production objectives, and the age and origin of the main decision-makers. However, other unmeasured factors, such as prior training or farming experience, educational level, or connectivity could also influence this pattern (Batas et al., 2025; Kanjanja et al., 2022). Globally, women have been widely recognized as leaders in agroecological initiatives (FAO, 2014; Seibert et al., 2010; Trevilla Espinal et al., 2021), often driven by the motivation to provide healthy, diverse, and culturally appropriate food for their families and communities, while preserving the ecological foundations of food systems (Gomori-Ruben and Reid, 2023; Laborda et al., 2019, 2023; Wells and Gradwell, 2001). In the case of CAP42, this pathway may be further reinforced by the importance of self-provisioning, where demand and supply frequently converge within the same household or individual. Taken together with the strong ties between farming families and actors from public institutions such as the National Institute of Agricultural Technology, the National University of Río Negro, and other civil society organizations, these findings suggest that CAP42 has the potential to function as an *agroecological living laboratory*—that is, “an open innovation ecosystem centered on farmers, based on a systematic approach to co-creating agroecological innovation in real-life contexts” (Kiseleva, 2021; Lucchesi, 2019; Trivellas et al., 2023). Further insight into the diversity of pathways is provided by the identification of four distinct archetypes/groups. These types reflect heterogeneous configurations of agroecological attributes and reveal different opportunities and constraints along the transition continuum. *Agroecology Keepers* represent farms with a balanced integration of agroecological principles, combining sustainable production with strong social values and community engagement. They exemplify mature systems and serve as reference points for transition. In contrast, *Community Pillars* display high scores in social and institutional dimensions—particularly in *Co-creation and Sharing of Knowledge* and *Responsible Governance*. However, lag behind in the adoption of agroecological practices at the farm level. Their strength lies in human and organizational capital, which may provide a foundation for future productive transformation. *Social Weavers*, meanwhile, are characterized by partial and unbalanced implementation of agroecological

principles, with relatively greater progress in social aspects than in ecological management. These farms show potential for further development, contingent on targeted support. Finally, *Agroecology Seekers* are at the early stages of the transition, with limited application of agroecological practices and the lowest overall scores. While they show interest in transformation, they require continued accompaniment and integration into agroecological learning and support networks.

Taking together, these narrative types offer a more nuanced and actionable understanding of the transition process. They also underscore the importance of context-sensitive policies that are tailored to the specific configurations and capacities of each group (Mier y Terán Giménez Cacho et al., 2018). For instance, *Agroecology Keepers* may benefit from mechanisms that stabilize long-term sustainability and foster knowledge exchange (Rosset and Altieri, 2017; Utter et al., 2021). *Community Pillars* would require support to strengthen their productive base and consolidate agroecological practices (Ernesto Méndez et al., 2013). *Social Weavers* may benefit from targeted extension and infrastructure to bridge ecological management gaps (Wezel et al., 2009). *Agroecology Seekers*, finally, need low-barrier entry points and structured support to initiate and sustain the transition process (Tittonell, 2014, 2019). Understanding and addressing these differentiated needs can enhance the effectiveness of agroecological transitions across the region and support the construction of more resilient food systems (Anderson et al., 2020; Tittonell, 2023).

The typology also proved informative in interpreting biophysical outcomes associated with different transition pathways. Differences in soil properties across the identified farm types aligned closely with the Farm–CAET scores (*Agroecology Keepers*: 75%; *Community Pillars*: 59%; *Social Weavers*: 65%; *Agroecology Seekers*: 57%, cf. Figure 8), suggesting that this indicator may better reflect ecological performance than the CAET or the Social–CAET. This alignment is expected, as the Farm–CAET explicitly incorporates the elements related to management practices—i.e., *Diversity*, *Resilience*, *Synergies*, *Efficiency*, and *Recycling*—which directly influence soil quality and ecological outcomes (Mottet et al., 2020; Wezel et al., 2020). *Agroecology Keepers* exhibited the most favorable soil conditions, with above-average levels of soil organic matter, nitrogen, potassium, and phosphorus—nutrients typically enhanced by diversified crop-livestock systems, organic amendments, and reduced tillage—(Krauss et al., 2020; Sekaran et al., 2021). Their relatively neutral pH and moderate bulk density further support the presence of active soil conservation measures. In contrast, *Agroecology Seekers* showed signs of pronounced degradation, with the lowest values of key physicochemical indicators and the highest bulk density, pointing to nutrient depletion and compaction potentially linked to extractive soil management, insufficient ground cover, or high animal stocking rates (Bashagaluke et al., 2018; Batey, 2009; Futa et al., 2024). *Community Pillars* also scored poorly in terms of soil organic matter and nitrogen, but their slightly better nutrient availability and lower compaction suggest transitional practices or external constraints limiting system

improvement. *Social Weavers* presented intermediate conditions, with physicochemical indicators near the dataset average but the lowest bulk density and highest electrical conductivity—possibly reflecting localized organic inputs, green manures, or site-specific salinity— (Angelova et al., 2013; Masto et al., 2008). These patterns underscore how agroecological performance, particularly regarding soil quality, can diverge across transition pathways and highlight the relevance of farm-level assessment tools in revealing such differences. While preliminary, these findings are consistent with previous studies suggesting that the adoption of agroecological practices can contribute positively to key indicators of soil health (Reganold and Wachter, 2016; Sokolowski et al., 2023). Nevertheless, due to the limited number of farms with available soil data, these findings should be interpreted with caution. The patterns observed here are indicative rather than conclusive and should be viewed as a first step towards understanding soil–typology linkages across the CAP42. Further research with broader and more systematic soil sampling is required to confirm and refine these preliminary trends.

4.2 Methodological considerations: archetypes vs. Reinert's classification

Classifying the diversity of rural households in terms of their stage in agroecological transitions and their structural-functional traits requires analytical methods capable of accurately reflecting such heterogeneity. In this study, based on results from agroecological transition assessment (Step 1 of TAPE), two approaches were compared: Archetypal Analysis and Reinert's descending hierarchical classification. These methods differ fundamentally in their treatment of data. Archetypal analysis retains continuous variables and captures multivariate relationships without predefined groupings (Cutler and Breiman, 1993), whereas the Reinert's method work with categorical forms and uses co-occurrence and frequency to identify classes (Reinert, 1983), requiring in the case of Step 1 of TAPE moving from quantitative numerical data to categorical data. Archetypal Analysis offers a valuable approach for capturing the complexity of agroecological systems, as it enables the exploration of gradients and hybrid configurations of transition. By identifying subtle patterns and intra-group variation, it provides a nuanced understanding of multidimensional datasets. However, this method may be more sensitive to measurement error and requires careful interpretation. In contrast, Reinert's classification offers more easily interpretable classes with lower sensitivity to noise, making it suitable for exploratory or policy-oriented analyses, though potentially at the expense of detail and flexibility in high-dimensional contexts.

In the application of TAPE, both methods yielded coherent and meaningful typologies, each reflecting distinct configurations of the Elements of Agroecology across CAP42 farming systems (cf. Table 2). The selection of one method should therefore depend on the specific aims of the study and the nature and complexity of the available data. Archetypal analysis is particularly advantageous

in academic or research contexts, where the aim is to explore variation within archetypes and investigate transition pathways in depth. In contrast, Reinert's classification method may be preferred in policy or applied contexts, where clear, operational categories are needed for communication, reporting, or comparative assessments. Despite the presence of farms occupying intermediate positions between archetypes, Archetypal Analysis proved robust in capturing the structural and functional diversity within CAP42. Rather than limiting its utility, this finding underscores the potential of hybrid classification approaches or modifications to the original method—such as archetypoid analysis—to accommodate transitional or ambiguous cases more effectively (Epifanio, 2016; Vinué et al., 2015).

5 Conclusions

This study advances methodological approaches for characterizing farming systems undergoing agroecological transitions and demonstrates the value of typological methods for informing both research and practice in agroecology. The findings underscore the importance of balancing analytical depth with clarity of interpretation when working with complex, multidimensional data. Key insights include:

- The agroecological transition in CAP42 is primarily socially driven, underscored by enabling territorial environments, institutional support, collective action, strong social organization, gender-inclusive governance, and dense networks of knowledge exchange, complemented by diversified, low-input farming practices.
- Both Archetypal Analysis and Reinert's classification effectively captured meaningful and comparable farm types based on the configuration of Agroecology Elements.
- The resulting typology—including *Agroecology Keepers*, *Community Pillars*, *Social Weavers*, and *Agroecology Seekers*—reflects the multidimensional character of agroecological transitions and provides a practical basis for guiding context-specific support strategies.

This work strengthens the empirical basis for agroecological research by providing a replicable framework for typology construction, while also deepening our understanding of the territorial dynamics that sustain agroecological transformations. These findings emphasize that agroecological performance arises not only from biophysical or management innovations but also from collective capacities and social relations that shape transition trajectories and resilience.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

VÁ: Data curation, Software, Conceptualization, Visualization, Writing – original draft, Writing – review & editing, Investigation, Methodology, Formal analysis, Resources. VE: Funding acquisition, Supervision, Writing – review & editing, Investigation, Resources, Conceptualization, Methodology, Project administration. AC: Resources, Methodology, Writing – review & editing, Investigation. LS: Resources, Investigation, Writing – review & editing. LH: Investigation, Resources, Writing – review & editing. EC: Investigation, Writing – review & editing, Resources. PT: Funding acquisition, Methodology, Supervision, Writing – review & editing, Project administration, Conceptualization.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2025.1657083/full#supplementary-material>

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