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Spatiotemporal Patterns and Drivers of Agroecosystem Change in Camargo, Bolivia

Patrones espaciotemporales y factores que impulsan el cambio en los agroecosistemas de Camargo, Bolivia

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Abstract

This study analyzed the long-term spatiotemporal trajectories of agroecosystems in the municipality of Camargo, Bolivia, from 1985 to 2024. The study area was stratified into two elevation zones: the Lowland Zone (LZ; 2,258–3,205 m a.s.l.) and the Highland Zone (HZ; 3,205-4,742 m a.s.l.). We integrate field assessments of 100 agroecosystems (50 per zone) and interviews with 15 key informants with high-resolution Airbus satellite imagery. We calculated landscape metrics at the class level using FRAGSTATS v4.2 with a minimum mapping unit (MMU) of 0.09 ha to evaluate processes of expansion, fragmentation, shape complexity, and edge effects through five metrics: total area (TA), number of patches (NP), mean patch size (MPS), mean shape index (MSI), and total edge (TE). Factors associated with agroecosystem persistence or transformation, were determined using descriptive statistics, Fisher's exact test, Haldane-Anscombe-corrected relative risk, and the Relative Importance Index (RII). The results indicate active spatiotemporal dynamics across the landscape. However, agroecosystem persistence was predominantly concentrated in the LZ compared to the HZ (100% vs. 58%, $p < 0.01$). Key drivers of this persistent dynamic include continuous water availability, thermal stability, favorable edaphic conditions, and effective generational succession. Persistence is observed primarily in the ZB, in contrast to the ZA. The factors that may drive these dynamics include permanent water availability, thermal stability, edaphic conditions, and effective generational turnover. These findings provide an empirical basis to guide land-use planning policies and sustainable agricultural management strategies in inter-Andean dry valleys.

Keywords: remote sensing; multitemporal analysis; persistence and transition; agricultural frontier; inter-Andean dry valleys.

Resumen

En el presente estudio, se analizaron las trayectorias de los agroecosistemas en el municipio de Camargo entre 1985 y 2024. El área de estudio fue subdividido en dos zonas: Zona Baja (ZB) (2.258-3.205 m s.n.m.) y Zona Alta (ZA) (3.205-4.742 m s.n.m.). Se integraron evaluaciones de campo de 100 agroecosistemas (50 por zona) y entrevistas a 15 informantes clave con imágenes satelitales multitemporales (incluyendo imágenes de alta resolución de Airbus). Se evaluaron a nivel de clase los procesos de expansión, fragmentación, geometría y efecto de borde de los agroecosistemas, utilizando cinco métricas: Área Total (TA,), número de parches (NP), Tamaño medio de parche (MPS), índice medio de forma (MSI) y borde total (TE). Los factores asociados, la permanencia o transición de los agroecosistemas entre 1985 y 2024 se determinaron mediante estadística descriptiva, el test de Fisher, el riesgo relativo corregido por Haldane-Anscombe y el Índice de Importancia Relativa (IIR). Los resultados sugieren que los agroecosistemas presentan una dinámica espacio-temporal activa. La persistencia se observa principalmente en la ZB, a diferencia de la ZA (100% y 58% respectivamente, $p < 0.01$). Los factores que posiblemente impulsan esta dinámica son la disponibilidad hídrica permanente, la estabilidad térmica, las condiciones edáficas y un recambio generacional efectivo. Estos hallazgos aportan una base empírica para orientar políticas de ordenamiento territorial y estrategias de manejo agrícola sostenible en los valles secos interandinos.

Palabras clave: teledetección; análisis multitemporal; persistencia y transición; frontera agrícola; valles secos interandinos.

Introduction

The interandine dry valleys harbor some of the most unique agricultural landscapes in the Andes, characterized by high biodiversity (**López, 2003a, 2003b; Larrea-Alcázar & López, 2005**), pronounced environmental heterogeneity (**Thomas et al., 2010**), and a long history of human occupation and agricultural use (**Rodríguez-Echeverry, 2023**). However, land use transformation and increased environmental pressures are significantly altering the structure and functionality of these territories (**Polo-Murcia et al., 2026**).

From a socioecological perspective, agroecosystems are systems of agricultural production in which ecological, productive, economic, and cultural processes interact, influencing their functioning and persistence over time (**Adams et al., 2025**). In this context, sustainability does not depend solely on productivity, but also on the conservation of natural resources, the maintenance of essential ecological functions, and the ability to adapt to environmental and socio-economic disturbances (**Candelario-Rosales et al., 2025**). Additionally, the spatial configuration of the landscape influences the resilience of agroecosystems by affecting ecological connectivity, resource flow, and the capacity to respond to external changes (**León-Sicard et al., 2018**). The expansion of the productive frontier can increase pressure on natural ecosystems and reduce landscape connectivity, while fragmentation alters key ecological processes and increases the isolation of remaining patches of vegetation (**Velasco-Aceves et al., 2021**).

At the same time, numerous agroecosystems are facing processes of agricultural abandonment, which are often associated with biophysical limitations (**Levers et al., 2018; Kabadayı et al., 2022**). This abandonment, beyond its economic implications, reflects profound historical and cultural transformations in the relationship between communities and their territories, affecting the transmission of knowledge and the continuity of traditional productive practices (**Scamardì, 2020; Fagundes & Arcuri, 2023**). To analyse these dynamics, it is essential to employ approaches that explicitly integrate the spatial and temporal dimensions of landscape change (**Levers et al., 2018**). Additionally, considering biophysical variables, accessibility conditions, and the perceptions of producers enables a better understanding of the mechanisms that explain the vulnerability of agroecosystems (**Kabadayı et al., 2022; Fagundes & Arcuri, 2023**). This approach is particularly relevant in semi-arid regions, where small environmental or socio-economic variations can lead to significant changes in the occupation and use of agro-ecosystems (**Quichimbo et al., 2025**).

In Bolivia, the expansion of extractive activities has generated conflicts related to access to resources and territorial decision-making (**Hinojosa et al., 2015; Radhuber et al., 2021**). In arid ecosystems, losses of forest cover and fragmentation have been documented, so it is important to evaluate the amount of remaining vegetation and its spatial configuration to understand the changes in the landscape and their effects on connectivity and biodiversity (**Turner & Davidson-Hunt, 2016; Rogan & Lacher, 2026**). However, these trends have been little studied in dry valleys.

Furthermore, agricultural land abandonment, driven by factors such as rural out-migration, urbanization, economic pressures, and biophysical terrain traits (**Kabadayı et al., 2022; Levers et al., 2018**), can also reflect broader historical and cultural transformations (**Fagundes & Arcuri, 2023; Scamardì, 2020**). In Chuquisaca, land degradation across Andean valleys has been attributed to both inherent landscape fragility and the diversification of rural livelihood activities (**Preston, 2008; Scamardì, 2020**). Consequently, assessing land expansion, fragmentation, and abandonment across the dry valleys of Bolivia, and specifically within Camargo, requires disentangling documented regional paradigms from locally observed empirical dynamics through the integrated analysis of satellite imagery, landscape metrics, and socioecological data (**Velasco-Aceves et al., 2021**).

In this context, the present study examines the spatiotemporal trajectories of traditional agroecosystems in the municipality of Camargo, Bolivia, between 1985 and 2024. Specifically, it addresses three research questions: (i) How have the extent and spatial structure of agroecosystems varied over the last four decades? (ii) What patterns of persistence, expansion and transition are observed along the altitudinal gradient of the territory? and (iii) What are the main biophysical and sociocultural factors that explain the persistence of these traditional agricultural systems? Thus, the study aims to provide scientific evidence to understand the mechanisms that explain the persistence of traditional agroecosystems in semi-arid Andean environments and contribute to the design of sustainable development strategies in the interandine dry valleys.

Materials and Methods

Study area

The study was conducted in the municipality of Camargo, located in the department of Chuquisaca in the dry interandine valleys of southern Bolivia (**Figure 1A, 1B, 1C**), at coordinates 20°31' S, 65°0' W. The climate is semi-arid, with an average annual temperature of 18 °C and an average annual precipitation of 300 mm, concentrated mainly between November and March (**Oller et al., 2022**). The predominant edaphic texture is loamy clay, with an average pH value of 7.3 and an organic matter (OM) content of 2.1% (**Molina Antelo et al., 2011**). Among the most representative production systems, grapevine (*Vitis vinifera*) and peach (*Prunus persica*) agroecosystems are particularly prominent (**Figures 1D, E**).

Grapevine is widely utilized for the production of wine, Singani, and other derived products, thereby contributing to regional economies and landscape preservation (**Fortes & Pais, 2015; Wang et al., 2021**). Complementarily, peach cultivation constitutes a major source of income for rural households, offering opportunities for both fresh consumption and agro-industrial processing (**Reig et al., 2025; Huang et al., 2024**). Together, both crops are integrated into agricultural systems adapted to Andean environmental conditions, playing a key role in preserving the productive and cultural heritage of these valleys (**Nissen, 2014**).

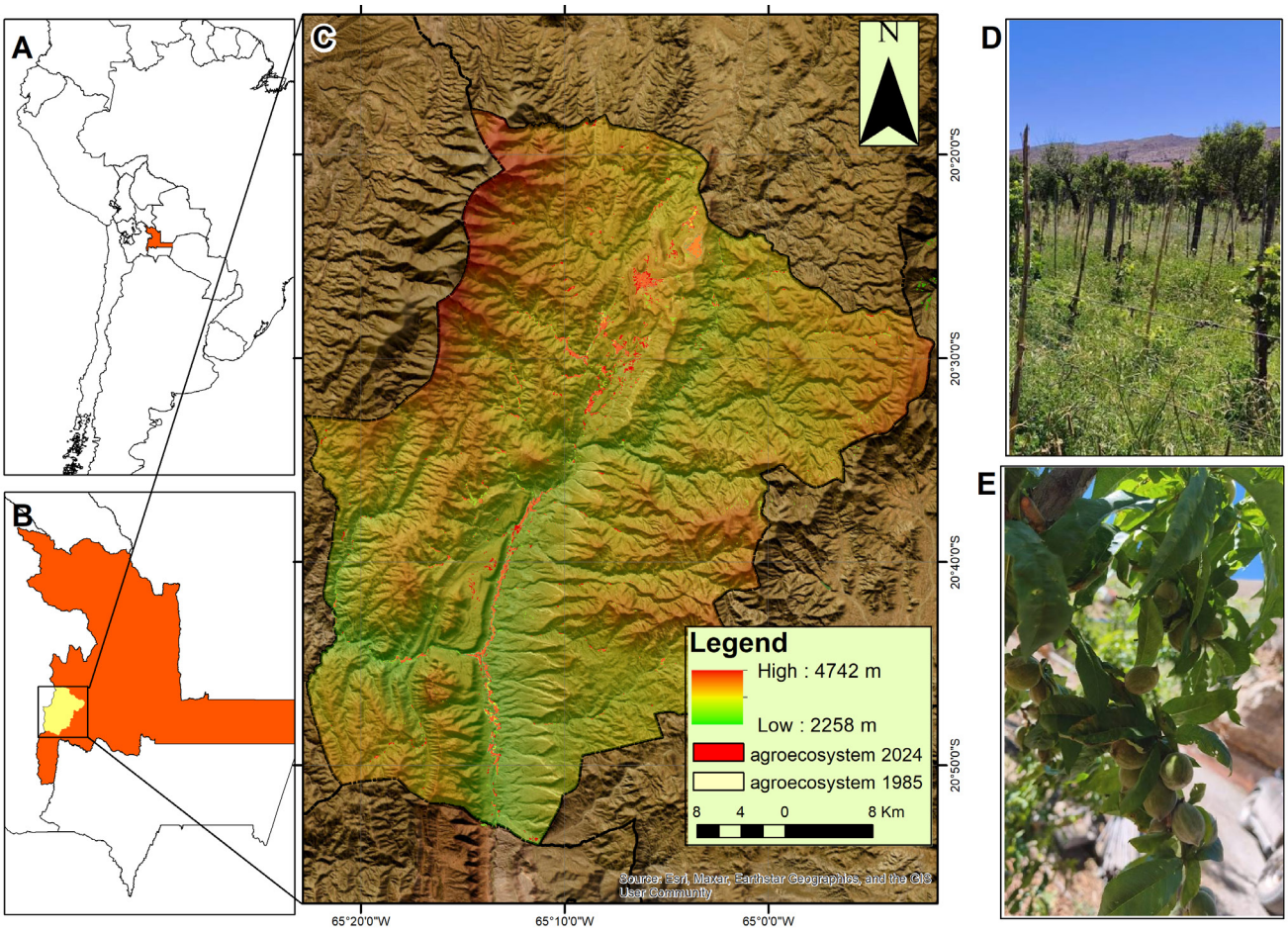


Figure 1. Geographical location and physiographic characterization of the study area. (**A**) Location of Bolivia in South America. (B) Location of the municipality of Camargo within the Department of Chuquisaca (highlighted in yellow). (**C**) Digital Elevation Model (ASTER GDEM, https://search.earthdata.nasa.gov/search/) with a yellow-to-red color gradient indicating the Highland Zone (HZ) and a light-to-dark green gradient indicating the Lowland Zone (LZ), overlaid with the spatial distribution of agroecosystems identified in 2024 (red markers). (**D**) Vineyard in the community of Vivicha located in LZ. (**E**) Peach production (*Prunus persica*) in the community of Malcastaca located in HZ, Camargo.

Spatiotemporal analysis of agroecosystems

Agroecosystems were delineated using the land use and land cover (LULC) dataset from MapBiomas Bolivia (**Collection 4; https://bolivia.mapbiomas.org/**), accessed between July and September 2026. The thematic class Agriculture (Pixel ID: 18), representing areas managed for crop production, was selected as the most suitable proxy to evaluate municipal-scale spatial dynamics for 1985 and 2024. Raster layers were clipped to the administrative boundaries of the Camargo municipality and processed in ArcGIS 10.4 (**https://desktop.arcgis.com/**) to map agroecosystems for both years. From these layers, total agricultural area and both absolute and relative changes between periods were quantified.

Given that the 30-m spatial resolution of MapBiomas provides a generalized classification of croplands, an analytical sample of 100 agroecosystem patches was evaluated for 2024: 10 were validated in the field and 90 were verified using Airbus Very High Resolution (VHR) satellite imagery. The accuracy of the MapBiomas dataset is documented as "Good" according to its methodological report (ATBD; **https://bolivia.mapbiomas.org/downloads/documentos-descriptivos-del-metodo-atbd/**). The stratification into the Lowland Zone (LZ; 2,258-3,205 m a.s.l.) and the Highland Zone (HZ; 3,205-4,742 m a.s.l.) was established based on morphological and thermal criteria across the altitudinal gradient of the study area. The LZ encompasses alluvial valley-bottom soils with continuous water availability for regular irrigation and grapevine cultivation, whereas the HZ corresponds to rainfed agricultural systems located on mountain slopes.

Table 1. Landscape structure metrics, adapted from Barwicka & Milecka (2021)

Metric	Abbreviation	Ecological Interpretation
Total Area	TA	Total surface area occupied by fruit agroecosystems.
Number of Patches	NP	Total number of discrete spatial units.
Mean Patch Size	MPS	Average surface area of each mapped spatial unit.
Mean Shape Index	MSI	Geometric complexity of patch boundaries.
Total Edge	TE	Cumulative length of patch edges (boundaries).

Landscape configuration metrics

Landscape structure and spatial configuration were quantified at the class level using FRAGSTATS v4.2 (**McGarigal, 1995**) by delineating individual patches. Landscape metrics were selected to evaluate processes of expansion, fragmentation, shape geometry, and edge effects (**Table 1**). Metrics were calculated for each year (1985 and 2024) using an 8-neighbor connectivity rule. The minimum mapping unit (MMU) was set to 1 pixel (0.09 ha), and no artificial edge depths were specified.

Análisis de persistencia temporal de los agroecosistemas

A total of 100 randomly selected agroecosystems were evaluated—equally distributed as 50 plots in the LZ and 50 in the HZ, using an integrated approach combining descriptive statistics and Shannon entropy (H′) quantification (Rioul, 2021), as expressed in Equation 1:

$$H' = -\sum_{i=1} p_i \log_2(p_i) \quad (1)$$

Where (pi) represents the proportion of plots in each persistence state (i) within its respective territorial unit. Entropy was expressed in bits and interpreted based on the balance between both states: values approaching zero indicate the dominance of a single trajectory, whereas values near one bit represent a balanced distribution between persistence and transition. Consequently, the index was utilized as a measure of state diversity and compositional uncertainty, without assuming that it directly reflects spatial fragmentation.

Association between elevational gradient and temporal trajectories

Temporal trajectories were binary-coded as 0 for state persistence and 1 for transition or change between 1985 and 2024. Trajectory distributions were summarized using absolute frequencies and percentages calculated within each physiographic zone. The association between zone and transition occurrence was evaluated using a two-tailed Fisher's exact test based on a 2x2 contingency table. This test was selected due to a cell with an observed frequency of zero, corresponding to the absence of transitions in the Lowland Zone (LZ). The significance level was set at α = 0,05 and interpreted in conjunction with the observed differences in persistence and transition proportions.

Relative risk estimation

The magnitude of the association was quantified using the relative risk (RR), defined as the ratio of the transition probability in the Highland Zone (HZ) to that in the Lowland Zone (LZ). To obtain a finite estimate, the Haldane-Anscombe continuity correction was applied by adding 0.5 to each of the four cells of the contingency table. The corrected RR was calculated as the ratio of the transition proportions obtained after correction. Its 95% confidence interval (95%) was estimated using the log-Wald method, based on the approximate variance of the log-transformed corrected RR. This estimate was interpreted considering the zero-event frequency in the reference zone and the uncertainty arising from the applied correction.

Analysis of factors influencing agroecosystem persistence

A descriptive analysis of 100 agroecosystems was conducted, combining in situ field assessments (n = 10) and satellite evaluations (n = 90) using Airbus Very High-Resolution (VHR) imagery via Google Earth. Fifteen key informants, selected based on their track record, extensive experience, and in-depth knowledge of the study area, including local farmers and domain specialists, evaluated eight environmental and socioecological factors: elevation, slope, soil type, temperature, precipitation, permanent water availability, proximity to roads, and generational succession. Factors were descriptively ranked using the Relative Importance Index (RII), computed as the sum of scores assigned to each factor divided by the maximum possible score and multiplied by 100, following **Sourav et al. (2024)** as expressed in **Equation 2**.

$$IIR = \frac{\sum W}{A \times N} x100 \quad (2)$$

Where, RII Relative Importance Index; W represents the ordinal Likert score assigned to each factor by respondents, ranging from 1 (Very low importance) to 5 (Very high importance); A = 5 is the maximum possible score on the scale; and N = 100 is the total number of respondents. Factors were ranked in descending order based on their RII values. Non-parametric 95% confidence intervals (95%) were estimated using percentile bootstrap resampling with 5,000 replications. The Friedman test was used to assess differences among the eight factor scores, treating each agroecosystem as a repeated-measures unit. Kendall's coefficient of concordance (W) quantified rank differentiation. Interpretation required all factors to share a common, conceptually comparable scale. Additionally, scores were compared between persistent and transitional agroecosystems using the Mann–Whitney U test. P-values were adjusted using Holm's procedure to control the family-wise error rate. Statistical significance was set at $\alpha = 0.05$.

Statistical analysis

All statistical analyses were executed in Python using the pandas, NumPy, SciPy, statsmodels, and Matplotlib libraries within the Google Colab environment (**https://colab.research.google.com/**). Spatial processing and landscape metric calculations were conducted using ArcMap and FRAGSTATS v4.2 (**https://www.fragstats.org/**).

Results

Spatiotemporal dynamics of agroecosystems

Quantitative analysis of agroecosystems in Camargo (1985-2024) revealed descriptive shifts in the spatial extent and geometric configuration of the evaluated metrics (**Table 2**). In 1985, total area (TA) was 1,239.00 ha, distributed across 1,443 patches (NP), with a mean patch size (MPS) of 0.80 ha. By 2024, TA had increased to 2,478.00 ha, comprising 1,742 patches with an MPS of 1.42 ha. Based on the relative rates of change reported in **Table 2**, TA increased by 100.0%, NP grew by 20.7%, and MPS expanded by 77.5%. This spatial restructuring was further characterized by an increase in the Mean Shape Index (MSI, from 1.18 to 1.57; 33.1%) and a near-doubling of Total Edge (TE, from 28.00 km to 54.00 km; 92.9%).

Table 2. Agroecosystem landscape metrics across the study period (1985, 2024)

Landscape Metric	1985	2024	Absolute Change	Relative Change (%)
Total Area (TA, ha)	1,239	2,478	1,239	100
Number of Patches (NP)	1,443	1,742	299	20.7
Mean Patch Size (MPS, ha)	0.80	1.42	0.62	77.5
Mean Shape Index (MSI)	1.18	1.57	0.39	33.1
Total Edge (TE, km)	28.00	54.00	26.00	92.9

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Spatial contrast in agroecosystem persistence and transitions

The distribution of temporal trajectories revealed a marked spatial asymmetry between physiographic zones across the study area (**Table 3, Figure 2**). In the LZ, all 50 evaluated agroecosystems remained structurally unchanged over the 1985–2024 period, exhibiting 100% persistence and a 0% transition rate (**Figure 2A**). Conversely, in the HZ, 29 agroecosystems retained their initial state (58%), whereas 21 units underwent state transitions (42%; **Table 3**). At the municipal scale, persistence accounted for 79 agroecosystems out of the total evaluated sample (N = 100), compared to 21 units displaying structural shifts.

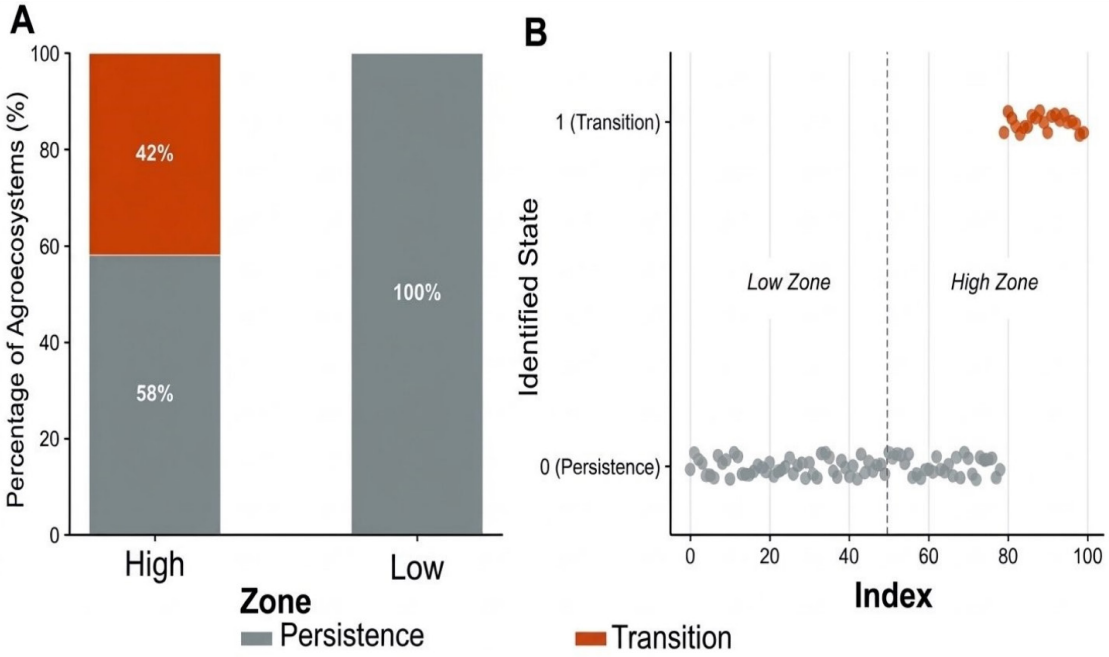


Figure 2. Distribution and frequencies of persistence and transition trajectories in the agroecosystems of Camargo (1985, 2024). **(A)** Relative proportion of stable (gray) and transitioning (orange) states across elevational zones. **(B)** Spatial dispersion of the sampled agroecosystems.

Table 3. Structural persistence and Shannon entropy of agroecosystems across physiographic zones in Camargo

Physiographic Zone	Sample Size (n)	Persistence Rate (%)	Transition Rate (%)	Shannon Entropy (H′, bits)	Structural Trajectory
Lowland Zone (LZ)	79	100.0%	0.0%	0.00	Consolidated / Stable
Highland Zone (HZ)	21	58.0%	42.0%	1.00	Dynamic / Transitional
Total / Overall	100	91.0%	9.0%	—	Mixed

Table 4. Descriptive ranking (RII, %), global Friedman test (Mean Rank) and bivariate Mann-Whitney U(Mann-Whitney) comparison between productive trajectories.

Evaluated Driver / Factor	Mean	SD	RII (%)	Friedman rank	U	p-value	r (rrb)
Permanent water availability	4.99	0.10	99.80	6.02	868.5	0.0560	-0.046
Temperature	4.98	0.14	99.60	5.98	808.0	0.4680	0.026
Soil type	4.98	0.14	99.60	5.98	857.5	0.3200	-0.034
Elevation	4.97	0.17	99.40	5.94	797.5	0.3680	0.039
Generational succession	4.97	0.17	99.40	5.94	847.0	0.6100	-0.021
Slope	4.01	0.10	80.20	2.59	839.5	0.6180	-0.012
Precipitation	3.99	0.10	79.80	2.54	818.5	0.6180	0.013
Road proximity	2.98	0.14	59.60	1.01	808.0	0.4680	0.026

Note: Factor, evaluated variable; Mean, mean score; SD (standard deviation); RII (Relative Importance Index, expressed as a percentage); Friedman rank (mean rank obtained from the Friedman test); U (Mann–Whitney U statistic); p (statistical significance level, unadjusted p-value); rrb (rank-biserial correlation coefficient, effect size).

Two-tailed Fisher's exact test confirmed a statistically significant association between physiographic zone and temporal trajectory ($p < 0.001$), quantifying the frequency distribution divergence between both strata (**Figure 2B**). Shannon entropy (H') analysis further quantified this spatial trajectory differentiation. In LZ, entropy was zero (H' = 0 bits) owing to the complete homogeneity of absolute state persistence. In HZ, entropy reached H' = 1.00 bit, reflecting maximum trajectory uncertainty and a nearly balanced distribution between persistence and transition (**Table 3**).

Drivers of agroecosystem persistence

Descriptive ranking of the eight evaluated factors across the sample of 100 agroecosystems placed permanent water availability (RII = 99.80%; 95% CI: 99.40-100.00%), temperature (RII = 99.60%), soil type (RII = 99.60%), elevation (RII = 99.40%), and generational succession (RII = 99.40%) within the dominant tier of highest perceived importance (**Table 4**). The non-parametric Friedman test confirmed highly significant overall differences among factor score distributions (χ_F^² (7)=672,45; p<0,001), supported by exceptionally strong inter-rater concordance (W = 0.961). Conversely, bivariate comparisons using the Mann-Whitney U test revealed no statistically significant differences between persistent (n = 79) and transitioning (n = 21) agroecosystems following Holm's adjustment for multiple comparisons (p_"Holm" >0,05 across all cases), yielding negligible effect sizes (|r_rb |<0,05).

Discussion

Spatiotemporal dynamics and landscape transformations (1985, 2024)

The increase in the Mean Shape Index (MSI) and Total Edge (TE) indicates growing geometric complexity in agroecosystem spatial configuration. Exhibiting dendritic expansion along irrigation canals and the valley floor, these agroecosystems display a spatial structure analogous to that documented by **Gavier-Pizarro et al. (2012)**. Furthermore, the higher proportion of transitions observed in the HZ relative to the LZ contrasts with the valley-bottom water deficit and thermal stress reported by de la **Riva et al. (2013)**. Nevertheless, the state transitions observed in HZ warrant future assessments of agricultural intensification and its potential impacts on environmental stability, a phenomenon also documented by **Oliveira et al. (2023)**.

Spatial and temporal trends (1985, 2024)

The LZ, exhibiting 100% persistence and zero Shannon entropy (H' = 0 bits), reflects a consolidated yet spatially saturated agricultural matrix. In contrast, the HZ displays higher entropy (H' = 1.00 bit) and a 42% transition rate. Furthermore, the contrast between persistence in LZ and active state transitions in HZ highlights the need to assess how agricultural decision-making is mediated by biophysical gradients and socioeconomic drivers (**Garcia et al., 2020**). From this socioecological perspective, the observed transformation patterns outline distinct trajectories of landscape change. As documented in mountain agro-pastoral systems, the absence of flexible local institutions adapted to elevational gradients accelerates soil degradation and exacerbates water vulnerability in transitional zones (**Wynants et al., 2019**). Integrating local knowledge into productive restructuring processes could enhance agrobiodiversity and ecosystem services, while informing differentiated land management strategies to sustain stability in LZ and address the observed transitions in HZ (**Puppo et al., 2023; Wynants et al., 2019**).

Drivers of agroecosystem dynamics

Permanent water availability, temperature, and edaphic properties within the dominant tier (RII > 99.5%) are likely linked to agroecosystem persistence, functioning as structural biophysical thresholds. Furthermore, the homogeneity observed via the Mann–Whitney U test between persistence (n = 79) and transition (n = 21) trajectories offers a fundamental theoretical insight into agrarian change processes. The absence of statistically significant differences ($p > 0.05$) indicates that factor scores did not diverge between persistent and transitioning agroecosystems within this sample. Specifically, trajectory comparisons detected no significant differences regarding permanent water scarcity (r= -0.046) or generational succession (r= -0.021), precluding a definitive conclusion on whether state transitions represent an adaptive response. Consequently, these findings cannot resolve whether shifts in management practices reflect an effort to mitigate local socio-environmental vulnerabilities or compromise long-term viability.

Conclusions

Between 1985 and 2024, spatial dynamics showed a substantial expansion of agroecosystems in Camargo, marked by a territorial contrast between spatial persistence in the LZ and active state transitions in the HZ. Key informants identified permanent water availability, temperature, soil properties, and generational succession as dominant drivers of highest perceived importance. However, factor score distributions did not differ significantly between persistent and transitioning agroecosystems ($p > 0.05$), precluding a definitive conclusion on whether these transitions represent a cultural disruption or an adaptive response designed to mitigate socio-environmental vulnerabilities and preserve rural habitability. Future research should integrate advanced biophysical analyses across denser multi-temporal series to better resolve long-term trajectory shifts. Employing high-resolution multispectral sensors and expanding the ecohydrological characterization of key environmental drivers will be essential to fully elucidate the mechanisms governing agroecosystem persistence and transition across elevational gradients.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

RL: Formal analysis, data curation, and fieldwork. EPR: Writing, review & editing, and fieldwork. MSP: Writing , review & editing. And all authors have read and agreed to the published version of the manuscript.

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