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Functional responses and adaptation strategies of pastoral households to drought and volcanic ashfall in Northern Patagonia

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ABSTRACT

Livestock is the main source of food and income, as well as a key socio-cultural asset for pastoralist households in arid and marginalized environments. Pastoral households in the drylands of Northern Patagonia in Argentina have faced repeated droughts over the past two decades and a large volcanic ashfall in 2011 that halved their livestock herds. While most households were severely affected by these events, some were able to withstand or recover over time while others suffered prolonged stress or even out-migrated. Through in-depth interviews with 33 pastoral households in Pilcaniyeu (Río Negro Province), we investigated the factors that shaped their functional responses and adaptive strategies in the face of these shocks, under the lenses of ethnobiology and systemic resilience theories. We assessed livelihood decisions, social interactions and changes in household assets before the ashfall (2011), during the six months following it, and eight years later (2019), and identified four structural and four functional responses archetypes (Anticipatory, Reactive, Conservative and Passive) and their adaptation strategies (Tolerance, Resistance, Avoidance, Diversification and Transformation). Household structural characteristics were less instrumental at determining the adaptive responses observed in the community than their ethnobiological and biocultural characteristics. Household responses were enabled by assets, local knowledge and social capital, mediated by individual motivation, collective agency and culturally situated values. Our findings further highlight that in such marginalized environments access to telecommunication or road connectivity are critical at enabling a range of functional responses and adaptive strategies, especially when they rely on collective action. Policies to support resilience of pastoral livelihoods should consider the diversity of strategies as identified here, prioritizing aids for households exhibiting passive responses while enhancing the adaptive potential of those already able to mobilize conservative, anticipatory and reactive strategies. Overall, this study contributes a novel, complementary methodology for understanding and categorizing household adaptation from an ethnobiological and biocultural perspective.

Keywords: Archetype analysis; Collective action; Connectivity; Kosmos–corpus–praxis; Dryland; Resilience.

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SIGNIFICANCE STATEMENT

This manuscript offers an original contribution to unravel endogenous socio-ecological resilience of pastoral peoples in arid environments by integrating knowledge on household characteristics, functional responses, and adaptive strategies through archetype analysis. Based on longitudinal qualitative data from pastoral households in Northern Patagonia, it captures how rural communities facing recurrent droughts and volcanic ashfalls learn and adapt over time. The research advances methodological innovation by applying archetype analysis to social-ecological systems, adding to the existing body of semi-quantitative methods in social science, and empirical significance by documenting adaptation processes in a remote, underrepresented dryland region. The findings highlight the central role of social networks, connectivity, and individual and collective agency in shaping adaptive responses beyond structural assets. By revealing the complexity and diversity of community responses in so-called "desert" landscapes, this work contributes to broader discussions on resilience, sustainability, and the co-production of knowledge for local and global adaptation strategies.

INTRODUCTION

The increasing frequency of adverse climatic conditions, coupled with other global change drivers, represents a threat to the persistence of dryland pastoral communities, their food security and livelihoods (*e.g.*, Dossouhoui et al. 2023 and Godde et al. 2019). The coping and adaptation strategies deployed by pastoral households rely on both social and ecological processes and may vary from small adjustments to their livelihood activities to thorough reconfiguration of their socio-ecosystems (Tittonell 2023). Certain strategies may also imply outmigration or further pressure on natural resources, with negative consequences for the long-term sustainability of pastoral livelihoods (Novotny et al. 2021).

Rural households in Northern Patagonia are no exception to this. Throughout their history, they have faced economic instability, an increase in the frequency and intensity of droughts, and recurring volcanic ashfalls. In the face of these adverse conditions, there has been a constant tension between abandoning the territory and the rural livelihoods, or persisting in it (Zubizarretta 2015). Understanding the diversity of adaptation strategies employed by pastoral households in the face of such adversities will contribute to guide development interventions and public policies to enhance their resilience in a targeted and locally relevant manner.

The study of rural livelihood strategies aims to understand agricultural dynamics and processes of change or transformation (*e.g.*, Jiao et al. 2017). This approach can be applied at different levels (regional, national, local or household) and has been addressed using different types of categorization methods, from the study of trajectories of change (*e.g.*, Scoones 1998; Dorward et al. 2009; Novotny et al. 2021) to the assessment of community strategies (*e.g.*, Acosta et al. 2021; Imperiale and Vanclay 2021). At community level, short term responses and long-term adaptation strategies differ across households, as influenced by their characteristics, history and context, and categorizing such diversity through household typologies has been the focus of several studies (Alvarez et al. 2018).

Most of the typologies proposed to categorize rural households are structural, considering their family structure and assets, often leaving out their functional aspects. Alternatively, the diversity of livelihood and adaptation strategies can be assessed through the delineation of functional typologies that allow categorizing households not only based on their structural characteristics (*e.g.*, size, resources, activities, etc.) but also according to their responses to adverse situations. Functional responses and adaptation strategies are shaped by local ethnobiological knowledge and biocultural heritage (Casas et al. 2015; Ferreira Júnior et al. 2015), as studied in the field of evolutionary ethnobiology (Santoro et al. 2018). One way to categorize the diversity of functional responses is through archetype analysis (*cf.* Sietz et al. 2017), a multivariate statistical method to identify and characterize archetypes or extreme points in a dataset, which may represent prominent behaviours among households (Tittonell et al. 2020). This methodology allows dealing with a combination of quantitative and qualitative variables, common in the construction of functional response typologies, whose variables generally arise from non-structured interviews with household and community members.

Evidence from Northern Patagonia already shows how the structural characteristics of rural households can influence their functional responses (*e.g.*, Hara et al. 2022; Laborda et al. 2024; Reising et al. 2022). Production diversification, associative action, and off-farm income diversification were identified as main strategies of rural households to deal with droughts (Easdale and Rosso 2010). The perception of droughts by rural actors and their palliative and adaptive strategies were also documented in the region (Solano-Hernandez et al. 2020), as were their persistence strategies and resistance to territorial expulsion, focusing on migrations, social organization and livelihoods (Bendini and Steimbreger 2013; Zu-

bizarreta 2015). In the last 20 years, pastoral households experienced a significant impact on their herds, which are their main production activity and source of food and income, with reductions in the order of 50% due to a major volcanic ashfall (*cf.* Figure 1 D) during a long-lasting drought (Laborda et al. 2024). Many families abandoned the land, while others remained in the area. Those who remained were households that exhibited resilient rural livelihoods, capable of facing adverse conditions through adaptation strategies Despite household functional responses and adaptation strategies being shaped by local knowledge, individual experiences and intangible biocultural assets, in other words, their *kosmos-corpus-praxis* (Toledo 2022), we hypothesise that there are recognisable patterns in such responses that can be categorised through a combination of (quali- and quantitative) methods. Here, we combined qualitative knowledge with the use of structural and functional archetype analyses to explore such patterns. The heuristic advantage of this approach resides in the identification of enabling conditions, behavioural and contextual patterns shaping responses beyond deterministic structure–function relationships, providing a more nuanced and process-oriented understanding of household adaptation strategies. A previous study in Northern Patagonia examined palliative measures of households facing environmental adversities without considering the reconversion or transformability of rural livelihood systems (Tittonell et al. 2020). They suggested a co-existence of adaptive strategies of 'Tolerance', 'Resistance', 'Avoidance', 'Diversification', and 'Transformation', analogous to ecological strategies of plant communities. Building on such initial findings, the present study relies on in-depth interviews to test the hypothesis of co-exiting strategies shaped by individual experience and local knowledge and their relationship with collective strategies ('Mutualism') based on reciprocity and associative action among individuals.

Pastoral livelihoods in Patagonia and other drylands worldwide are inextricably linked to rangeland biodiversity, and pastoralist ethnobiological knowledge and belief systems (*corpus* and *kosmos*) translates into a diversity of herding practices (*praxis*) that make use of rangeland heterogeneity. Here, however, we focus on how the *kosmos-corpus-praxis* complex shapes adaptation strategies through people's agency, and not on the specific role played by rangeland biological diversity. Through a longitudinal analysis of 33 households in two localities of Northern Patagonia at three specific moments — before the volcanic ashfall in 2011, in the six months following it, and in 2019 — we aimed to evaluate (i) whether household structural characteristics condition their functional responses to environmental adversities as postulated in previous studies, and (ii) whether the archetypal typologies of household functional responses (pattern) bear a relation to their adaptive strategies (process). To describe and analyse the strategies implemented by households, we first consider their social, human, natural, productive, and financial capitals. Then, we analyse the archetypal responses that emerged after the volcanic ashfall in 2011 and recurrent droughts and evaluate their relationship with household structural characteristics and associated adaptive strategies. The identified patterns were used to infer household adaptation strategies, contributing new evidence to ethnobiological debates on resilience and the role of local *kosmos-corpus-praxis* at shaping the persistence of the households under environmental stress.

MATERIAL AND METHODS

Study area

Pastoral livelihoods in Patagonia and other drylands worldwide are inextricably linked to rangeland biodiversity, and pastoralist ethnobiological knowledge and belief systems (*corpus* and *kosmos*) translates into a diversity of herding practices (*praxis*). The research was carried out in the dryland region of North Patagonia Argentina, known as Patagonian steppe ecoregion, in Pilcaniyeu department of Río Negro province as shown in the Figure 1 A and C. Pilcaniyeu covers an area of 10,545 km^2 with a population of 7,428 in 2010 and 9,373 in 2022 (INDEC 2023). The study region has a cold and arid climate with annual precipitation ranging from 452 mm in the west to 299 mm in the east, concentrated in fall and winter. The region is exposed to recurrent droughts (Solano-Hernandez et al. 2020) and, less frequently, volcanic ashfalls. These events, together with overgrazing, reinforce grassland degradation (López et al. 2013). Potable water, electricity and gas supplies are available to only some households. Roads are insufficient (Figure 1 E) and often interrupted due to snowfall and rainfall erosion. Telecommunication signals are scarce. Household's access to credit and financial resources and the possibility of developing off-farm and non-agricultural activities are limited, as well as their access to health and education services.

As documented in previous studies, the area is characterised by the presence of Mapuche Indigenous communities, as well as cooperatives focused on wool, seeds, forage, and crafts. Households participate in different local and regional fair markets, most of which are supported by public institutions (such as INTA at the national level, as well as provincial and municipal governments) through training, technical assistance in production, support for organizational processes, and the provision of municipal spaces for their operation

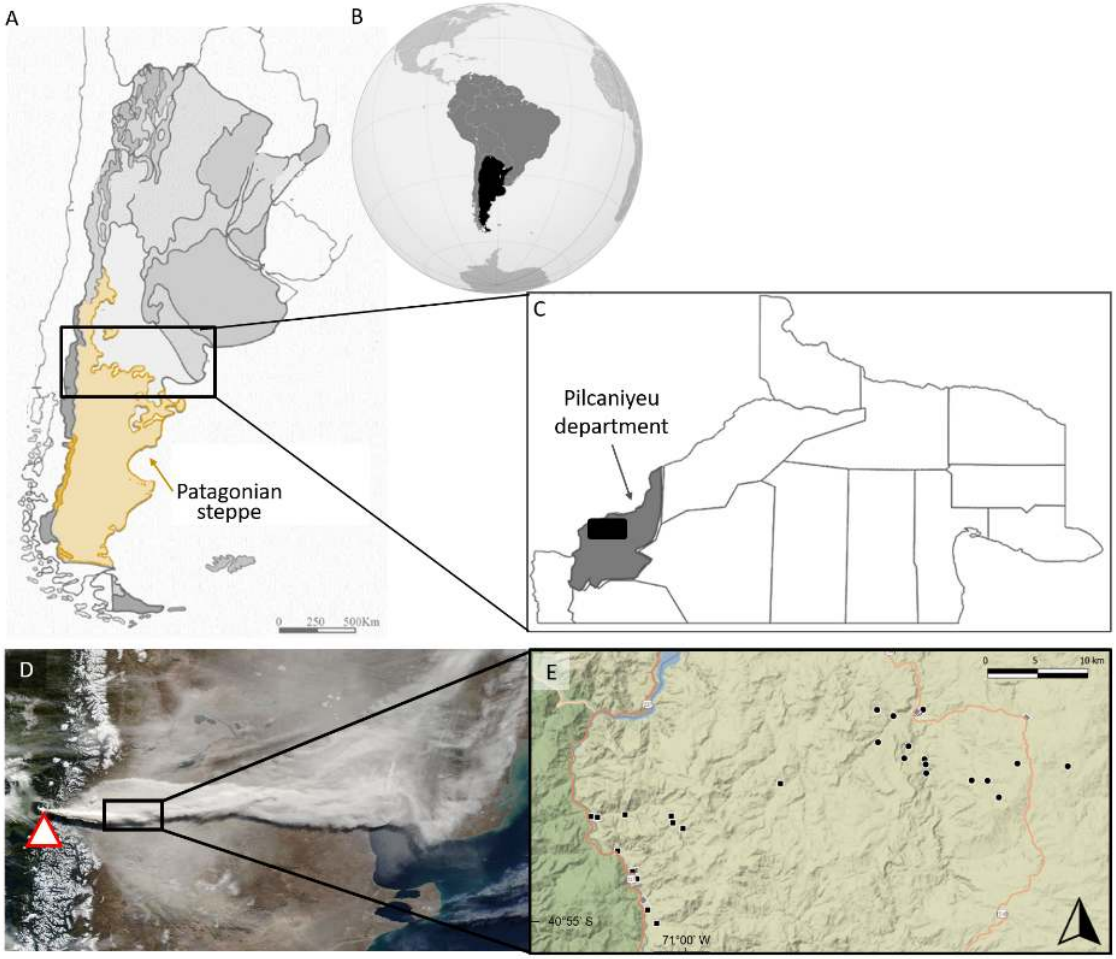


Figure 1. Location of the Patagonian steppe ecoregion (yellow area) in Argentina (A) and in the world (black area; B); the perimeter of the area shown in figure C is indicated by a black perimeter of a rectangle. The study area (solid black rectangle) is in the Pilcaniyeu department (grey area) of Río Negro province (C). The location of the Puyehue-Cordón Caulle volcano (red triangle) is marked, along with its volcanic ash plume, which appears as a whitish cloud extending eastward from the triangle. The black rectangle indicates the area shown in figure E (Image obtained on June 13, 2011 by NASA (2021); D). The study area displays the interviewed households (black dots), roads (orange lines), schools (grey dots), and the Limay River (light blue; E).

(Kropff et al. 2019; Longo Blason et al. 2024; Núñez and Conti 2015). This support was particularly strong in the years around 2011 (Grinberg 2014). In the study area – between 2011 and 2019 – there were two rural health posts and three schools (Figure 1 E). The presence of the Catholic Church and these public institutions has contributed to strengthening social organization, while kinship networks have often functioned as important support systems, transcending the geographical boundaries of individual communities. Sport fishing in the region's rivers and the relative proximity to mountain resorts create some opportunities for rural tourism activities (Laborda et al. 2024; Núñez and Conti 2015).

Pastoral households

Pastoral systems in the Río Negro province are predominantly sedentary, with 89% of households having defined boundaries (INDEC 2019). We define pastoral households as those that are closely linked to their land, traditions, and local culture, with landholdings ranging from 30 to 1,600 hectares. Most of their income-monetary or not-derives from livestock, and most production activities are carried out by household members and their relatives. It is common for members to temporarily or permanently migrate to neighbouring estates, rural towns, or cities, supplementing their income with off-farm work and accessing essential services such as healthcare and education (Bendini and Steimbreger 2013). In our study area,

rural households are classified as sedentary pastoral units (Tittonell et al. 2021).

Historical dispossession of pre-existing indigenous communities in the region has resulted in an asymmetric land tenure system, wherein most households lack formal title deeds and acquire land primarily through direct inheritance (Kropff et al. 2019). Livestock activities, primarily focused on wool production for the export market, are rooted in traditional practices and social networks but are also enhanced by the adoption of modern technologies (Hara et al. 2022; Reising et al. 2022). Non-agricultural ones complement these agricultural activities. Decision making around natural resources and livelihood activities are shaped by what Toledo and Barrera-Bassols (2008) described as *kosmos-corpus-praxis*. This framework posits that the body of knowledge (*corpus*) that household members possess regarding land management stems from their worldview, their system of beliefs, desires, and symbolic representations (*kosmos*) and the set of practices they implement (*praxis*) as illustrated in Figure 2. In this context, knowledge, practices, and products circulate within the system among households through processes of social reproduction and transmission.

Volcanic ashfalls

The eruption of the Puyehue Cordón-Caulle Volcanic Complex (40°58' S, 72°11' W) occurred over 10 days, starting on June 4, 2011. The eruption dispersed approximately 100 million tons of pyroclastic materials over Argentine Patagonia, affecting more than 24.4 million hectares with ash deposition reaching a thickness of 3–5 cm in the study area (Gaitán et al. 2011). An image of this event is shown in Figure 1 D. The event occurred without warning due to lack of a volcanic crisis management protocol. Ash pollution affected the availability of water sources for both human and animal consumption. Regarding the health of exposed people, it caused ocular and respiratory ailments, and symptoms of psychological stress such as anxiety and depression (Wilson et al. 2013). In animals, the ash caused dehydration, starvation, rumen obstruction and dental abrasion (Wilson et al. 2013).

Data collection

To identify prominent behaviours of farms, examining rural households' response to drought and volcanic ashfall, we conducted semi-structured interviews with the purpose of obtaining situated information. All interviews were conducted with prior, free, and informed consent of the interviewees, in accordance with the provisions of the Ethnobiological Ethics Code (ISE 2006). During the seasons of 2018 and 2019, we interviewed 33 rural households from Pilcaniyeu department.

The interviews were conducted following the snowball methodology, whereby one person is recommended by another beforehand (Albuquerque et al. 2010), based on an initial presentation made by local agricultural extension agents. The rural households selected for study were those composed of individuals who resided in the countryside for most of the year, where labour was predominantly family-based, as was the responsibility and control over agricultural activities. The unit of analysis used was the household, which integrates biophysical, social, cultural, and production information as illustrated in Figure 2. The coverage area was 500 km^2. We interviewed pastoral households that had experienced the 2011 ashfall event in the territory, excluding large farms. We interviewed approximately 66% of the households that met these criteria in the study area, totalling 84 permanent residents.

The average number of visits per household was 2.5 times, ranging from one to five visits per household. Each interview lasted a minimum of 2 hours, during which dialogues were held with household members involved in the topics of each interview, and in the company of other household members. Generally, in households with more than one person, responses were discussed and agreed upon among those present (from children to elderly adults). In cases where we observed that women were not given a voice by men, we aimed to direct questions to them as well and include them in the conversation to the extent possible. Participant observation was conducted, accompanying interviewed participants on their premises, assisting in tasks such as harvesting, cooking, tending to gardens, gathering firewood, and fetching water, among others.

Data handling and scoring

We characterized households in terms of resources and structural characteristics (land tenure, water source and availability, presence of wetlands, field size). We inquired about their production activities (number of livestock by species, farm animals, presence of orchards, fruit trees, production and/or use of forage), economy (types of on-farm and off-farm income) and household composition (number of permanent and sporadic members, migrations, age and gender of household members) before and after the volcanic ash fall in 2011, and during 2018/2019 (Additional File 1. We processed and interpreted the written records quantitatively and qualitatively, storing them in databases (database Laborda 2025).

Utilizing qualitative discourse analysis, we retrospectively converted the interview data into structural and functional variables associated with the livelihoods of the household units. In total, we identified

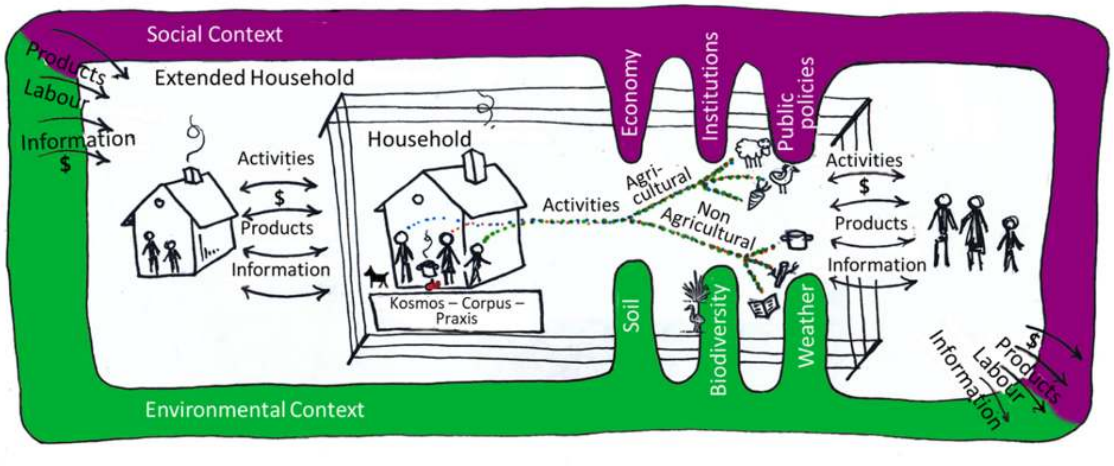


Figure 2. Diagram of the socio-ecological system of rural livelihoods, composed of the Household Unit (including the household members and their *kosmos-corpus-praxis*), a secondary residence (belonging to the household), and individuals who are not part of the household but participate in agricultural and social reproduction activities (usually relatives). Among them and within their context, money, products, information, and production and social reproduction activities flow. This system is embedded in and traversed spatially and temporally by a specific socio-environmental context. The environmental components (soil, biota, climate) are represented in green, while the social components (economy, institutions, public policies) are represented in violet.

31 variables, including 13 functional variables (depicting how households responded to the disturbance) and 18 structural variables (representing fixed or relatively stable attributes). Based on this, we built a structural and a functional data table. For each selected variable (quantitative and qualitative), we created ordinal classes, seeking to avoid or reduce atypical cases. We assigned between two and six classes to each variable (Additional File 1), assigning scores to each one starting from 0 onwards (whole numbers). Both databases were analysed using archetypal analysis.

To compare different livestock species, we used the Sheep Livestock Unit (SLU), as suggested by Argentina's National Institute of Agricultural Technology (INTA). This unit considers the forage needs of a SLU to be equivalent to those of a 40 kg live-weight Merino sheep (Siffredi et al. 2013). We converted all livestock species into SLU values. Young local sheep corresponded to 1.14 SLU; for cattle, a Criollo heifer corresponded to 8.97 SLU; for goats, we averaged the SLU values of Angora and Criollo goats, resulting in 1.29 SLU. Regarding horses, we averaged the SLU between a grazing horse and a working horse, resulting in 12.32 SLU.

Social networks were treated as a situational and relational variable, focusing on whether households reported activating formal or informal ties during the volcanic ashfall. Given their fluid and intermittent nature of participation in these organizations, the analysis does not quantify prior membership or participation intensity. Instead, it emphasizes the functional role of social ties as resources mobilized or not activated during and after the crisis.

Construction of the typology

Archetype Analysis (AA) identifies extreme points (archetypes) in the multi-dimensional distribution of data. Each household unit is referenced to each archetype to some extent, with greater reference indicating higher correspondence to that model. The sum of references for a household unit across all archetypes equals 1. When a household unit's reference to a given archetype is '1' (100%), it is an archetypoid for that archetype, with references to other archetypes being '0' (0%). Each archetype can have zero, one or multiple archetypoids associated with it (Tittonell et al. 2020). The number of archetypes was determined using the AICc criterion, and we identified the descriptive variables for each archetype (see methodological details in the Section 1 of the Supplementary Material).

Structural and functional characteristics of rural households have a degree of interdependence; therefore, we divided the analysis into two instances. Firstly, we conducted an AA to develop a typology of structural characteristics, using variables such as the number of livestock units, field surface area, household

composition (See 'Structural Characteristics Variables' from variable 'N' to 'AE' in Additional File 1). On the other hand, we carried out a functional typology, considering variables that would represent the responses of rural households (*e.g.*, their decisions on what actions to take or avoid; see 'Functional Response Variables' from 'A' to 'M' in Additional File 1). Then, we evaluated the degree of convergence between the results of the functional and structural AA. In this context, a household was associated with a given structural archetype if its correspondence with that archetype was greater than 0.5 (50%). To verify whether structure influences potential functions, we expected that all households associated with a given functional response archetype would also be associated with the same structural archetype. After that, we linked the adaptation strategies to each type of functional response (Next Section).

Livelihood-based adaptation strategies

To identify livelihood-based adaptation strategies associated with types of functional responses, we established relationships with the previously mentioned strategies: Tolerance, Resistance, Avoidance, Diversification, Transformation, and Mutualism (Tittonell et al. 2020). We expanded on the concepts and defined them as follows:

- Tolerance strategies: Allow survival in an acceptable manner without reacting to adverse conditions.
- Resistance strategies: Enable active reduction or defence against adverse conditions without modifying structural or functional characteristics. Involves structures or technologies to reduce losses or enhance efficiency in confronting adverse situations.
- Avoidance strategies: Prevent or minimize exposure to stress factors by avoiding risky situations. This is achieved through specific behaviours or livelihood arrangements to optimize adaptation to the environment without investing resources in resisting or tolerating losses. Involves avoiding a risky situation to prevent harmful consequences.
- Diversification strategies: Reduce risk or mitigate the negative impact of an adverse event in a particular area by increasing the system's stability through resource or activity diversification. Increases the likelihood that at least one area/activity/resource can thrive in changing conditions or unpredictable environments.
- Transformation strategies: Involve a significant change in the structure or functioning of the system, directed towards long-term adaptation.
- Mutualism strategies: Contribute to acquiring resources, assistance, care, and mutual well-being in the face of stressful conditions through reciprocal associations.

We assigned a score to each functional response according to its relationship with the six predefined adaptation strategies (Tolerance, Resistance, Avoidance, Diversification, Transformation and Mutualism), which allowed us to assess which strategies dominated in each functional archetype (see methodological details in the Section 2 of the Supplementary Material). Using this information, we looked for patterns among structural characteristics, functional responses, and adaptation strategies. We then interpreted these patterns by integrating the archetype results, the strategy scores, and the class of social network strategy.

RESULTS

Household categorization through structural attributes

Four archetypal household types were identified through the analysis based solely on structural variables (Figure 3 and Table 1). The variables that predominantly influenced the classification were household composition, herds, connectivity and accessibility, income and field characteristics. The four archetypes identified were:

Structural Archetype 1. Connected multigenerational pastoral households (1.CM): was characterized by multi-generational households with the presence of women. These households typically had high connectivity and accessibility, and water availability. They reside in rural areas, possessed relatively large herds, fully fenced perimeters, and internal paddock subdivisions. They have stable income sources, such as pensions.

Structural Archetype 2. Extensive pastoral households with dual residence (2.ED): corresponded to household units without young members under 18 years old, with relatively large herds and extensive livestock sales. These households had extensive land areas without property deeds and usually have a second residence.

Structural Archetype 3. Aging isolated pastoral households (3.AI): corresponded to household units composed only of adults over 60 years old, who lived isolated on their land without a second residence. These households generally did not have agricultural income beyond extensive livestock activities and had small, well-fenced land areas.

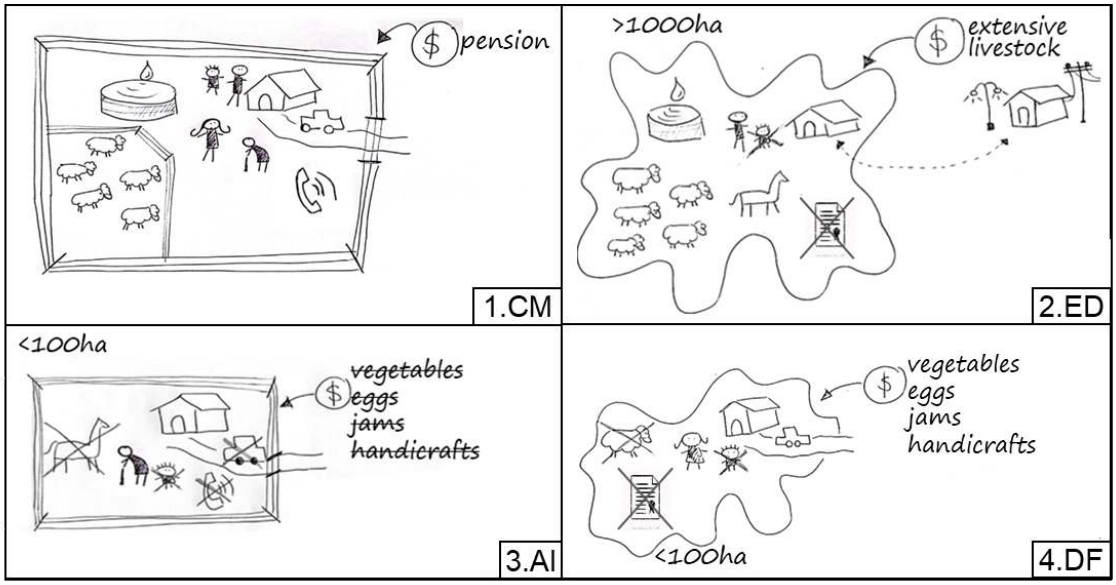


Figure 3. Diagram with archetypes of structural characteristics: 1. Connected multi-generational pastoral households (1.CM); 2. Extensive pastoral households with dual residence (2.ED); 3. Aging isolated pastoral households (3.AI); 4. Diversified female-led pastoral households (4.DF). The symbols representing each type of household unit explicitly indicate the presence of that characteristic or its absence if marked with a cross. The characteristics that proved descriptive in different types were the presence of water, extensive livestock, connectivity, accessibility, women, children and adolescents, property title, fencing, second residence, and types of financial economic incomes. The absence of a symbol regarding a particular characteristic indicates that such a feature does not define the archetype.

Table 1. Description of the Structural Archetypes of households based on their structural variables.

Archetype	Household composition	Herd	Connectivity and accessibility	Income characteristics	Field and residence characteristics
Connected multi-generational pastoral households (1.CM).	With children or young people under 18 years old between 2011 and 2019, with individuals aged 18 to 60 residing permanently, and with adult women residing permanently in 2019.	≥411 SLU in 2011 pre-ashfall and in 2019.	High connectivity and accessibility: own telephone and signal within the home or up to 1 km around; distance to school less than 5 km (1 hour walking), permanent road access and own vehicle.	With pension.	Without water shortages for consumption or with a reservoir, 100% perimeter fenced. Without a second residence.
Extensive pastoral households with dual residence (2.ED).	Without children or young people under 18 years old between 2011 and 2019, and without individuals younger than 60 residing permanently in 2019.	≥411 SLU in 2011 pre-ashfall and in 2019. With equines for trade and consumption.		Economic income from extensive livestock: products and animals (wool/hair, meat, and animals).	Large land area (>1000 ha), without property title deeds. With a second residence.
Aging isolated pastoral households (3.AI).	Without children or young people under 18 years old between 2011 and 2019, with individuals aged 18 to 60 residing permanently in 2019.	Without equines.	Low connectivity and accessibility: no own telephone; distance to school equal to or greater than 5 km, temporary road access, no own vehicle.	None of 'other' agricultural income.	Small land area (<100 ha), 100% perimeter fenced. Without a second residence.
Diversified female-led rural households (4.DF).	Without children or young people under 18 years old between 2011 and 2019 and with adult women residing permanently in 2019.	0 SLU in 2011 and in 2019.	High accessibility: distance to school less than 5 km (1 hour walking), permanent road access and own vehicle.	High diversity (more than 3 types) of 'other' agricultural income such as fruits and vegetables and/or processed goods; weaving or textiles; pigs; local eggs; layers and broilers; turkeys and ducks; seeds.	Small land area (<100 ha), 0% perimeter fenced, without property title deeds.

Structural Archetype 4. Diversified female-led rural households (4.DF): did not include children or young adults under 18, but they had adult women residing permanently. These households were characterized by a diverse range of agricultural income sources – different from livestock in 2019 – and typically had small land areas without fencing or property deeds, yet they enjoyed high accessibility.

Household categorization through functional responses

From the analysis carried out with functional variables, we identified four archetypes of functional responses to the combined impacts of droughts and volcanic ashfall over the considered period (Figure 1). The interpretation of each archetype based on their descriptive variables (*cf.* "Construction of the typology" section and Additional File 5) and the analysis of actors' narrative responses during interviews allowed us to assign four response descriptors, namely Anticipatory, Reactive, Conservative, and Passive (Figure 4).

The Anticipatory archetypal responses were observed among households that continued some of the management activities they were carrying out before the ashfall, such as selective herding based on their knowledge on rangeland heterogeneity, animal supplementation and forage production. Additionally, they increased agricultural production in their vegetable garden, diversified farm animals, and increased the ratio of on-farm to off-farm income over time. These responses were considered anticipatory as they reflected preventive Diversification strategies (*ex post*) as described by (Acosta et al. 2021). These households reduced the consumption of their own livestock after the ashfall, experienced outmigration of household members, activated social networks, and did not engage in tourism (neither before nor after the ashfall).

The Reactive archetypal responses did not anticipate but implemented measures to address the situation after the ashfall (*ex post*). They increased the cultivated area and biodiversity of their vegetable gardens, began supplementing animals and producing forage, activated formal social networks, and diversified their livelihoods by investing in or engaging in tourism, in detriment of herding activities. They temporarily diversified farm animals but decreased the consumption of their own livestock. There was no migration.

The Conservative archetypal responses were characterized by continued consumption of self-produced livestock, traditional herding praxis and animal supplementation as before the ashfall. These households remained in the rural area (without outmigration) and continued not to invest or engage in tourism. In other words, households with conservative responses attempted to maintain the *status quo* of their socio-ecosystems throughout the environmental crisis.

The Passive archetypal responses were exhibited by households that decreased their consumption of self-produced livestock, reduced on-farm income relative to off-farm income (mostly in the form of retirement pensions), consequently reducing their herding effort, and experienced temporary outmigration from rural to urban areas. These households did not diversify their farm animals and did not invest in or engage in tourism.

Convergence between functional and structural household archetypes

When comparing the archetypoids of functional responses with those based on structural characteristics, we found that functional responses were not strongly associated with the structural characteristics of households in a direct manner. However, we observed some convergence (Additional File 6): Anticipatory functional response archetypoids (n=4) were associated with structural archetype "1. Connected multi-generational pastoral households" (one archetypoid and two cases associated by more than 50%); Reactive functional response archetypoid (n=1) was more closely associated with structural archetype "4. Diversified female-led rural households"; Conservative functional response archetypoids (n=3) were associated by more than 50% with structural archetypes "1. Connected multi-generational pastoral households", "3. Aging isolated pastoral households" and "2. Extensive pastoral households with dual residence"; Passive functional response archetypoids (n=3) were associated with structural archetypes "3. Aging isolated pastoral households" and "2. Extensive pastoral households with dual residence" (Figure 5).

Livelihood-based adaptation strategies

We found different associations between functional response archetypes and the postulated adaptation strategies, *i.e.*, Tolerance, Resistance, Avoidance, Diversification and Transformation. While two of the functional response archetypes (Passive and Conservative) were predominantly associated with a single adaptation strategy, the other two (Anticipatory and Reactive) were associated with all, with emphasis on the remaining three strategies (*cf.* Figure 6).

The Passive functional response archetype was primarily associated with Tolerance (Figure 6). As defined earlier, Tolerance strategies allow households to endure adverse conditions in an acceptable manner without actively modifying their practices. In this case, Tolerance was expressed through reliance on external economic incomes, not initiating new activities

Responce types	Vegetable garden	Livestock self-consumption	Farm animals (pigs, chicken)	Supplementary feeding	Fodder production	Activate formal social networks	Farm to off-farm income ratio	Remained in rural area	Invests or employer in tourism
Anticipatory	↑	↓	↑	●	●	↑	↑	↓	○
Reactive	↑	↓	↑	↑	↑	↑		●	↑
Conservative		●		●				●	○
Passive		↓	○				↓	↓	○

Figure 4. Types of archetypal functional responses in relation to the actions indicated in the columns: vegetable garden (cultivated area); consumption of self-produced livestock; (diversification of) farm animals as pigs, chicken, and laying hens; supplementary feeding (of extensive livestock); fodder production; activate formal social networks; farm to off-farm (economic) income ratio; individuals who remained (in their household) of rural area (without temporary or permanent migration); invests in or engages in tourism. The shapes of the symbols indicate an increase in activity (upward arrow), decrease (downward arrow), and continuity (circle). Colours indicate permanence (black), temporality (grey), and absence (white). Rows specify the responses assigned to each archetype.

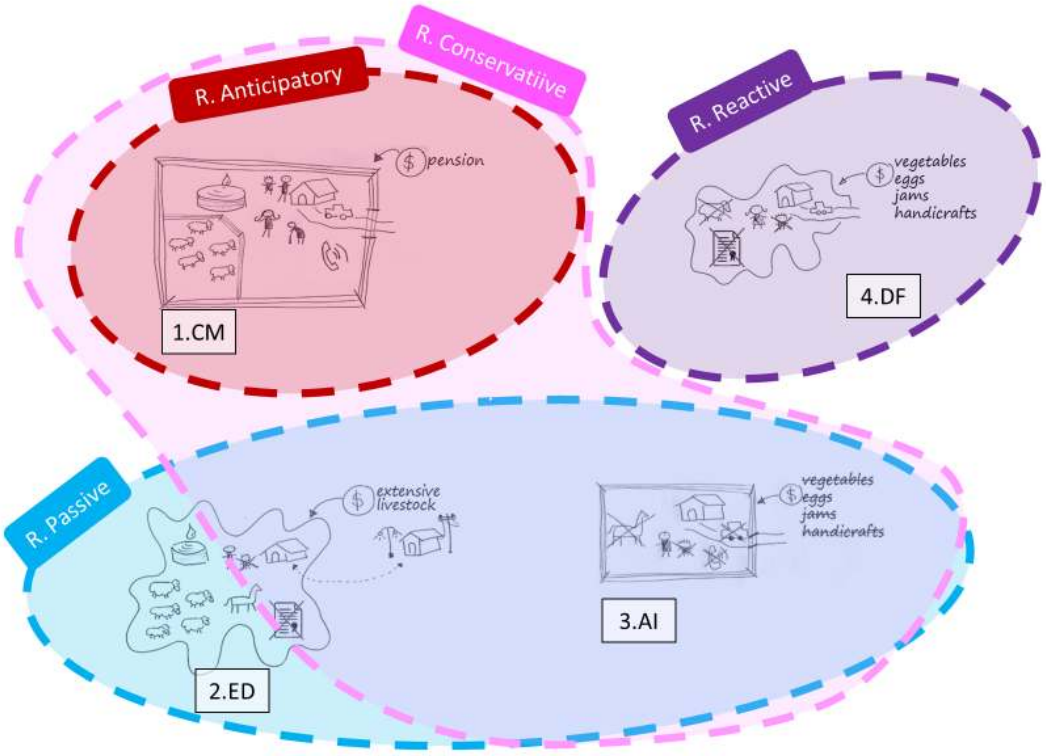


Figure 5. Diagrams of archetypoids of functional responses in colours (Anticipatory in dark red, Proactive in pink, Passive in light blue, and Reactive in violet), indicating with which types of structural characteristics they are associated (structural archetypes Connected multigenerational pastoral households (1.CM); extensive pastoral households with dual residence (2.ED); Aging isolated pastoral households (3.AI); Diversified female-led rural households (4.DF).

(whether agricultural or non-agricultural) after the volcanic ashfall, and reducing the self-consumption of

ruminant livestock. The Conservative functional response archetype was mainly associated with Resistance strategies which, as defined above, involve active efforts to reduce losses or defend ongoing activities without altering structural or functional characteristics. This response was characterized by maintaining ongoing activities without incorporating new ones. Both Passive and Conservative did not exhibit Transformation strategies and scored very low in Diversification and Avoidance (Figure 6; Additional File 7).

Regarding the Anticipatory and Reactive functional response archetypes, both scored points in all five strategies although with different emphases. The Anticipatory response was more associated with Diversification, Resistance and Avoidance (Figure 6, dark red line). In line with our definitions, diversification strategies reduce risk by expanding the range of activities and resources, while Resistance involves active efforts to buffer losses without altering the system's core structure, and Avoidance minimizes exposure to stressors through behavioural or livelihood adjustments. This response undertook immediate and long-term actions, maintained agricultural production, incorporated farm animals, and saw some household members migrate as a way to reduce exposure to risk while sustaining the household system. The Reactive response was more associated with Diversification, Avoidance, and Transformation (Figure 6, purple line). Here, Diversification and Avoidance were expressed through the reorientation of livelihoods while Transformation entailed more substantial changes in the structure and functioning of the household. This response involved immediate actions and developed a strong connection with tourism through steady employment or investments, reflecting a shift away from pastoralism toward alternative livelihood configurations.

When the volcanic ashfall took place in 2011, 70% of the households were primarily herders relying on rangeland biodiversity but exhibited mixed income sources, combining on-farm and off-farm incomes; 15% of them depended exclusively on external income; the remaining 15% relied completely on their own production and ecological capital. In the subsequent years, the latter had to resort to mixed sources of income, combining their own production with employment or a pension. Examining livestock performance — in terms of percentage of SLU — across the functional archetypoid, we found that all types were significantly impacted by the volcanic ashfall, but there was variability in their recovery eight years later as shown in Figure 7. The Anticipatory and Conservative types exhibited lower sensitivity to the disturbance and showed greater recovery related to pre-ashfall livestock numbers, but with differences: conservative households (with their economy based on off-farm income) almost maintained their pre-ashfall livestock levels, whereas Anticipatory households displayed a wide range of outcomes (from reductions of up to 60% to nearly doubling their pre-ashfall herd size). In contrast, the Passive and Reactive types exhibited lower recovery after the disturbances of ashfall and droughts.

Social networks

Participation in social networks is reported here in terms of whether households activated formal and/or informal ties during the ashfall (independently of when these links were originally formed). Out of the 33 households interviewed, 22 mentioned activating some type of formal social organization (one or more) associated with institutions such as indigenous communities (24%), cooperatives (36%), farmer fairs (39%), handicraft markets (12%) and religious organizations (22%). Besides, 30 households (including the 22 mentioned above) activated informal networks through family and relatives (70%), and neighbours (61%). Only three households (0.09%) expressed not having activated any social networks.

The Anticipatory and Reactive functional archetypes activated both formal and informal networks (and were associated with structural archetypes 1.CM and 4.DF, respectively). The Conservative functional archetype only activated informal networks (associated with structural archetypes 1.CM, 2.ED and 3.AI), while the Passive functional archetype either activated informal networks or none (and associated with the structural archetype 2.ED).

DISCUSSION

We assessed the relationship between pastoral household characteristics and functional responses in the face of socio-environmental disturbances, shaped by their *kosmos-corpus-praxis* (Toledo and Barrera-Bassols 2008), and enabled by contextual factors and social organization in Northern Patagonia. All the households interviewed were those that remained in the territory between 2011 and 2019 despite the adversities imposed by a volcanic ashfall and recurrent droughts in the last decade. This evidence suggests that they mobilised different mechanisms of livelihood resilience and adaptability that we aimed at describing and categorising as adaptation strategies. We identified four archetypes of pastoral households from a structural point of view and four archetypes of functional responses, which influenced their herding practices and livelihood activities. We then highlighted the relationship between these response patterns and six types of predefined adaptive strategies that were hypothesised: Tolerance, Resistance, Avoidance, Diversification, Transformation and Mutualism. Beyond the specific case of Northern Patagonia, the approach

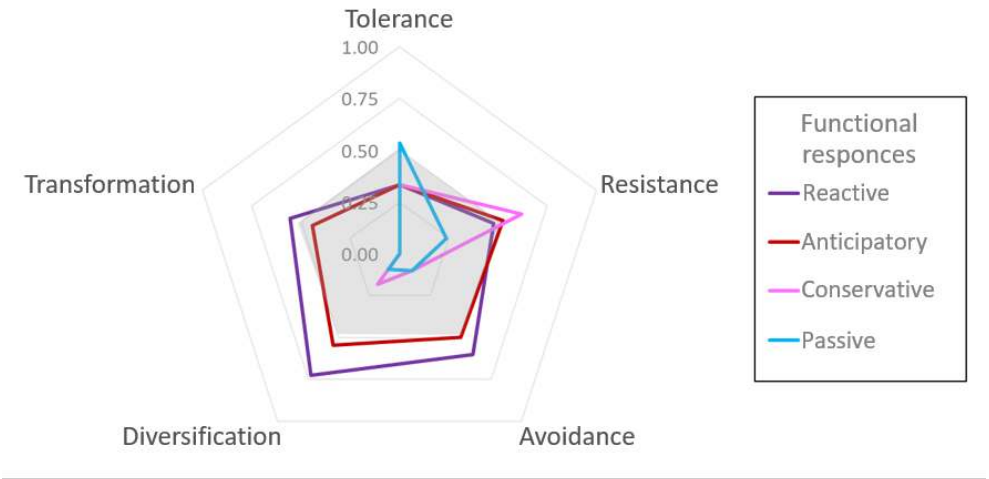


Figure 6. Types of adaptation strategies: Tolerance, Resistance, Avoidance, Diversification, and Transformation (vertices of the pentagon) on a scale from 0 to 1. Types of functional responses: Anticipatory (dark red line), Reactive (violet), Conservative (pink), and Passive (light blue). A grey background indicates the threshold (0.5) where we begin to consider the response as associated with the archetype of functional response.

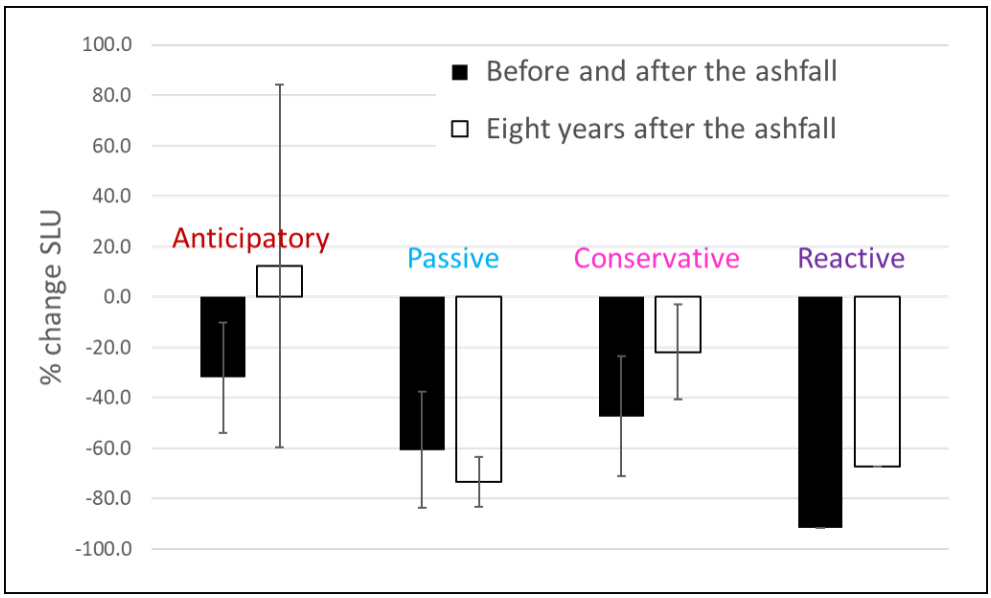


Figure 7. Changes over time in the quantity of SLU (Sheep Livestock Units) among archetypal households associated with the described functional archetypes (Anticipatory, Passive, Conservative, and Reactive). The solid black bars represent the impact of the 2011 ashfall on SLU at the farm level, comparing pre- and post-ashfall values. The hollow bars represent changes comparing pre-ashfall values with values from 2019.

adopted here offers a methodological contribution for ethnobiological research by providing a way to identify and compare patterns of household responses (*praxis*) to environmental shocks in a situated way considering - indirectly- people knowledge and desires. As such, this study is proposed as a bridge between ethnobiological theory and the socio-ecological system theory that underpins resilience and adaptability studies (*e.g.,* Ladio 2017 and Tittonell 2014, respectively). In the following paragraphs we analyse our findings in the light of the existing literature on ethnobiology and the resilience of complex adaptive systems.

Household responses and adaptation strategies

Livestock dynamics, a key indicator for the dynamics of livelihoods used in pastoralism studies (*e.g.,* Engler et al. 2021), showed variability across the functional archetypes identified here. The differences in the rate of recovery in livestock numbers after the ashfall shown in Figure 7 suggest that functional responses characterized by Anticipatory or Conservative strategies may buffer long-term impacts more effectively than Passive or Reactive strategies. The persistence of households with Conservative responses — who maintain their herd size despite environmental pressure — reflects a worldview where livestock are not merely economic assets but biocultural heritage (Reising and Ladio 2025). As observed in studies on traditional livestock such as the *Linca* sheep (Reising et al. 2022), the maintenance of animals is intrinsically linked to the *'criancero'* (local farmer identity) and the preservation of local ecological knowledge. Losing the herd implies a loss of cultural function and prestige within the community. Thus, the Resistance strategy is associated by a *kosmos* that prioritizes territorial permanence and cultural continuity over economic maximization.

Similarly, Passive responses, often associated with elderly residents, may be underpinned by a deep attachment to place (topophilia), where the psychological cost of migration outweighs the risks of remaining in a precarious productive state (Zubizarreta 2015). In this sense, the decision to stay cannot be interpreted solely through economic rationality, a livelihood strategy pattern that has been earlier described as 'hanging-in' (Dorward et al. 2009). Livestock, particularly sheep, may function as identity-bearing elements rather than merely productive assets, embodying personal histories, family trajectories and a sense of continuity with past generations. Such meanings, documented in previous pastoral ethnobiological studies (Reising et al. 2022; Reising and Ladio 2025), help explain why some households persist despite declining economic returns, framing persistence as a culturally grounded choice rather than a passive failure to adapt.

At the same time, while some households maintain livestock as a culturally meaningful anchor of identity and continuity, others reconfigure their livelihoods by combining or replacing pastoral activities with alternative sources of income. These divergent trajectories should therefore be understood not as simple gradations of resilience, but as distinct adaptive pathways emerging from different configurations of *kosmos*, *corpus* and *praxis*. Because of that, livestock alone is not a sufficient indicator to fully explain resilience. In other words, a decrease in livestock numbers may not necessarily indicate lower resilience but rather a shift away from pastoralism, as seen in other pastoral regions (*e.g.*, Dossouhoui et al. 2025; Lecegui et al. 2022).

Tolerance strategies with passive responses may arise from not crossing a threshold of need or not having the desire to act. For example, single adults living alone, without dependents, who could have sustained some agricultural production, may not have perceived the need or motivation to respond actively, choosing to remain living in the area in a frugal manner. In other cases, fear, uncertainty, sadness, tiredness, or frustration may paralyze individuals from acting on their desires, leading them to resign themselves to endure (and eventually even abandon (Vazquez 2012)). In the work of Wilson et al. (2013), where they reported on the impacts of the Puyehue Cordón-Caulle volcanic eruption, they recorded psychological stress, anxiety, and depression associated with uncertainty and destabilizing economic effects.

From an ethnobiological perspective, the association between Diversified female-led households (4.DF) and 'Reactive' responses (Figure 5) —characterized by diversification and tourism— is not coincidental but rooted in the gendered division of labour and knowledge (*corpus*) (Ladio 2020). In Patagonian pastoralism, while men have traditionally focused on extensive livestock, women have acted as guardians of agrobiodiversity and multipurpose, managing home gardens, poultry, and textile crafts (Eyssartier et al. 2011). This accumulated female knowledge provides a reservoir of functional plasticity that becomes critical during crises. As noted by Reising et al. (2022) regarding *Linca* sheep, women are often the ones who preserve unique genetic resources and cultural practices (*e.g.,* spinning, weaving) that allow for economic diversification when the main productive system fails. Laborda et al. (2024) documented more resilient responses of pastoral households in which decisions were made together by men and women, particularly when the land was inherited from the woman's family. Therefore, the 'Reactive' capacity observed in these households can be interpreted as the mobilization of a diversified *corpus* that was previously invisible or undervalued in purely productive analyses, highlighting the role of women not just as domestic caretakers but as active agents of biocultural resilience. Besides, the structural characteristics of this household type were not robust enough to adopt Resistance or Tolerance strategies (*e.g.,* the smaller fields, no land title deeds, no fencing).

Finally, the 'Anticipatory' and 'Reactive' archetypes illustrate the plasticity of the *corpus*. These households demonstrate a hybridization of knowledge (Ladio and Albuquerque, 2014) integrating traditional pastoral practices with novel activities like tourism or new foraging strategies. This ability

to update the *corpus* without abandoning the *kosmos* (the rural lifestyle) is a key indicator of resilience and it is mediated by cultural transmission processes (Barrera Bassols and Toledo 2005; Eyssartier et al. 2008). It suggests that successful adaptation in Northern Patagonia involves a dynamic negotiation between tradition and modernity, rather than a replacement of one by the other.

Beyond the diversity of household responses, these dynamics must also be understood within broader regional processes. These households undergo a deep reconfiguration of their *corpus* and *praxis* shifting, from pure pastoralism to pluriactivity (*e.g.,* tourism, specialized crafts, alternative livestock) precisely to maintain their *kosmos*: the connection to the land, family and ways of life. As suggested by Folke et al. (2010), this ability to transform at a smaller scale (the economic activities) is what may allow the system to persist at a larger scale (the biocultural landscape). However, since the 1960s, the region has experienced structural processes of rural-to-urban migration (Bendini and Steimbreger 2013) and a decline in sheep farming (Coronato 2010), a trend that was accentuated during the volcanic ashfall. For some households, the environmental crisis acted as a tipping point leading to permanent outmigration (Vazquez 2012), illustrating the complexity of the process: when transformation is forced by external pressures and exceeds a certain threshold, it may lead to the loss of the rural system rather than its adaptation. In this context, household persistence should be understood alongside broader processes of transformation and abandonment of rural livelihoods.

Structural-functional interactions and system resilience

The evidence collected through this study did not fully support the existence of strong links between household structural characteristics and functional responses. However, the structural characteristics of a household did condition which responses and strategies were enabled, allowing people to choose whether to carry them out. For instance, structural characteristics such as limited connectivity (transport, communication) could hinder the adoption of strategies like Diversification, Transformation and Avoidance; but on the other hand, not all the household that were well connected necessarily engaged these strategies. The structural characteristics of a system can function as enablers or constraints for certain functional responses and adaptive strategies. Yet, when these characteristics are not limiting, and responses or strategies are enabled, their implementation still depends on individual household desires and agency. As Lade et al. (2020) pointed out, household agency depends on structural limitations (financial, natural, productive, human, or social capital) and the opportunities they face, as well as their knowledge and motivation, shaping their temporal trajectories.

Agency among pastoral households can be also largely explained by perceptions, preferences, and resources (*e.g.*, Solano-Hernandez et al. 2020) and shaped by values and belief systems (Toledo and Barrera-Bassols 2008). Resilience studies have been criticized for failing to adequately address the role of actors and the factors that limit their agency (Lade et al. 2020). Hence, the absence of a direct relationship between structure and function in our findings can be further proof that actors and agency are the key elements of resilience. Structural characteristics (capitals) either enable or constrain agency, while individuals' perceptions, local values and belief systems play a significant role in shaping outcomes.

Structural typologies are commonly employed to assess the resilience of rural households to disturbances and socio-environmental change, with system functions often inferred from these structures (*e.g.*, Davidson et al. 2016; Galluzzo 2020; Laurien et al. 2020). However, our findings highlight the importance of considering the functional characteristics of household systems and the individual and community agency. Functional household typologies were earlier described as 'farming styles' by van der Ploeg (1994), focusing on how farmers behaved and made production decisions, which were enabled or constrained by their structural characteristics, although not necessarily in response to natural disasters. Others, such as Vanclay et al. (2006), described functional responses to environmental hazards based on community agency. Other approaches include the socio-ecological resilience, as described by Walker et al. (2009) and Folke et al. (2016), which are similarly based on the influence of structure on function. In practice, however, this approach has been difficult to apply, with most contributions from this school of thought remaining theoretical, despite the existence of some assessment frameworks based on them (*e.g.*, Meuwissen et al. 2019).

Off-farm income, gender and collective action

Access to off- and non-farm income, gender of the decision maker(s) and collective action shaped functional responses and were three key enablers of adaptation strategies. We found that none of the pastoral households analysed were financially self-sufficient through their main livestock production in 2019. Off-farm incomes can mitigate the impact of disturbances that directly affect natural, production, and economic capital. Previous studies in the region have shown how income diversification helped mitigate the

impact of drought on rural households (Easdale and Rosso 2010). Livelihood strategies based on off-farm incomes have been widely documented globally (*e.g.*, Valbuena et al. 2015 in Kenya; Hauswirth et al. 2015 in Vietnam; Alvarez et al. 2018 in Zambia; Teixeira et al. 2018 in Brazil; Novotny et al. 2021 in Mexico), although there are fewer studies evaluating the buffering effect of these strategies in practice.

The main sources of off-farm income among the households studied were employment and stable income sources provided through social protection schemes (including contributory and non-contributory pensions). These alternative incomes functioned as a subsidy during this environmental and productive crisis, even though they were not specifically designed for it. They ensured a monthly economic income that – when it did not involve time-consuming employment – allowed households to remain on their land and continue to care for people, crops, and animals that survived the disturbance, sustaining both productive and reproductive activities. Other studies in Patagonia, such as Bendini and Steimbreger (2013), also mention that off-farm incomes favour the permanence of people in the territory, yet they warn that it can also stimulate processes of *de-peasantization*. In the context of our study region, alternative off-farm incomes –from special protection schemes– cannot be considered as a household-level adaptation strategy but rather as a structural component of the household's life strategy, pre-dating the environmental disturbance. Off-farm income from pensions or subsidies may also be strategy to foster adaptation when deployed by national or regional governments, as public policies or contingency programs.

The presence of women in the household was another characteristic associated with the adaptation strategies of Diversification, Avoidance, Transformation and Formal social networks. This is in line with previous studies on emerging production activities in Northern Patagonia (Laborda et al. 2024). More broadly, gender and intra-household diversity (Laborda et al. 2024 and Michalscheck et al. 2018 respectively) have been shown to play major roles in rural household resilience by shaping decision-making processes. Four years after the volcanic ashfall, Núñez and Conti (2015) described women's organizations as agents of change, as women constituted up to 90% of the newly created production associations, highlighting the limited presence of men in these groups. In Northern Patagonia, where male rural employment (such as shearer or farm labourer) is more common than female employment, this may have led women to self-employment, performing multiple tasks in their households, and forming associations as a persistence strategy. It is important to note that these processes can lead to an overload of work for women, a burden that often goes unrecognized within the local community (Ladio 2024).

Diversification, Avoidance, and Transformation are strategies that represent a certain buffering effect against environmental hazards, and these can be facilitated by engaging in formal social networks. For example, the legal establishment of registered *Mapuche* indigenous community associations and cooperatives can channel collective actions and attract funds from the state or non-governmental organizations. Formal social networks are likely to enable and enhance responses associated with new productions (laying hens, balanced feed) or rural tourism. According to previous studies in the region, the association of individuals can serve as a channel for the exchange of information and technological innovations, promote technical assistance, and allow access to better selling prices and financing the collective purchase of inputs (Hara *et al.* 2022).

The activation of these networks should be understood as the mobilization of biocultural memory (Toledo and Barrera-Bassols 2008). The 'associationism' observed during the crisis was not created *ex nihilo* but relied on pre-existing structures of reciprocity and exchange, including cooperatives (*e.g.,* Cooperativa Agrícola Ganadera Pichi Cullín Ltda.), fair markets (*e.g.,* Feria Franca Agricultores Bariloche and Mercado de la Estepa Quimey Piuke), religious institutions (as Cáritas), Indigenous communities (*e.g.,* Wefu Wechu) and kinship-based support networks (see Longo-Blasón et al. 2024; Laborda et al. 2024; Conti and Sánchez 2020). As Longo Blason et al. (2024) showed, these spaces function as reservoirs of resilience where knowledge, seeds, yarn and social support circulate. The volcanic eruption acted as a trigger that transformed latent social capital into active 'Mutualism'. Households with Anticipatory and Reactive responses were successful largely because they could tap into this accumulated collective memory, translating social interactions into adaptive *praxis*.

In this context, the activation of social networks observed in our study can be interpreted not only as an immediate response to environmental disturbance but also as the mobilization of previously accumulated relational experience and organizational trajectories being specially remarkable the presence of informal social networks among most households. These findings resonate with ethnobiological and social–ecological perspectives that emphasize the role of cultural values, place attachment, and biocultural memory in shaping adaptive responses (Berkes et al. 2000; Maffi 2005). From this perspective, household decisions facing different crisis reflect culturally embedded logics rather than purely economic optimization.

Archetypes analysis in ethnobiological studies

In this study, archetype analysis was employed not merely as a statistical reduction tool, but as a heuristic device to bridge quantitative structural data with qualitative ethnographic insights (Reising et al. 2022). Unlike rigid clustering methods that assign households to mutually exclusive groups, archetype analysis identifies 'extreme' or 'pure' patterns (archetypes) and allows each household to be represented as a mixture of these patterns. From an ethnobiological perspective, this approach is particularly valuable for capturing the fluidity of local ecological knowledge and associated management strategies. It acknowledges that rural households often deploy hybrid strategies —combining traditional pastoralism with modern diversification— rather than fitting into static categories. By quantifying the 'degree of membership' to each archetype, we can operationalize the complexity of the *kosmos-corpus-praxis* concept (Toledo and Barrera-Bassols 2008), revealing how structural assets (*e.g.,* land, livestock) constrain or enable specific functional responses (*praxis*) rooted in cultural logics. Thus, archetype analysis serves as a methodological innovation in ethnobiology by preserving the internal diversity of the community and making visible the 'grey areas' of adaptation that standard typologies often obscure.

CONCLUSION

Various responses were observed among pastoral households in Northern Patagonia reflecting different types and degrees of resilience in the face of environmental disturbances, in this case a volcanic ashfall and recurrent droughts. Households were heterogeneous in terms of structural characteristics, functional responses, and adaptation strategies implemented to face these environmental hazards. These strategies can be seen as adaptations of their *praxis*, embedded within their *kosmos*. After all, ashfalls and droughts are not a novelty in these territories; they have shaped the evolving *corpus* of these communities. It was not our goal to evaluate which adaptation strategy was more resilient but to describe and understand the key mechanisms behind these strategies.

Our results show that household structure plays an enabling role by shaping the range of possible functional responses, but it does not directly determine them. Instead, adaptive practices (*praxis*) ultimately emerge from the interaction between the structure and the household's knowledge systems and values (*corpus* and *kosmos*) expressed thought individual and collective agency. These results contribute to ethnobiological theory by showing that adaptation to environmental disturbances emerges from the dynamic interaction between knowledge, social relations, and agency, aligning with the approach that emphasize *kosmos-corpus-praxis.*

Although responses and strategies differed across household types, the activation of social networks (many of them pre-existing) was a common denominator to most of them and seems to be a key mechanism enabling adaptation. The few cases in which social networks were absent, where associated with a specific structural configuration (Extensive households with dual residence). From a policy perspective, interventions aimed at sustaining rural livelihoods in arid environments may be more effective when they focus on ensuring minimum enabling conditions —such as access to health, education, connectivity, and stable income sources— while recognizing the differentiated capacities of households to mobilize adaptive responses. This can stimulate to carry conservative strategies while anticipate to future crisis. However, If the goal is to maintain the people on the land (in a dignified way) and avoid the de-peasantization, public policies could have more impact if focused on households with "passive" type of responses.

Although pastoral households in Northern Patagonia exhibited resilience and adaptability over their history, policies and interventions to enhance the sustainability and resilience of rural livelihoods should consider the diversity of structural-functional household configuration —as the identified here—, prioritizing aid schemes for households exhibiting passive responses while enhancing the response opportunities and adaptive potential of those already able to mobilize conservative, anticipatory and reactive strategies.

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DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon reasonable request and in the repository of CONICET: Laborda, L. (2025). Características estructurales y

respuestas funcionales de hogares pastoriles en la estepa de Patagonia Norte. Consejo Nacional de Investigaciones Científicas y Técnicas (dataset). http://hdl.handle.net/11336/252333

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

CONTRIBUTION STATEMENT

Conceived the presented idea: LL, PT, MHE
Carried out the field work: LL, MPO, PT
Carried out the data analysis: VEA, OB, LL
Wrote the first draft of the manuscript: LL
Review and final write of the manuscript: LL, PT, MHE, VEA, AHL, MPO, OB
Supervision: PT, AHL, MHE

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DISCLOSURE OF AI USE

The authors used ChatGPT to assist in improving language clarity. The content was reviewed and edited by the authors to ensure accuracy and appropriateness.

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Additional Files

Add File 1. Functional response variables (A-M) and structural characteristics (N-AE) with their respective classes and numeric coding by class. SLU = Sheep Livestock Unit, to compare between different livestock species.

Functional variables	Response	A. Sale of livestock (sheep, goats, cattle): immediately post-ash	0. They did not sell 1. They sold at least some of the livestock
		B. Livestock consumption (sheep, goats, cattle): immediately post-ash to present	0. They did not stop consuming 1. They stopped consuming to some extent
		C. 'Immediate' incorporation of other animals for consumption and/or sale (T2)	0. No 1. Yes (poultry/pig)
		D. Diversification of farm animals (poultry/pigs) (T3)	0. They did not diversify (no farm animals or kept what they had before) 1. They diversified (incorporated new types of farm animals)
		E. Extensive livestock foraging	0. They started foraging (at least for a while) 1. They continued foraging
		F. Forage production	0. They have not produced or stopped producing with the ashfall 1. They started producing after the ashfall 2. They continued to produce forage
		G. Vegetable garden after ashfall to the present	0. No vegetable garden in the period or they abandoned it 1. They maintained/enhanced the garden (they did it before the ash and in 2018 they continued)

	H. Networks that were activated: family (family help), social (neighbors), institutional (indigenous community, cooperative, fairs, markets, state institutions)	0. None or informal (family, neighbors) 1. Institutional (and informal)
	I. Economic support of the system during the disturbance and thereafter	0. Relied on extra-farm income (employment/pension) 1. Field production was maintained or enhanced
	J. Degrees of livestock intensification: % of cattle in the herd (sheep, goats, cattle) compared between before the ashfall and 2018/2019	0. Less intensification and/or reduction of livestock depopulation 1. Maintenance (the proportion of cattle in the livestock was maintained) 2. Intensification (the proportion of cattle in the livestock increased)
	k. People who make up the household	0. Field alone or with a position holder in some period 2011-2019 1. One permanent person in the field and no one else, neither temporary nor sporadic 2. One permanent person and other temporary and/or sporadic person(s) 3. More than one permanent person
	L. Did anyone migrate from the countryside between 2011 and 2019?	0. No 1. Yes
	M. Link with tourism	0. None 1. 'Opportunistic' sale of products, odd job 2. With investments (accommodation, camping) or permanent employment
Structural characteristic variables	N. Pre-ashfall total SLU (sheep, goats, cattle)	0. 0 SLU 1. <54 SLU

	2. <105 SLU
	3. <184 SLU
	4. <411 SLU
	5. >= 411 SLU
O. Post-ashfall total SLU (sheep, goats, cattle)	0. 0 SLU
	1. <54 SLU
	2. <105 SLU
	3. <184 SLU
	4. <411 SLU
	5. >= 411 SLU
P. Current total SLU (sheep, goats, cattle)	0. 0 SLU
	1. <54 SLU
	2. <105 SLU
	3. <184 SLU
	4. <411 SLU
	5. >= 411 SLU
Q. Extensive livestock economic income	0. None
	1. Products (wool/ fibers)
	2. Products and animals (wool/ fibers and meat, resale of animals)
R. Diversity of types of agricultural income: F&V and/or processed; spinning or weaving; pigs; creole eggs; grill layers; turkeys; ducks; seeds	0. None
	1. One type
	2. Two types
	3. Three types of products or more
S. Spatial home	0. Home = farm
	1. Home = farm and urban house

T. Drinking water	0. Without water for permanent consumption or in times of drought 1. Without water shortage or with reservoir
U. Type of wetlands	0. Without, or dry, or small (<0.5ha) 1. Yes/important
V. Physical accessibility of the field (proximity / condition of the road / own vehicle)	0. Low: distance to school equal or greater than 5km walking, the path is temporary, without own vehicle 1. Medium low: 2 characteristics 'high' + 1 'low' 2. Medium high: 2 characteristics 'low' + 1 'high' 3. High: distance to school less than 5 km (1 hour walking), permanent road, with own vehicle
W. Connectivity of people in the field. (Telephony/signal)	0. Low: without own phone 1. Medium: own phone and signal farther than 1km 2. High: own telephone and signal in the house or max. 1km around the house.
X. Field surface	0. Small (<100ha) 1. Medium small (100; <500ha) 2. Medium large (500; <1000) 3. Large (=>1000ha)
Y. Perimeter fence	0. Without 1. Incomplete 2. Complete
Z. Household with any retirement/pension from 2011 to 2019?	0. No 1. Yes
AA. Horses at T1: presence and type of use	0. No horses 1. One to seven horses, not used for exchange or consumption (may be work and transport horses)

	2. Eight or more horses, not used for exchange or consumption (may be work and transport horses)
	3. They use the horses for exchange and/or consumption (there were six or more horses in T1)
AB. Household members under 18 years old?	0. Household with no young children since before 2011
	1. Household with young children during 2011
	2. Household with young children during 2011 and/or 2019
AC. Are there people between 18 and 60 years old in the household permanently?	0. No
	1. Yes
AD. Household with adult woman in 2019?	0. No
	1. Yes
AE. Title deeds	0. No
	1. Yes

Section 1. *Archetype Methodology Section*

1.1. Selection of the number of archetypes

We performed the archetype analysis on both data matrices (database Laborda 2025), processing each of them in the same way. The number of archetypes was determined using the corrected Akaike Information Criterion (AICc). We initiated this procedure with a relative minimum of three archetypes (the minimum number of points to form a plane in space) and gradually increased it until the AICc value started to rise. We selected the output with the second-best AICc criterion (the second lowest) because it demonstrated better explanatory power of the data. The analysis was conducted by processing the data matrices according to the algorithm developed by Chen (2014), using the py_pcha module for convex hull analysis in Python (Aslak 2020).

Section 1.2. Information obtained and processing

The archetype analysis provides two types of information. On the one hand, it offers the proportion of correspondence of each household to each archetype. On the other hand, the analysis generates a database with the values that each category of each variable take within each archetype. However, these values are decimal numbers, whereas the classes are represented by integer values. Therefore, we use the classes with exact decimal values to select which variables will describe each archetype (referred to as 'descriptive variables'). Additionally, to qualify as a descriptive variable, a variable must match the archetype-like values for the given class. For example, if for archetype 'A', Variable '1' takes a value of 2.00, we consider it a 'descriptive variable' only if all associated archetypoid values for that same variable also take the value of 2.00.

In the description of each archetype, the classes associated with each relevant descriptive variable are detailed; however, not all archetypes consider the same variables. Therefore, if specific characteristics are not explicitly mentioned for an archetype, it indicates that the archetype does not have a particular class assigned to that variable. For example, regarding the 'Title deed' variable, an archetype may: 1) 'have property deed' if the analysis and associated archetypes indicate so; 2) 'not have property deed' if the analysis shows otherwise; or 3) make no mention of it, implying that this characteristic is not

defining for the archetype in question. In this latter case, associated cases may or may not have a property title.

Section 2. *Livelihood-based adaptation strategies methodology.*

Section 2.1. Adaptation strategies scores

We assigned an individual score for each strategy relative to the classes of functional variables (responses). When a response was unrelated to a strategy zero (0) points were assigned; when the relationship between the response and the strategy was weak or partial, one (1) point was assigned; and when the relationship between the response and the strategy was direct, two (2) points were assigned. It is important to note that the categories are not mutually exclusive; a single practice may involve more than one strategy. This criterion was used to encompass the complexity of the behaviors indicated in the surveys. Although this categorization is subjective, it was created after a systematic evaluation of all responses (Additional File 2).

Add File 2. Score of adaptation strategies for functional archetypes. Types of archetypes of functional responses: Anticipatory (A), Conservative (C), Passive (P), and Reactive (R) and the score assigned to each strategy (Tolerance, Resistance, Avoidance, Diversification and Transformation) per variable. The cells with a dash ('-') indicate that the variable in question was not descriptive for that archetype. In the bottom cell, the sum of the maximum score for each archetype is shown. Then, the total score per archetype, broken down by how many points corresponded to each strategy.

Functional Variable	**Strategy**	**Functional archetype**			
		A	C	P	R
B. Livestock consumption: mmediately post-ash to present	Tolerance	2	0	2	2
	Resistance	0	2	0	0
	Avoidance	0	0	0	0
	Diversification	0	0	0	0
	Transformation	0	0	0	0
C. Immediate incorporation of other animals for consumption and/or sale (T2)	Tolerance	0	1	1	0
	Resistance	0	2	2	0
	Avoidance	1	0	0	1
	Diversification	2	0	0	2
	Transformation	1	0	0	1
D. Diversification of farm animals (poultry/pigs) (T3)	Tolerance	0	1	-	-
	Resistance	0	2	-	-
	Avoidance	1	0	-	-
	Diversification	2	0	-	-
	Transformation	2	0	-	-
E. Extensive livestock foraging	Tolerance	1	1	-	0
	Resistance	2	2	-	1
	Avoidance	1	1	-	2
	Diversification	0	1	-	3
	Transformation	0	0	-	1

to be continued...

Functional Variable	**Strategy**	**Functional archetype**			
		A	C	P	R
F. Forage production	Tolerance	1	-	-	1
	Resistance	2	-	-	0
	Avoidance	0	-	-	1
	Diversification	0	-	-	0
	Transformation	0	-	-	0
G. Garden after ash to present	Tolerance	-	-	-	1
	Resistance	-	-	-	2
	Avoidance	-	-	-	0
	Diversification	-	-	-	0
	Transformation	-	-	-	1
H. Networks that were activated: family (family assistance), social (neighbor assistance), institutional (indigenous community, cooperative, fairs, markets, INTA)	Tolerance	0	-	-	0
	Resistance	2	-	-	2
	Avoidance	0	-	-	0
	Diversification	0	-	-	0
	Transformation	0	-	-	0
I. Economic support of the system	Tolerance	0	-	2	-
	Resistance	2	-	0	-
	Avoidance	0	-	1	-
	Diversification	0	-	1	-
	Transformation	0	-	0	-
K. People who make up the household in the field	Tolerance	0	0	1	0
	Resistance	2	2	0	2
	Avoidance	0	0	0	0
	Diversification	1	1	0	1

to be continued...

Functional Variable	Strategy	Functional archetype			
		A	C	P	R
L. Did anyone migrate from the field between 2011 and 2019?	Transformation	0	0	0	0
	Tolerance	0	1	1	1
	Resistance	0	2	2	2
	Avoidance	2	0	0	0
	Diversification	1	0	0	0
	Transformation	1	0	0	0
M. Link with tourism	Tolerance	1	1	1	0
	Resistance	1	1	1	1
	Avoidance	0	0	0	2
	Diversification	0	0	0	2
	Transformation	0	0	0	2
Strategy score	Total score	31	21	15	34
	Tolerance	5	5	8	5
	Resistance	11	13	5	10
	Avoidance	5	1	1	6
	Diversification	6	2	1	8
	Transformation	4	0	0	5

For example, as it is shown in Additional File 3, in the case of the functional variable 'Livestock self-consumption from post-ashfall to 2019', within the category '0. did not stop consuming', we assigned '2' points to the Resistance strategy. This decision was based on our assessment of the direct relationship between the response and the strategy. Continuing to consume their livestock after this event represents an active avoidance against adverse conditions without deformation or 'breaking', which aligns with our definition of the Resistance strategy. Regarding the other strategies, we assigned '0' points to this category because we deemed the response unrelated to them (Tolerance, Avoidance, Diversification, or Transformation). Continuing to consume their livestock does not represent a Tolerance strategy because it implies an active reaction to be able to continue consuming after this kind of shock (which is directly related to the category '1. stopped consuming to some extent'). Similarly, it does not represent an Avoidance strategy because it does not increase the likelihood that at least one area, activity or resource can thrive in changing conditions or unpredictable environments. Furthermore, it does not represent a Diversification or Transformation strategy.

Add File 3. Scores of responses (classes of variables) for each strategy.

Functional variables	Categories	Strategies				
		Tolerance	Resistance	Avoidance	Diversifi -cation	Transfor -mation
B. Livestock consumption (sheep, goats, cattle): immediately post-ash to present	0. they did not stop consuming	0	2	0	0	0
	1. they stopped consuming to some extent	2	0	0	0	0
C. 'Immediate' incorporation of other animals for consumption and/or sale (T2)	0. no	1	2	0	0	0
	1. yes (poultry/pigs)	0	0	1	2	1
D. Diversification of farm animals (poultry/pigs) (T3)	0. they did not diversify	1	2	0	0	0
	1. they diversified	0	0	1	2	2
E. Extensive livestock foraging	0. they started foraging (at least for a while)	0	1	2	0	1
	1. they continued foraging	1	2	1	0	0
F. Forage production	0. they have not produced or stopped producing with the ashfall	1	0	1	0	0
	1. they started producing after the ashfall	0	0	1	2	1
	2. they continued to produce forage	1	2	0	0	0
G. Vegetable garden after ashfall to the present	0. no vegetable garden in the period or they abandoned it	2	0	0	0	0
	1. They maintained/enhanced the garden (they did it before the ash and in 2018 they continued)	1	2	0	0	1
H. Networks that were activated	0. None or informal (family, neighbors)	1	2	0	0	0
	1. institutional (and informal)	0	2	0	0	0
I. Economic support of the system during the disturbance and thereafter	0. relied on extra-farm income (employment/pension)	2	0	1	1	0
	1. field production was maintained or enhanced	0	2	0	0	0
k. People who make up the household	0. field alone or with a position holder in some period 2011-2019	1	0	0	0	0
	1. one permanent person in the field and no one else, neither temporary nor sporadic	2	1	0	0	0
	2. a permanent person and other temporary and/or sporadic person(s)	1	2	0	1	0
	3. more than one permanent person	0	2	0	1	0
L. Did anyone migrate from the countryside between 2011 and 2019?	0. no	1	2	0	0	0
	1. yes	0	0	2	1	1
	0. none	1	1	0	0	0
M. Link with tourism	1. sale of products, odd job	0	1	0	1	0
	2. with investments or permanent employment	0	1	2	2	2

Section 2.2. *Adaptation strategies standardization of scores*

To compare the strategies with each other, given that each strategy obtained different values, it was necessary to normalize the scores afterward. To do this, we calculated the 'maximum possible total value' that a household could obtain per strategy through the summation of the maximum scores for each variable (for each strategy). For example, if a given variable with two categories options was assigned a score of '2' to the first and '1' to the second for the 'Tolerance' strategy, the score of '2' was considered for the summation of the 'maximum possible total value' for that strategy (Example in Additional File 4). These normalized values were then used after calculating the scores for each strategy for each archetype of functional response (Example in Additional Files 4) to be able to compare them with each other.

Add File 4. Example of scores per class of each variable for each adaptive strategy. In bold variable's values considered for the sum.

		Adaptive strategy				
Functional variable	**Category**	**Tolerance**	**Resistance**	**Avoidance**	**Diversifi-cation**	**Transfor-mation**
A	A.0	0	0	**1**	**2**	**0**
	A.1	**1**	**2**	0	0	0
B	B.0	**2**	**0**	0	0	0
	B.1	0	0	0	**2**	**1**
	B.2	1	0	**1**	2	0
Maximum possible total value		3	2	2	4	1

To calculate the scores for each strategy within each functional archetype, we utilized Additional File 4. We summed the scores based on their responses, considering only the descriptive variables for each archetype. Each archetype's score for a given strategy was then normalized by dividing it by the 'maximum possible total value' for that strategy. This normalization enabled us to assess the relationship between each functional archetype and the different strategies on a scale from 0 to 1. We established a minimum threshold of 0.5 to determine whether a strategy is characteristic of an archetype.

Section 2.3. *Mutualist Strategy* To incorporate this strategy into the analysis, we adopted a different approach that did not rely on scores for two reasons. On the one hand, it was not feasible for us to quantify the strategy, and on the other hand, mutualist strategies (understood as social network agency) were a common denominator across nearly all interviewed households, albeit with nuanced differences. This strategy was directly associated with the variable H. 'Activated Networks'. Class 0. 'None or informal' (family, neighbors) and 1. 'Institutional' (in addition to informal). Additionally, within class 0, we further differentiated households that mentioned not receiving any type of assistance. We considered the mutualist strategy (or social network strategy) to be engaged when households received some form of assistance (economic, logistical, emotional, support, labor) from other people. We analyzed the type of social networks that were activated (relatives, neighbors, formal institutions). The classes of mutualism were defined as follows:

1. None: No social networks were activated, and no assistance was received from any person or institution.
2. Informal: Networks of families, relatives, and neighbors were activated for assistance, collaborative work, and cooperation.
3. Formalized: Assistance and collaborative work were framed within formal work cooperatives, legally recognized indigenous community associations, and coordination with state institutions, Non-Governmental Organizations and the churches.

Add File 5. Functional archetype classes for Descriptive variables: This table presents the classes assigned to each functional archetype, limited to integer values (no decimals). The corresponding classes are Anticipatory, Conservative, Passive, and Reactive. Integer values are highlighted in bold, while values with decimals (which were not considered) are displayed in regular font.

Descriptive Functional Variable	Functional Archetype Class			
	Anticipatory	Conservative	Passive	Reactive
B. Livestock consumption: immediately post-ash to present	**1.00**	**0.00**	**1.00**	**1.00**
C. Immediate incorporation of other animals for consumption and/or sale (T2)	**1.00**	**0.00**	**0.00**	**1.00**
D. Diversification of farm animals (poultry/pigs) (T3)	**1.00**	**0.00**	0.79	0.80
E. Extensive livestock foraging	**1.00**	**1.00**	0.55	**0.00**
F. Forage production	**2.00**	1.05	0.01	**0.00**
G. Garden after ash to present	0.77	0.81	0.47	**1.00**
H. Networks that were activated: family (family assistance), social (neighbor assistance), institutional (indigenous community, cooperative, fairs, markets, INTA)	**1.00**	0.34	0.07	**1.00**
I. Economic support of the system	**1.00**	0.59	**0.00**	0.65
K. People who make up the household in the field	**3.00**	**3.00**	**0.00**	**3.00**
L. Did anyone migrate from the field between 2011 and 2019?	**1.00**	**0.00**	**0.00**	**0.00**
M. Link with tourism	**0.00**	**0.00**	**0.00**	**2.00**

Add File 6. Comparison between functional archetypoids and correspondence with archetypes according to structural characteristics. The cell values range from '0' (0%), indicating no correspondence, to '1' (100%), indicating maximum correspondence.

Functional archetypoids				Structural archetypoids			
Anticipatory	Conservative	Passive	Reactive	1.CM	4.DF	3.AI	2.ED
1.00	0.00	0.00	0.00	**1.00**	0.00	0.00	0.00
1.00	0.00	0.00	0.00	0.68	0.00	0.18	0.15
1.00	0.00	0.00	0.00	0.64	0.23	0.12	0.00
1.00	0.00	0.00	0.00	0.42	0.50	0.08	0.00
0.00	**1.00**	0.00	0.00	0.55	0.28	0.03	0.14
0.00	**1.00**	0.00	0.00	0.17	0.18	0.65	0.00
0.00	**1.00**	0.00	0.00	0.00	0.00	0.31	0.69
0.00	0.00	**1.00**	0.00	0.20	0.02	0.78	0.00
0.00	0.00	**1.00**	0.00	0.13	0.00	0.46	0.40
0.00	0.00	**1.00**	0.00	0.00	0.45	0.00	0.55
0.00	0.00	0.00	**1.00**	0.31	0.51	0.00	0.19

Add File 7. Association between functional response archetypes and the adaptation strategies. The functional response are Passive (P), Conservative (C), Anticipatory (A), and Reactive (R). The scores are assigned as a proportion of the total score for each archetype.

		Functional archetype			
	Normalized Strategy Score	P	C	A	R
Adaptation Strategies	Tolerance	0.53	0.33	0.33	0.33
	Resistance	0.24	0.62	0.52	0.48
	Avoidance	0.10	0.10	0.50	0.60
	Diversification	0.09	0.18	0.55	0.73
	Transformation	0.00	0.00	0.44	0.56

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