



OPEN ACCESS

EDITED BY

Palden Tsering,
Qinghai Nationalities University, China

*CORRESPONDENCE

Elisabeth Huber-Sannwald,
✉ ehs@ipicyt.edu.mx

†PRESENT ADDRESS

Andrea Valeria Guzmán-Miranda,
Universidad Nacional Rosario Castellanos,
Soledad de Graciano Sánchez, San Luis
Potosí, Mexico
Rodrigo Dávila-Ortiz,
Department Geociencias Aplicadas,
Instituto Potosino de Investigación
Científica y Tecnológica (IPICYT), San Luis
Potosí, Mexico

RECEIVED 19 June 2026

REVISED 24 September 2026

ACCEPTED 30 September 2026

PUBLISHED 28 October 2026

CITATION

Guzmán-Miranda AV, Huber-Sannwald E,
Dávila-Ortiz R, Martínez-Tagüña N,
Alvarado F, Mora-Ledesma MI and
Velázquez-Martínez M (2026)
Understanding social-ecological
vulnerability in goat pastoral systems
through a participatory multi-stakeholder
spatial assessment.
Pastoralism 16:17175.
doi: 10.3389/past.2026.17175

COPYRIGHT

© 2026 Guzmán-Miranda, Huber-Sannwald, Dávila-Ortiz, Martínez-Tagüña, Alvarado, Mora-Ledesma and Velázquez-Martínez. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Understanding social-ecological vulnerability in goat pastoral systems through a participatory multi-stakeholder spatial assessment

Andrea Valeria Guzmán-Miranda^{1†}, Elisabeth Huber-Sannwald^{1*}, Rodrigo Dávila-Ortiz^{2†}, Natalia Martínez-Tagüña³, Fredy Alvarado¹, María Isabel Mora-Ledesma⁴ and Mauricio Velázquez-Martínez⁵

¹División de Ciencias Ambientales, Instituto Potosino de Investigación Científica y Tecnológica (IPICYT), San Luis Potosí, Mexico, ²Universidad Nacional Rosario Castellanos, Soledad de Graciano Sánchez, San Luis Potosí, Mexico, ³Centro de Investigación en Ciencias Sociales y Estudios Regionales, Universidad Autónoma del Estado de Morelos (UAEM), Cuernavaca, Mexico, ⁴El Colegio de San Luis (COLSAN), San Luis Potosí, Mexico, ⁵Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Campo Experimental San Luis, San Luis Potosí, Mexico

Dryland pastoral systems are increasingly affected by the interrelation between socioenvironmental variability and change with land degradation. In Mexico, goat pastoralism (CaprinoCultura) represents a key social-ecological system (SES) that sustains rural livelihoods under highly constrained conditions. This study examined how social-ecological drivers operating across household, ejido and regional scales shape the vulnerability of CaprinoCultura in the Altiplano Potosino. It also questioned how different stakeholder groups perceive and prioritize these drivers. Thus, we developed a novel Participatory Vulnerability Assessment Framework (PVAf) that combined SES characterization, stakeholder-based criteria selection, and weighting and spatial multi-criteria analysis. The assessment integrated biophysical, socio-economic and institutional dimensions co-defined by pastoralists, academics, government representatives and civil society organizations. Results revealed marked spatial heterogeneity in the convergence of vulnerability-associated conditions in the integrated assessment, with northern and eastern municipalities showing greater concentrations of conditions like ecosystem degradation, high grazing pressure, migration, limited access to resources, and governance and institutional constraints. In contrast, southwestern municipalities generally showed lower and more heterogeneous levels of convergence across these conditions. Stakeholder-specific assessments showed broadly similar spatial patterns but differed in the relative importance assigned to individual conditions. Pastoralists tended to prioritize drivers directly affecting daily herd management, such as grazing pressure and ecosystem degradation, whereas government, academics and civil society organizations placed greater emphasis on broader institutional, ecological and social processes, including communal land-governance constraints and migration. Despite these differences, stakeholder perspectives converged on several key challenges affecting CaprinoCultura's long-term viability. These findings underscore the importance of using participatory knowledge in spatial analysis to coproduce more context-

specific and socially informed strategies for the management and sustainability of pastoral systems. Therefore, by integrating stakeholder knowledge and priorities into spatial analysis, this study provides a novel operational approach for a participatory vulnerability assessment that enhances adaptive governance in dryland pastoral systems.

KEYWORDS

caprinocultura, goat pastoralism, Mexico, multicriteria analysis, participatory mapping, pastoral system

Introduction

Pastoral systems are inherent elements of most dryland regions worldwide (Reid et al., 2008). Pastoralist livelihoods have developed under resource scarcity by harnessing synergies between livestock, rangelands and adaptive management practices (Sharifian et al., 2023), while remaining deeply connected to their land (Fernández-Giménez and Estaque, 2012; Oba, 2013). Herders adapt by adjusting livestock mobility, herd size or composition and diversifying livelihood activities (Amsidder et al., 2021; Bostedt et al., 2023). Place-based knowledge and adaptive capacity have enabled pastoral societies and dryland ecosystems to co-evolve as interconnected social-ecological systems (SES) (Huber-Sannwald et al., 2012; Reid et al., 2014). However, pastoral systems increasingly face megadroughts, agro-industrial expansion, migration, cultural transformations, land privatization, degradation and desertification (Reid et al., 2014; Cherlet et al., 2018; Manzano et al., 2021).

The Southern Chihuahua Desert in Mexico has a long-standing tradition of goat pastoralism (Urquijo Torres, 2017), supporting regional livelihoods and pastoral identities rooted in ecological knowledge, sociocultural values, and strong relationships with grazing territories (Brondizio et al., 2021; Fernández-Giménez and Wilmer, 2025). From now on, we will refer to this regional goat pastoral system as *CaprinoCultura*, a term intended to emphasize its cultural heritage, institutional relevance, and contribution to dryland livelihoods (Mora-Ledesma, 2011; Urquijo Torres, 2017; Wurzinger et al., 2013; Barrera-Perales et al., 2018; Trenti-Veru et al., 2021).

These goat pastoral systems are extensively grazed under communal land tenure regimes (ejidos) in designated open rangelands (Pinos-Rodríguez et al., 2013). Their functioning relies on interactions between community decision-making, communal land governance, local ecological knowledge and intrinsic social-ecological dynamics (Mora-Ledesma, 2011; Urquijo Torres, 2017; Gómez-Ruiz et al., 2012; Huber-Sannwald et al., 2012; Barrera-Perales et al., 2018). As in other pastoral regions, *CaprinoCultura* is vulnerable to increasing environmental and socioeconomic pressures (Barrera-Perales et al., 2018; Mora-Ledesma, 2020). Yet, how these pressures interact with communal governance, household organization, and local knowledge to shape pastoral vulnerability remains insufficiently understood. Hence, a systematic assessment of multiple dimensions of vulnerability in these systems is needed to inform context-specific interventions towards sustainable solutions.

Vulnerability assessment in SES has evolved from approaches focused primarily on physical hazards toward more integrative frameworks emphasizing interactions among exposure, sensitivity and adaptive capacity (Turner et al., 2003; Bennett et al., 2016).

Exposure refers to the extent to which a system experiences socio-environmental trends and shocks; sensitivity addresses the degree to which a system's socio-ecological components are affected by external pressures; and adaptive capacity considers the ability of a SES to respond and adjust to disturbance. From an SES perspective, vulnerability is not simply the presence or intensity of a hazard, but an emergent property arising from interactions between society and nature and shaped by the characteristics and organization of the system (Depietri, 2020; Thiault et al., 2021). These interactions occur across spatial and organizational scales and are influenced by institutional, financial, technological, cultural, and political conditions that shape the adaptive capacity (Bennett et al., 2016). Consequently, understanding vulnerability requires examining not only what stressors affect the system, but why it is susceptible to them, how responses are organized and how vulnerability is distributed across space. For analytical purposes, we distinguish vulnerability itself from vulnerability-associated conditions through which its dimensions become observable in SES. These conditions may relate to exposure, sensitivity, or adaptive capacity and can be spatially assessed when appropriate indicators are available.

Evaluating pastoral vulnerability serves not only to characterize susceptible areas but also to identify priorities for context-specific intervention (Metcalf et al., 2015; Yang et al., 2023). As it has been suggested previously, SES vulnerability assessments need to bridge ecological and cultural dimensions (Long and Steel, 2020) and adopt flexible methodological frameworks (Singh et al., 2020; Thiault et al., 2021) capable of capturing the plurality of realities experienced by actors within these systems (Masterson et al., 2017). Understanding the causes and spatial distribution of vulnerability requires context-specific spatial and temporal indicators capable of capturing how multiple stressors are distributed and where they converge across heterogeneous landscapes (Kok et al., 2016; Li et al., 2025). Multi-Criteria Analysis (MCA) integrates heterogeneous socioenvironmental information by standardizing and weighting multiple criteria within a common spatial framework (Amiri et al., 2014; Balew et al., 2022). Thus, combined with participatory approaches, MCA incorporates the knowledge and priorities of actors embedded within the system (Bennett et al., 2016; Thiault et al., 2021).

Pastoral systems require place-based approaches because social practices, ecological interactions, and local knowledge shape vulnerability contexts (Johnsen et al., 2019; Manzano et al., 2021; Sharifian et al., 2022). Hence, deep local understanding is fundamental for assessing vulnerability and enhancing sustainability (Levin et al., 2013). Understanding pastoral systems as SES calls for a transdisciplinary approach that accounts for weaving different knowledge systems (Johansson and Isgren, 2017; Jamsranjav et al., 2019), diversity of local contexts

(Amsidder et al., 2021; Scoones, 2023), and joint exploration of resilience or vulnerability (Linstädter et al., 2016; Semplici et al., 2024). Engaging with this complexity through multi-stakeholder knowledge co-production foster social innovation and collective learning, support co-adaptive management, and reduce uncertainty in decision-making (Wilmer et al., 2018; 2022; Fernández-Giménez, 2020; Reid et al., 2021; Roche, 2021; Mata-Páez et al., 2025).

Effective transdisciplinary collaboration (i.e., Reid-Shaw et al., 2021), requires participatory approaches that foster inclusive intercultural dialogue and trust-building (Coppock, 2016; Pappagallo and Semplici, 2020). For pastoral systems, participatory methodologies are sensitive to the intertwined territorial, social, and ecological realities of each community, while drawing on the expertise of the main actors, the herders (Johnsen et al., 2019; Scoones, 2023). Through mobility and close interaction with nature, pastoralists garner extensive knowledge of the spatial and temporal characteristics of their rangelands (Fernández-Giménez, 2000; Oba, 2013). Acknowledging pastoralists' land-based knowledge affirms their cultural identity and sense of place linked to grazing territories, key aspects of community wellbeing and livelihoods (Frank et al., 2018; Fernández-Giménez et al., 2021).

Vulnerability assessments of pastoral systems adopting a SES framework remain relatively scarce (Yang et al., 2023; Gatew and Guyo, 2024). While participatory studies demonstrate the value of local knowledge (Ayantunde et al., 2015; Johnsen et al., 2019), and spatial assessments increasingly integrate indicators of pastoral vulnerability (Yang et al., 2023), but systematic integration of multiple stakeholder perspectives into the selection and prioritization of spatial vulnerability criteria remains limited. This gap is important because vulnerability in pastoral SES is shaped by ecological, territorial, institutional, and social processes that are perceived and prioritized differently by actors occupying different positions within the system. To address this gap, we developed a Participatory Vulnerability Assessment Framework (PVAf) combining social-ecological characterization, stakeholder-derived vulnerability criteria and priorities, and spatial MCA to examine the spatial differentiation of vulnerability-associated conditions in the Altiplano Potosino. Integrating multiple stakeholder perspectives into their identification and prioritization allows vulnerability to be examined as both spatially differentiated and socially situated.

Therefore, we asked how environmental, territorial, social, and institutional drivers operating across household, ejido, and regional scales shape vulnerability in CaprinoCultura. Specifically, we asked how stakeholder groups perceive and prioritize these drivers and how these can inform a participatory spatial assessment of vulnerability-associated conditions. Our objectives were to: (1) identify and characterize the main vulnerability drivers through a multi-stakeholder participatory process; (2) integrate pastoralist, academic, governmental, and civil society knowledge into their identification and prioritization; and (3) develop a participatory spatial multi-criteria assessment to identify areas where multiple vulnerability-associated conditions converge and where context-specific interventions may be prioritized.

This study contributes conceptually by showing how vulnerability-associated conditions are spatially differentiated in relation to the social, ecological, territorial, and institutional processes shaping pastoral SES, while recognizing that actors

perceive and prioritize these conditions differently. Rather than treating vulnerability as a directly measurable property, we approach it as an emergent and socially situated property whose spatial expression can be examined through stakeholder-informed indicators. Methodologically, the study expands participatory multi-criteria approaches by incorporating stakeholder-derived priorities rather than relying solely on researcher-defined criteria and weights, linking multiple knowledge systems with spatial decision support for more inclusive and context-specific processes of planning and governance.

Materials and methods

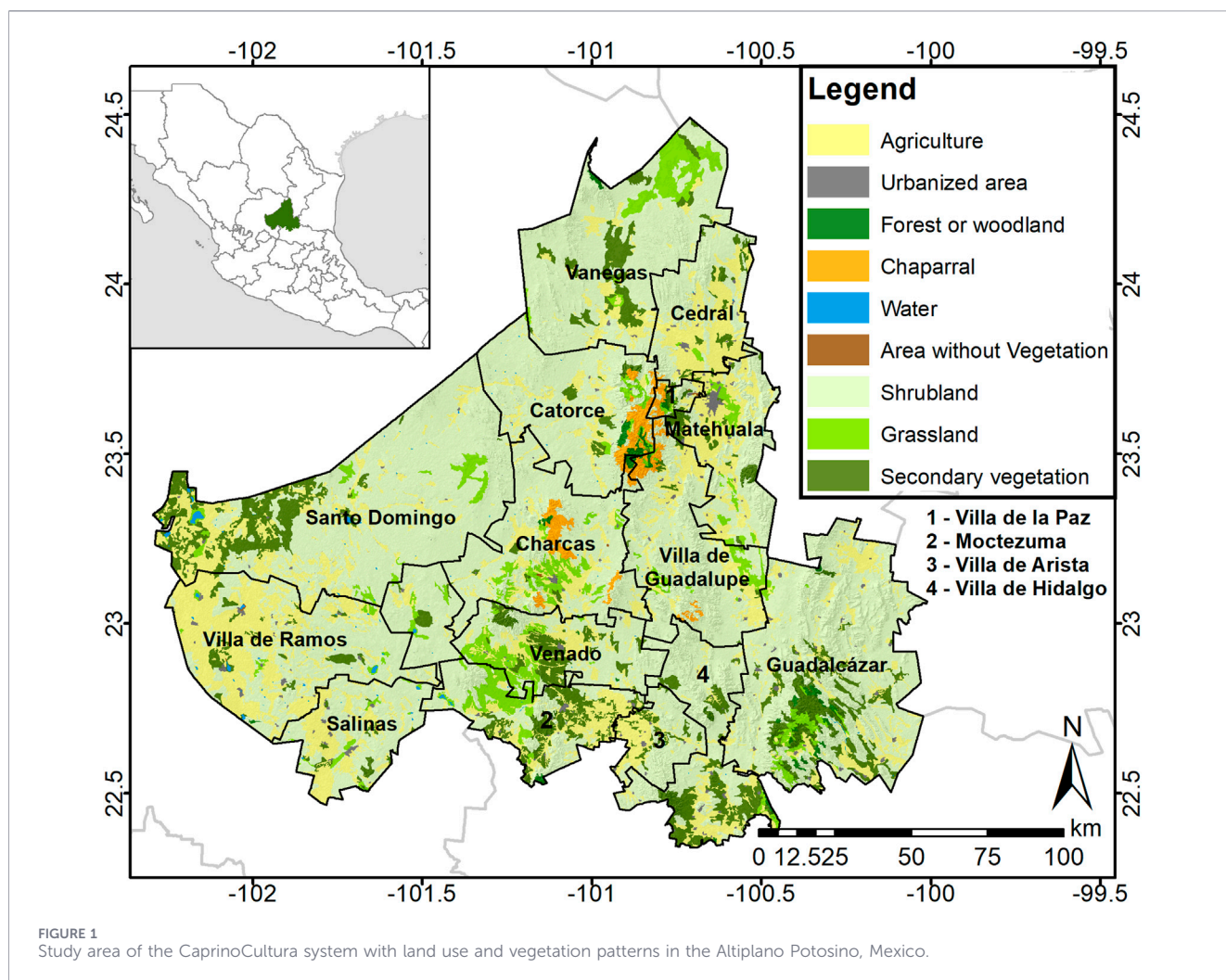
Study area

The Altiplano Potosino is located in the Southern Chihuahua Desert in San Luis Potosi, Mexico (Figure 1), covering approximately 21,510 km² within the Mesa Central physiographic province (Instituto Nacional de Estadística y Geografía [INEGI], 2001). The region comprises intermountain plains, tectonic depressions and north-south-oriented mountain ranges at 1,500–2,000 m a.s.l., shaped by a geological history of Mesozoic sedimentary basins overlain by Cenozoic volcanic sequences. Soils range from calcareous xerosols in western and northern areas to shallow lithosols and more fertile pheozems in the south.

The predominant climate is temperate dry (BS1) with seasonal rainfall concentrated between June and October and occasional precipitation events in December and January (García, 2004). Mean annual precipitation is below 400 mm, and the average annual temperature is approximately 18 °C, with extremes ranging from 8.4 °C to 32 °C (CONAGUA, 2023). The Altiplano Potosino falls within the administrative hydrological region of El Salado, the driest in the country, with an estimated annual runoff of 10–20 mm (Negrete, 2020).

Vegetation varies along gradients of altitude, water availability and topography. Xerophytic vegetation dominates most of the region, particularly microphyllous and rosetophyllous desert scrublands (Rzedowski, 1961), including species such as *Larrea tridentata*, *Flourensia cernua*, *Parthenium incanum*, *Agave lechuguilla*, and *Yucca filifera*. Microphyllous scrublands and grasslands cover the intermountain plains and lowlands, whereas rosetophyllous scrublands are more common on rocky slopes and mountainous areas. In higher elevations, these vegetation types gradually transition into temperate woodlands and conifer forests. Halophytic grasslands and mesquite woodlands occur locally depending on soil salinity, soil depth, and topographic conditions (Instituto Nacional de Estadística y Geografía [INEGI], 2018).

Goat pastoralism is concentrated in microphyllous and rosetophyllous scrublands, where goats are morphologically and behaviorally adapted to consume thorny and fibrous vegetation (Echavarría-Cháirez and Gómez-Ruiz, 2013). Pastoral mobility follows seasonal vegetation and rainfall dynamics: herds use grasslands and lowlands during the dry season and shift toward mountainous areas during the dry season (Mora-Ledesma, 2020). These movements are constrained by the limits of communal grazing territories and land-tenure arrangements



(Negrete-Sánchez et al., 2016; Rivera et al., 2020). Unlike cattle production, which is commonly associated with fenced properties, goat pastoralism is predominantly practiced by ejidal smallholders under communal open-grazing regimes (Trenti-Verly et al., 2021; Tajonar et al., 2022).

The Altiplano Potosino has dispersed rural settlements and high levels of marginalization, poverty, and inequality (CONEVAL, 2020). Over recent decades, it has undergone rapid territorial transformation driven by irrigated agriculture, mining, renewable energy projects, horticultural agro-industries and the automotive sector (Montiel Torres, 2019). These processes have fragmented rangelands, reduced rainfed farming areas, altered labor dynamics, and contributed to changes in communal tenure systems and land-use patterns (Ortega and Morán, 2020; Morán et al., 2023).

Mexican agricultural policy organizes farming and livestock activities into “production units,” which are operational entities comprising one or more land parcels and farming infrastructure managed under a shared household or collective decision-making structure (SADER, 2021). In the Altiplano Potosino, goat herding is largely organized through these units, which constitute an important operational scale for herd management, grazing mobility, labor organization, and resource allocation. Goat production has a long history in the region, dating back to the sixteenth century, when

herding was carried out by laborers working on haciendas within colonial production systems (Mellado, 1997; Oseguera Montiel et al., 2014). Following the Mexican Revolution, agrarian reforms established ejidal communal tenure, reshaping pastoral territorial organization. In 1992, PROCEDE (in Spanish: “Programa de Certificación de Derechos Ejidales y Titulación de Solares”) enabled the certification of ejidal rights and opened possibilities for changes in tenure and privatization, contributing to subsequent social-ecological transformations in pastoral systems (Huber-Sannwald et al., 2012; Mora-Ledesma, 2020).

Participatory vulnerability assessment framework

This study adopts a social-ecological systems (SES) approach (Reid et al., 2014), to characterize goat pastoral systems in the Altiplano Potosino and spatially assess their multidimensional vulnerability. A literature review was conducted on pastoral SES in drylands worldwide, focusing on pastoral mobility, rangeland governance, livelihood diversification and vulnerability dynamics (Guilherme et al., 2017; Vilá et al., 2020; Tajonar et al., 2022; Vargas et al., 2022; Sharifian et al., 2023), as well as the socio-economic, socio-political and socio-cultural dimensions of goat pastoralism in

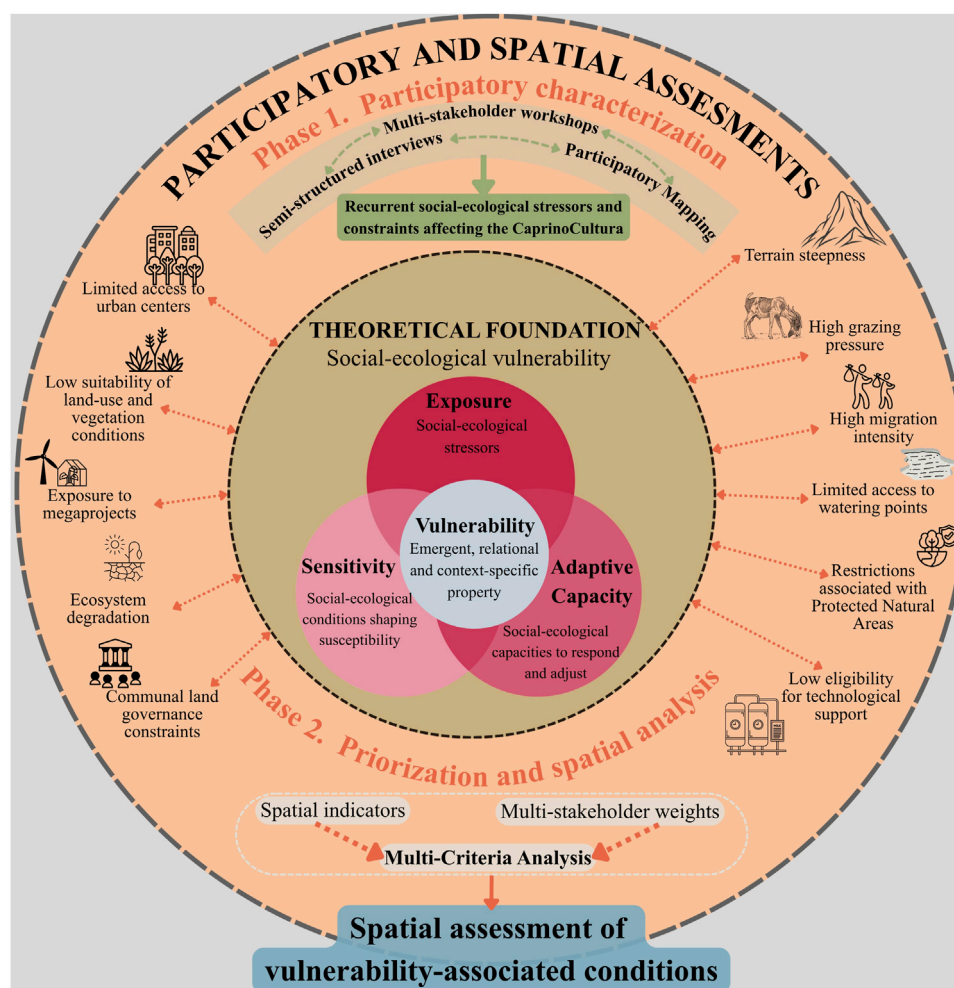


FIGURE 2

Conceptual representation of the Participatory Vulnerability Assessment Framework (PVAf) applied to CaprinoCultura in the Altiplano Potosino. The framework conceptualizes vulnerability as an emergent, relational and context-specific property of a social-ecological system, arising from interactions among exposure, sensitivity and adaptive capacity. In Phase 1, participatory methods were used to identify recurrent social-ecological stressors and constraints affecting CaprinoCultura, which were synthesized into vulnerability-associated criteria and interpreted according to their predominant relationship with the three vulnerability dimensions. In Phase 2, spatially operationalizable criteria were represented through geospatial indicators and combined with multistakeholder-derived weights using Multi-Criteria Analysis (MCA). The resulting spatial assessment represents the relative distribution and convergence of vulnerability-associated conditions rather than a direct measure of vulnerability.

the Altiplano Potosino (Mora-Ledesma, 2011; 2020; Urquijo Torres, 2017; Potosí, 2013; Barrera-Perales et al., 2018; Ortega and Morán, 2020). This review informed the participatory research design and provided contextual information on pastoral characteristics, challenges, and adaptive responses. Consultations with goat pastoralism specialists from Argentina, Chile and Mexico provided additional comparative insights.

For clarity, we distinguish among vulnerability, vulnerability-associated conditions, vulnerability drivers, vulnerability criteria, and vulnerability indicators. Vulnerability is understood as an emergent, relational, and context-specific property of a social-ecological system. Vulnerability-associated conditions refer to environmental, social, territorial, and institutional conditions through which vulnerability becomes observable in a particular context. Vulnerability drivers refer to stressors, changes, or constraints identified by stakeholders as influencing these vulnerability-associated conditions, without implying causal

relationships. Vulnerability criteria are broader analytical categories synthesized from recurring participatory evidence, while vulnerability indicators are measurable variables used to represent these criteria spatially when suitable data are available. For example, stakeholders identified drought, land-use change, migration, and limited access to resources as factors influencing vulnerability-associated conditions. These participatory findings were synthesized into vulnerability criteria such as ecosystem degradation, high migration intensity, and limited access to watering points, which were then represented using measurable spatial indicators where data allowed.

The Participatory Vulnerability Assessment Framework (PVAf) comprises two phases (Figure 2). Phase 1 characterizes CaprinoCultura as an SES across three interconnected spatial/institutional scales: (1) household/production unit, (2) ejido/shared territory, and (3) regional/shared landscape governance (Altiplano Potosino) (Figure 3). Phase 2 organizes stakeholder-

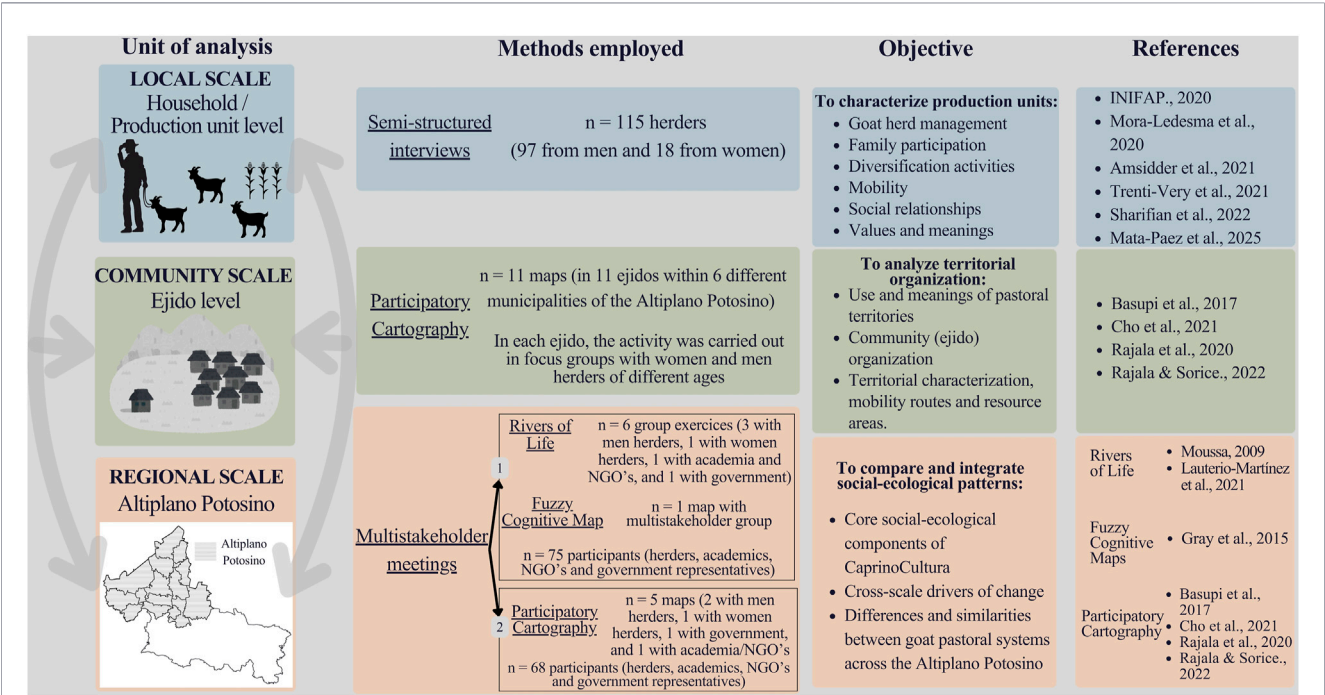


FIGURE 3
Phase 1 of the Participatory Vulnerability Assessment Framework: multi-scale participatory social-ecological characterization of goat pastoral systems in the Altiplano Potosino, showing the three spatial/institutional scales, participatory methodologies, objectives, and references.

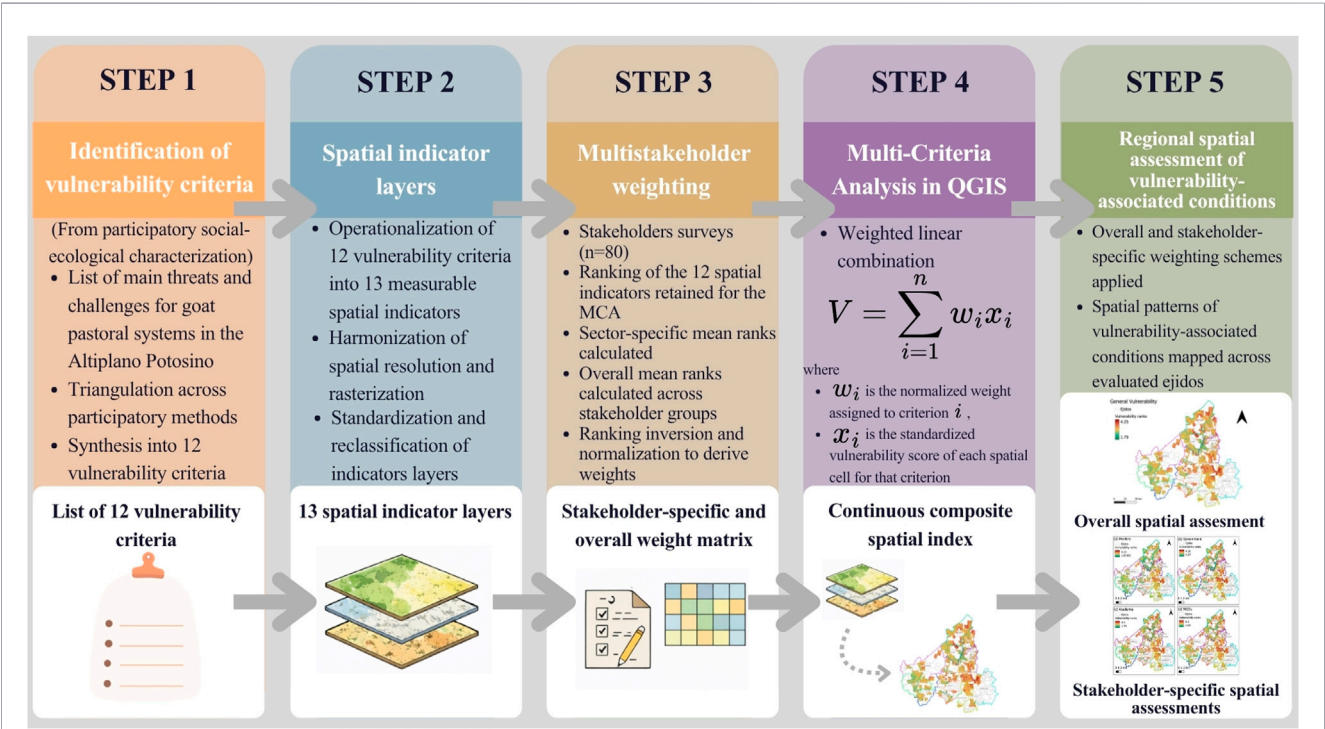


FIGURE 4
Phase 2 of Participatory Vulnerability Assessment Framework: conceptual and analytical workflow for assessing vulnerability-associated conditions in CaprinoCultura through stakeholder-derived weights and standardized geospatial indicators.

identified vulnerability-associated conditions into conceptual criteria, operationalizes them using spatially explicit indicators, and integrates them through Multi-Criteria Analysis (MCA) within a Geographic Information System (GIS) framework (Figure 4). The MCA does not directly measure vulnerability or model causal interactions; rather, it provides an integrative spatial representation of the relative convergence of vulnerability-associated conditions based on stakeholder-derived priorities. Details of each phase are described below.

Phase 1: participatory social-ecological characterization of goat pastoral systems

The participatory approach combined qualitative and multi-stakeholder methods to characterize CaprinoCultura as an SES across multiple scales and identify environmental, economic, social, institutional and territorial drivers considered relevant to its vulnerability. At the household/production-unit level, participants identified herd management, mobility, livelihood diversification, and family participation; at the ejido level, communal grazing practices, collective land-use arrangements and rangeland governance; and at the regional scale, broader environmental, institutional and socio-economic dynamics (Figure 3).

At the household/production unit level, we conducted semi-structured interviews in 2023 with 115 pastoralists (97 men and 18 women) managing goat production units (regardless of formal registration) from 17 ejidos in six municipalities of the Altiplano Potosino. Snowball sampling was used to broaden representation across pastoral and grazing contexts (Atkinson and Flint, 2001). Interviews addressed herding strategies, livelihood diversification, pastoral routes within communal grazing territories, family participation in pastoral activities, and experiences and projections regarding drivers jeopardizing pastoral development and territorial access (INEGI, 2020; Mora-Ledesma et al., 2020; Amsidder et al., 2021; Trenti-Very et al., 2021; Sharifian et al., 2022; Mata-Paez et al., 2022). They also explored cultural meanings and local knowledge associated with goat pastoralism, as well as perceived environmental, institutional and socioeconomic stressors.

Because interviews revealed ejido-specific territorial arrangements, grazing rules, and mobility patterns, then a participatory mapping was conducted between late 2023 and early 2024 with 11 pastoralist focus groups, one per ejido, in Catorce, Charcas, Vanegas, Villa de Guadalupe, Cedral and Matehuala (Figure 1). Participants mapped grazing territories, seasonal routes, management practices, mobility constraints, and areas considered constrained, degraded, threatened, or important for CaprinoCultura. These exercises also examined collective governance and the role of local ecological knowledge in pastoral decision-making (Rajala et al., 2020; Rajala and Sorice, 2022; Basupi et al., 2017; Cho and Mutanga, 2021).

To examine regional heterogeneity across municipalities of the Altiplano Potosino, two multi-stakeholder workshops were organized in Matehuala, San Luis Potosí (Table 1; Supplementary Material S2). The first, conducted in late 2023, included 75 participants: 52 pastoralists (42 men, 10 women), 8 academics, 11 government representatives, and 4 NGOs. Participants reconstructed the historical trajectory of CaprinoCultura through

six “Rivers of Life” (Moussa, 2009; Lauterio-Martínez et al., 2021), identifying different major social-environmental drivers, understood here as stressors, changes, or constraints perceived by participants as influencing the conditions of CaprinoCultura. Three Rivers of Life were produced by male pastoralists, one by female pastoralists, one by academics and NGOs, and one by government representatives. A collective Fuzzy Cognitive Map (FCM), based on Gray et al. (2015), was then developed to identify key social-ecological drivers influencing CaprinoCultura.

The second workshop, organized in 2024, gathered 68 participants: 50 pastoralists (38 men and 12 women), 10 academics, 5 government representatives and 3 NGO members. Participants used printed regional maps at a scale of 1: 50,000 derived from high-resolution Google Earth imagery to identify spatial similarities and differences in pastoral systems across the Altiplano Potosino. Stakeholder groups first discussed how landscapes, pastoral practices, environmental conditions, and threats vary throughout the region. They then identified core drivers causing these differences, including vegetation patterns, land-use change, water access, institutional constraints, market pressures and environmental degradation. Five maps were produced: two by male pastoralists, one by female pastoralists, one by government representatives, and one by academics and NGOs.

Phase 2: participatory vulnerability assessment of pastoral systems

Building on Phase 1, vulnerability drivers and associated conditions were identified across interviews, participatory mapping exercises, Rivers of Life, and multi-stakeholder workshops, where participants discussed the principal environmental, territorial, institutional and socio-economic stressors and constraints affecting the development and sustainability of CaprinoCultura.

Twelve vulnerability-associated criteria were derived from these complementary participatory sources through methodological triangulation (Patton, 1999). The research team compared evidence across methods and stakeholder groups to identify shared and complementary accounts of vulnerability drivers and associated conditions, grouping conceptually related concerns into broader social-ecological criteria. For example, concerns about excessive livestock use and limited regulation of herd sizes were considered together when defining a broader criterion related to grazing pressure. This interpretive synthesis did not involve formal thematic coding or counts of response frequencies. The resulting criteria were aligned with the vulnerability framework and operationalized using spatially explicit information (Figure 4).

The twelve vulnerability criteria are: (1) reduced annual precipitation, (2) limited access to urban centers, (3) low suitability of land-use and vegetation conditions for goat pastoralism, (4) exposure to megaprojects, (5) ecosystem degradation, (6) high grazing pressure, (7) communal land governance constraints, (8) terrain steepness limiting pastoral accessibility, (9) high migration intensity, (10) limited access to watering points, (11) restrictions associated with nearby Protected Natural Areas, and (12) low eligibility for technological support programs. Criteria were classified according to their relationship within the vulnerability framework as representing exposure,

TABLE 1 Social-ecological indicators used for the spatial assessment of CaprinoCultura in the Altiplano Potosino.

Vulnerability criterion	SES dimension	Geospatial indicator	Data source	Vulnerability-associated condition level				
				Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Limited access to urban centers	Market access	Distance to municipal urban centers (km)	INEGI* topographic data (2022)	0–10	11–20	21–30	31–40	>40
Low suitability of land-use and vegetation conditions	Biophysical suitability	Land use/Vegetation type	INEGI* series VII land use and vegetation dataset (2022)	Desert shrubland	Natural grassland	Cultivated grassland, mesquite woodland	Oak forest	Irrigated agriculture
Exposure to megaprojects	Land-use pressure	Distance to agroindustrial, mining and wind energy projects (km)	Participatory mapping and georeferencing	>40	31–40	21–30	11–20	0–10
Ecosystem degradation	Vegetation condition	Soil-adjusted vegetation index (SAVI)	Google earth Engine (2024)	≥0.58	>0.40 - <0.58	>0.231–0.40	>0.05–0.230	–0.10–0.05
	Soil degradation	Degree of soil degradation	CONABIO* national degradation datasets (2012)	Very low	Low	Moderate	High	Very high
Communal land governance constraints	Governance and institutional capacity	Ratio of communal land area to private land area	RAN* ejido land tenure data (2024)	0–0.20	0.21–0.40	0.41–0.60	0.61–0.80	0.81
Terrain steepness	Topographic constraint	Slope (%)	INEGI* digital elevation models (15 m) (2022)	0–10	11–20	21–30	31–40	>40
High grazing pressure	Grazing pressure	Stocking rate to carrying capacity ratio	SIAP* livestock data (2022) and COTECOCA* carrying capacity estimates	0–0.50	>0.50–1.0	>1.0–1.50	>1.50–2.0	>2.0
High migration intensity	Socio-demographic pressure	Migration intensity index	CONABIO*, migration intensity index (2020)	Very low	Low	Moderate	High	Very high
Limited access to watering points	Resource availability	Distance to livestock watering points (km)	CONABIO*, water bodies dataset (2022)	0–5	6–10	11–15	16–20	>20
Restrictions associated with protected natural areas	Institutional support	Distance to federal or state PNA (km)	CONANP* spatial data* (2025)	0–20	21–40	41–60	61–80	>80
Low eligibility for technological support	Adaptive capacity	Participation in goat development programs	SEDARH*, Goat Regional Program (2016)	Received support	-	-	-	No support

*INEGI, Instituto Nacional de Estadística y Geografía - National Institute of Statistics and Geography in Mexico.

*CONABIO, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad - National Commission for the Knowledge and Use of Biodiversity.

*RAN, Registro Agrario Nacional - National Agrarian Register.

*SIAP, Servicio de Información Agroalimentaria y Pesquera - Agri-Food and Fisheries Information Service.

*COTECOCA, Comisión Técnico Consultiva de Coeficientes de Agostadero - Technical Advisory Commission on Grazing Coefficients.

*CONANP, Comisión Nacional de Áreas Naturales Protegidas - National Commission of Natural Protected Areas.

*SEDARH, Secretaría de Desarrollo Agropecuario y Recursos Hidráulicos - Secretariat of Agricultural Development and Water Resources.

Indicator thresholds were defined based on participatory inputs, social-ecological literature, and statistical classification of spatial datasets. Indicators were standardized to a five-level ordinal scale prior to integration into the multi-criteria assessment; binary indicators were coded according to their observed categories.

sensitivity and adaptive capacity (Table 2). Although some criteria may relate to more than one vulnerability dimension, particularly those associated with adaptive capacity, they were assigned according to their predominant conceptual role.

The participatory characterization identified adaptive capacity processes, including pastoral mobility, local ecological knowledge, livelihood and product diversification, family organization, and flexible herd management. Processes that could not be systematically assessed or spatially extrapolated across the region informed the contextual interpretation, while spatially measurable constraints and enabling drivers, such as access to urban centers and institutional support, were incorporated into the MCA (Table 1).

Each criterion was operationalized using one or more measurable spatial indicators derived from publicly available geospatial datasets, initially resulting in 13 spatial indicators. Ecosystem degradation was represented by two complementary indicators: vegetation condition and soil degradation. Reduced annual precipitation was excluded from the spatial analysis and the stakeholder weighting exercise because it showed limited spatial differentiation across the study area, but it was retained as a regional background condition influencing CaprinoCultura. Thus, 11 criteria represented by 12 spatial indicators were retained for the spatial analysis and weighting exercise (Table 1).

MCA was used to integrate socioenvironmental indicators through weighted combinations of standardized values (Amiri et al., 2014; Balew et al., 2022; Rana and Moniruzzaman, 2023). This approach was considered adequate because the conditions identified through the participatory process are heterogeneous and cannot be represented by a single environmental or socioeconomic variable. MCA allowed indicators with different units, spatial distributions and conceptual dimensions to be standardized and integrated within a common spatial framework. The resulting index does not directly measure vulnerability or establish causal relationships, rather, it represents the relative spatial convergence of vulnerability-associated conditions and provides decision-support information to identify areas where context-specific interventions should be prioritized (Balew et al., 2022).

For each spatial indicator, datasets were prioritized that corresponded as closely as possible to the 2023–2024 participatory research period. When data were not available, we used the most recent dataset with adequate spatial coverage, methodological consistency and reliability. Since the participatory characterization captured processes occurring over time rather than conditions at a single point in time, the spatial indicators represent the most recent available expression of these conditions rather than vulnerability for a single reference year. The reference year and selection rationale for each dataset are reported in Table 1 and detailed in Supplementary Material S1.

All spatial processing was conducted using QGIS v3.40.6. To ensure spatial comparability, all layers were projected into a common coordinate reference system. Raster datasets were standardized to 15 m, while vector datasets were rasterized to maintain consistency in spatial structure. Indicators were reclassified into five-class ordinal classes representing increasing vulnerability-associated conditions: (1) very low vulnerability, (2) low vulnerability, (3) medium vulnerability, (4) high vulnerability, and (5) very high vulnerability. This classification facilitates spatial

comparison in multicriteria analyses (Mena et al., 2012; Balew et al., 2022).

To determine the relative importance assigned to the 12 spatial indicators, a structured survey was conducted with 80 stakeholders: pastoralists (60), academics (10), government representatives (7), and NGOs (3). The survey was administered online and in person in 2025. Participants ranked the 12 spatial indicators retained for the MCA from highest (1) to lowest (12) according to the extent to which they considered each condition to affect CaprinoCultura. Thus, participants expressed their relative priorities through ordinal rankings rather than directly assigning numerical weights. Participants were instructed to assign a unique rank to each indicator; tied rankings were not permitted and all 12 indicators were required to receive a rank. Because ordinal rankings indicate the order of priority but not the magnitude of differences between ranks, resulting weights were interpreted as relative priorities rather than interval-scale measures of preference (Roberts and Goodwin, 2002).

The four stakeholder categories, herders, government, academia and civil society organizations, were selected to represent distinct forms of knowledge, responsibilities, and institutional relationships with the CaprinoCultura system. Herders contributed place-based and experiential knowledge from direct engagement with pastoral production and territories; government representatives contributed institutional and policy perspectives; academic participants contributed scientific and analytical knowledge; and civil society organizations contributed experience in community-based initiatives and rural development. These categories were therefore used as analytical stakeholder perspectives rather than as statistically representative populations.

Because group sizes differed substantially, individual rankings were first aggregated within each stakeholder category using mean ranks. This prevented the larger pastoralist group from determining composite weighting solely through sample size. Mean ranks summarized relative priorities within each stakeholder category. The resulting mean ranks were converted into surrogate weights using an inverse-rank procedure, whereby higher-priority indicators (lower mean rank) received larger weights. Values were then normalized so that weights of the 12 spatial indicators summed to one. Rank-based procedures for deriving surrogate weights from ordinal rankings are established in multi-criteria decision analysis (Stillwell and Seaver, 1981; Roberts and Goodwin, 2002; Burk and Nehring, 2023).

The four stakeholder-specific weighting schemes were applied through weighted linear combination in QGIS to generate four spatial maps. A fifth, integrated map was produced by averaging the four weighting schemes, giving each stakeholder perspective equal influence regardless of group size. The integrated map reflects their combined priorities, while the stakeholder-specific maps show differences in spatial patterns arising from their respective priorities. Values ranged from 1 (very low) to 5 (very high), indicating increasing convergence of vulnerability-associated conditions. These maps were interpreted as relative spatial gradients rather than direct measures of absolute vulnerability.

Three complementary sensitivity analyses assessed the robustness of the spatial MCA to changes in criterion weights, criterion inclusion, and stakeholder aggregation. First, each

TABLE 2 Derivation of vulnerability criteria from participatory evidence and their conceptual classification within the vulnerability framework.

Evidence from participatory process	Vulnerability criterion	Conceptual dimension	Explanation
"There is less rain, and the droughts are becoming longer and harsher"	Reduced annual precipitation	Exposure	Represents a climatic stressor experienced by pastoral systems that directly affects water availability and rainfall-dependent vegetation productivity
"Being far from Matehuala (closest urban center) affects sales and access to services"	Limited access to urban centers	Adaptive capacity	Represents constraints on pastoral households' access to urban services, markets, institutional support, and other resources that may facilitate responses to environmental or socioeconomic disturbances
"There are types of vegetation and soil that are not suitable for goat pastoralism"	Low suitability of land-use and vegetation conditions	Sensitivity	Represents the susceptibility of pastoral production to land-use, soil and vegetation conditions that provide limited suitability for goat pastoralism
"Greenhouses take away our grazing lands . . . as do wind farms and mining companies"	Exposure to megaprojects	Exposure	Represents exposure to large-scale territorial transformations that can reduce access to communal grazing areas and modify the spatial availability of resources for pastoral activities
"Rangelands with poor vegetation are not good for grazing . . . the soil is very degraded, and nothing grows there anymore"	Ecosystem degradation	Sensitivity	Represents the degraded condition of ecosystems and their reduced capacity to sustain forage resources and pastoral production under environmental and production pressures. This criterion was operationalized through two complementary indicators: vegetation condition and soil degradation
"There are always conflicts about how to manage communal area . . . we can't agree on how to limit animal numbers for different livestock types to control overgrazing"	Communal land governance constraints	Adaptive capacity	Represents institutional and collective-action constraints that may limit the ability of communities to coordinate resource use, establish rules and collectively respond to changing environmental and production conditions
"There are very steep areas that limit where we can herd the goats"	Terrain steepness	Sensitivity	Represents physical landscape constraints that limit herd mobility and access to grazing areas, increasing the sensitivity of pastoral production to heterogeneous terrain conditions
"There is a lot of overgrazing . . . people don't regulate the number of their animals and monopolize all the vegetation in the rangeland"	High grazing pressure	Sensitivity	Represents the intensity of livestock use relative to the capacity of rangeland resources to sustain grazing, which may reduce forage availability and contribute to soil and ecosystem degradation
"There is a lot of migration . . . young people no longer want to continue . . . this activity will eventually be forgotten"	High migration intensity	Adaptive capacity	Represents demographic and labor dynamics that may reduce household labor availability and weaken the intergenerational continuity of pastoral knowledge and practices
"If you have access to an earthen dam or a well, you can keep more animals . . . if you don't have an earthen dam or it's too far away, you have to adjust the size of your herd"	Limited access to watering points	Sensitivity	Represents the susceptibility of pastoral production to limited availability or accessibility of water resources required for livestock management

(Continued)

TABLE 2 Continued

Evidence from participatory process	Vulnerability criterion	Conceptual dimension	Explanation
"Being close to protected natural areas gives us access to more training . . . we have to take better care of the vegetation; it encourages better conservation"	Restrictions associated with protected natural areas	Adaptive capacity	Represents institutional and land-use conditions associated with proximity to protected natural areas that may either constrain pastoral flexibility through land-use restrictions or enhance adaptive capacity through access to conservation programs and technical support. For the spatial assessment, this criterion was operationalized through distance to PNAs, with greater distance representing higher levels of vulnerability-associated conditions based on the participatory prioritization of access to institutional and conservation support
"The more support and technology we have, the better the production . . . the training sessions have taught us how to improve rangeland use and increase milk and cheese production"	Low eligibility for technological support	Adaptive capacity	Represents constraints on access to technological, institutional and technical support that can limit opportunities to improve pastoral management and respond to environmental and socioeconomic changes

criterion weight was increased and decreased by 20% relative to its baseline value, one criterion at a time. The remaining weights were proportionally rescaled to preserve a total weight of one. This procedure was repeated for all criteria within each stakeholder group, and each resulting surface was compared with its corresponding baseline using Spearman's rank correlation coefficient (ρ). Second, a leave-one-criterion-out analysis assessed the influence of individual criteria on spatial patterns. Each criterion was removed in turn, and the remaining weights were proportionally rescaled to sum to one. The resulting surfaces were compared with their corresponding baselines using Spearman's ρ , with lower correlations indicating greater changes in the spatial ranking of MCA values. Third, sensitivity to stakeholder aggregation was evaluated by comparing the primary integrated assessment, which assigned equal weight to each stakeholder group (25%), with an alternative weighted by group sample size (60 pastoralists, 10 academics, 7 government representatives, and 3 NGO representatives). The two integrated surfaces were compared using Spearman's ρ to assess similarity in spatial rankings and root mean square error (RMSE) to quantify differences in MCA values.

Results

Historical dynamics of goat populations in San Luis Potosí

Goat populations in San Luis Potosí (Figure 5) increased steadily starting in 1980 and reached over 1.2 million heads by 1994 (SIAP, 2022). This expansion coincided with economic restructuring associated with the General Agreement on Tariffs and Trade (GATT) in 1986 and the North American Free Trade Agreement (NAFTA) in 1994; it integrated Mexican agriculture into global markets and altered incentives for small-scale farmers. Despite these changes, goat numbers sharply declined after 1996, because of

market exposure and broader structural pressures (Montiel Torres, 2019) and out-migration and aging of the rural population thereby reducing labor availability and weakening generational continuity within pastoral systems (Gómez-Ruiz et al., 2012).

During the early 2000s, the nationwide livestock support program *Programa Pecuario Sustentable y Ordenamiento Ganadero y Apícola* (PROGAN) helped stabilize goat production; however, numbers declined after 2006 (Figure 5). Beyond policy and market factors, pronounced climate variability, particularly droughts in 1998, 2000–2001, 2005, and 2011, likely placed additional pressure on pastoral systems. Since 2016, goat numbers have shown moderate recovery, coinciding with the implementation of the Regional Goat Project (Proyecto Regional Caprino) promoted by the Secretaría de Desarrollo Agropecuario y Recursos Hidráulicos (SEDARH) in San Luis Potosí. This project aimed to strengthen goat production through genetic improvement, market development, and animal health management (Anzaldo Montoya, 2024). More favorable conditions may also have contributed to this recovery. The latest available estimate reported approximately 772,075 goats in San Luis Potosí in 2022, with most production units concentrated in the Altiplano Potosino (SIAP, 2022).

Phase 1: participatory characterization of vulnerability-associated conditions in CaprinoCultura

CaprinoCultura in the Altiplano Potosino constitutes a complex social-ecological system shaped by ecological, social, cultural and political interaction dynamics across multiple spatial and temporal scales (Figure 6). Participatory characterization identified vulnerability-associated conditions operating across household, ejido and regional levels, including environmental variability, territorial transformations, governance constraints and changes in household organization and resource

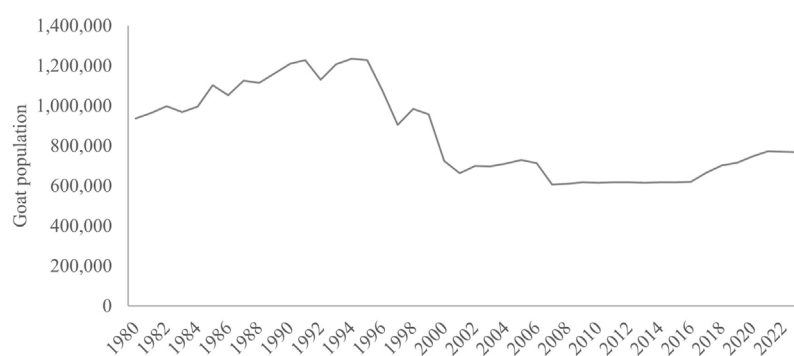


FIGURE 5

Temporal trend of goat population in San Luis Potosí, Mexico (1980–2022). The time series shows sustained growth through the 1980s and early 1990s, followed by a sharp drop after 1996, which extended until 2007; since 2016, goat population has been gradually recovering. Data source: (SIAP, 2022).

access. These conditions informed the vulnerability criteria developed in Phase 2.

Regional environmental and territorial conditions associated with vulnerability

The Altiplano Potosino provides the broader socioenvironmental context in which CaprinoCultura has developed over decades. Participants consistently identified rainfall variability and recurrent droughts as the major environmental constraints affecting forage availability and water access. Herders also described how heterogeneous topography shapes pastoral mobility, expressing a preference for gentle slopes with shrub vegetation over steep hills dominated by succulent vegetation. These observations indicate that grazing activities are spatially concentrated in areas perceived as more suitable for pastoral use.

The region contains three Protected Natural Areas (PNAs), including the Sierra La Mojonera, Wirikuta, and the Guadalcázar State Reserve. Participants described proximity to PNAs having constraining and enabling effects. Designated areas limit intensive livestock practices, land transformation and agrochemical use; while neighboring ejidos may benefit from conservation programs and alternative livelihood opportunities. Participants also associated land-use change, agro-industrial expansion, mining, and wind farms with the loss of communal grazing areas and the fragmentation of traditional pastoral territories following the implementation of PROCEDE in 1992 (Montiel Torres, 2019). This reduction in grazing space reportedly concentrated livestock pressure on the remaining rangelands and constrained traditional mobility. Out-migration among younger generations was likewise associated with reduced household labor availability, disrupted intergenerational knowledge transmission, and an aging herding population (Morán et al., 2023).

Ejido governance and communal resource management

Participants identified communal land governance as a vulnerability-associated condition that varied substantially

among ejidos. Governance structures include ejido assemblies and committee meetings. Relevant actors include *ejidatarios* (formal land rights holders), *posesionados* (possessory rights holders recognized by the ejidal assembly) and *avecindados* (recognized residents with no ejido or possessory rights), whose rights and roles in decision-making differ. Collective decisions address livestock numbers permitted in communal grazing areas, conservation practices, and access to designated areas, such as the “*pasta*”, a communal livestock enclosure reserved for periods of forage scarcity. Some herders also participate in regional organizations such as the Federation of Goat Producers, which integrates cooperatives across ejidos.

Participants described contrasting experiences of rule enforcement, grazing access and conflict resolution. Some reported that effective collective organization facilitated access to communal grazing areas and agreement on grazing rules, while others described conflicts that undermined coordination and rule enforcement. Women and younger generations were also described as having limited participation in ejidal decision-making despite their active involvement in pastoral systems. These accounts highlight both differences in collective governance among ejidos and inequalities of participation within them.

Access to water and the organization of grazing routes further illustrated how communal resource are used within ejidos. Water bodies within communal lands, including natural sources associated with local geological conditions and artificial structures such as troughs and small reservoirs (*bordos*) constructed through government support programs, serve as critical gathering points for livestock. Multiple herders within the same ejido share these sites, where herd convergence can increase grazing pressure in surrounding areas. Participatory mapping showed that herders often share grazing areas while following different routes. Route use varied with time of day, resource availability and internal agreements; some herders followed stable routes, while others adjusted their movements across grazing areas.

Herders described route selection as shaped by inherited knowledge, environmental conditions, and production objectives. Many followed routes established by previous generations, reflecting

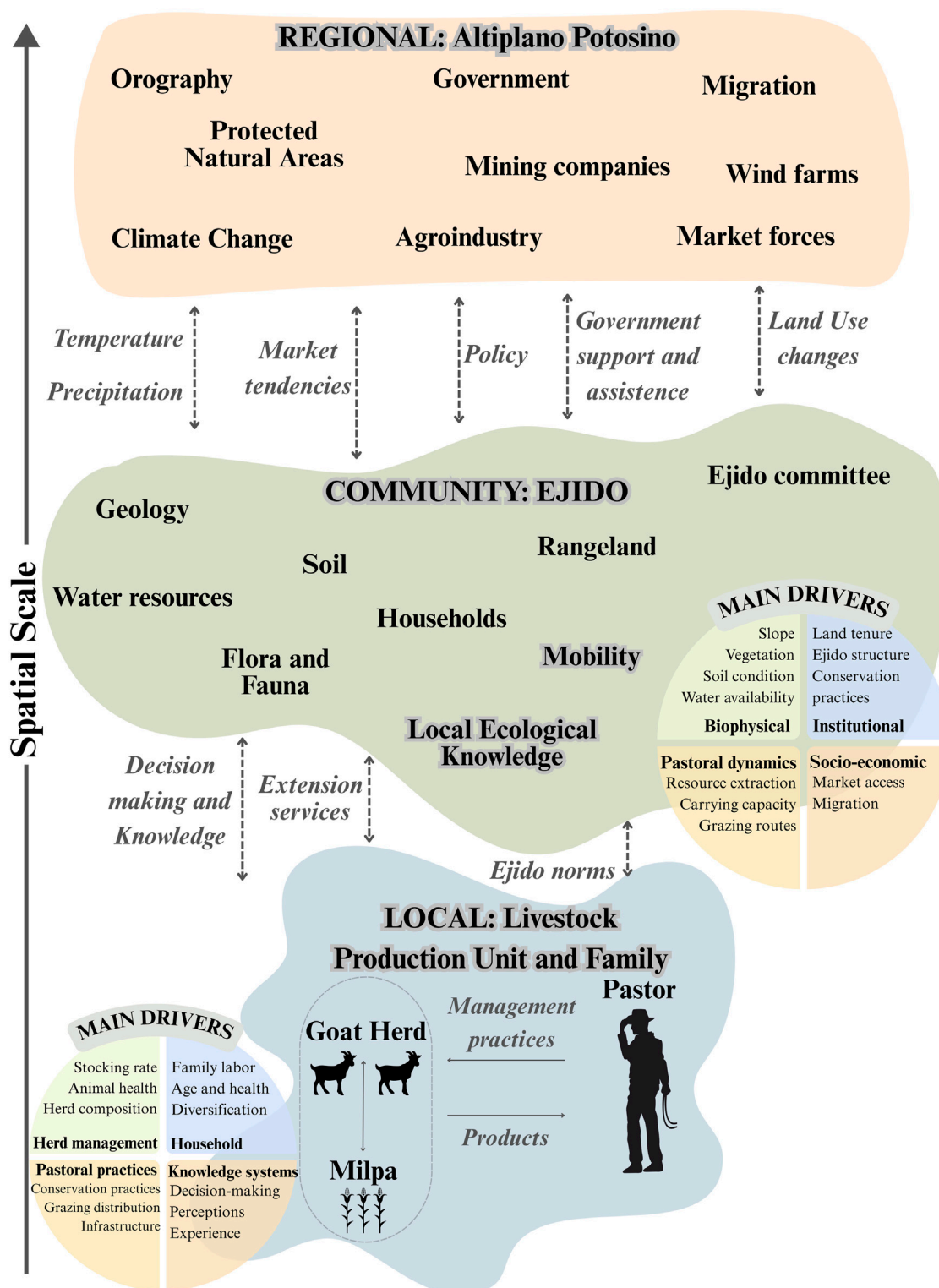


FIGURE 6

Multi-scale social-ecological system of CaprinoCultura in the Altiplano Potosino. The diagram represents interactions between biophysical, social, and institutional components across regional (Altiplano Potosino), community (ejido), and local (LPU and Family) scales. Regional drivers such as climate variability, markets, and public policy shape resource availability and land-use dynamics. At the community level, ejido governance, rangeland conditions, and social organization regulate access to communal grazing areas. At the local level, herd management, household characteristics, and knowledge systems determine pastoral practices and mobility. Arrows indicate cross-scale interactions, including policy, market, and extension influences. The main drivers inducing change are grouped by category at the community and local scales. The figure emphasizes the importance of mobility, local ecological knowledge, and family-based management in sustaining CaprinoCultura systems.

the intergenerational transmission of territorial knowledge. Overall, herders associated areas containing highly palatable forage species were associated with milk production, whereas areas with more drought-tolerant and fibrous vegetation serve for meat production. Alongside local knowledge and collective decision-making, external actors also influence pastoral practices. Interviewees reported receiving occasional technical advice on animal health and dairy processing, but noted that comparatively little support addressed on rangeland management or grazing practices.

Livestock production units and family-based management

At the household level, pastoral production combines herd management, grazing mobility, household labor and livelihood diversification. Livestock Production Unit (LPU) are the household-level unit through which livestock production is formally registered and managed, and represent the smallest operational unit considered in the analysis. Official records identify approximately 2,071 LPUs across 140 ejidos and 15 municipalities of the Altiplano Potosino. Registration provides access to animal health and traceability systems, facilitates livestock movement and marketing, and enables participation in government support programs. However, many herders reported remaining unregistering due to administrative barriers, costs, or limited trust in external regulations, indicating that official LPU records do not capture the full extent of CaprinoCultura.

Within these household-based production systems, a division of labor by gender and generational lines was described, with roles varying among households. Men are generally responsible for herding, while women play a central role in milking, processing dairy products such as cheese and traditional sweets, and selling these products. Elderly individuals and children also assist with herding, product preparation, or sales. These shared responsibilities underscore the importance of family organization in sustaining CaprinoCultura.

Rainfed agriculture, particularly the *milpa* system, is a central component of livelihood diversification and is closely integrated with goat husbandry. Herds are brought onto agricultural plots to fertilize soils with manure, while crop residues provide feed after harvest. Households also collect and sell locally valued natural resources (Supplementary Table S2), including edible and medicinal plants, and *escamoles* (*Liometopum* sp., ant larvae, a prized delicacy in Mexican cuisine), which constitute an important seasonal source of income in some communities (Lara-Juárez et al., 2018). Temporary off-farm employment in construction, agro-industrial activities, and other rural sectors provides additional income. Remittances from family members who have migrated to other regions of Mexico or the United States also help households manage economic uncertainty and sustain pastoral production.

Goat breed selection and herd size are central household management decisions. Herders select breeds according to milk or meat production objectives and adaptability to local environmental conditions. Herd size is influenced by communal grazing regulations, household labor availability, and climatic variability. During droughts many herders reduce their herds to minimize losses and adjust to declining forage availability. In more favorable years, herds may expand as resources and management capacity allow. Goat herds typically range from 5 to 100 animals per herder, with breeds

including Nubian, Alpine, Boer, Toggenburg, Saanen, and Creole. Herders expressed renewed interest in the original Granadina breed, valuing its adaptation to arid conditions and suitability for both milk and meat production. They also reported that animals retaining its original characteristics had become increasingly rare following successive cross-breeding.

Pastoral mobility also involves the use of *majadas*, remote and semi-permanent corrals within grazing areas. Their use depends on herd size, herder's ability to travel long distances, and available household labor. Younger herders may remain with their animals in *majadas* near grazing sites for extended periods (months), whereas older herders, particularly those with limited household support or competing livelihood responsibilities, may avoid distant grazing areas. Access to labor and the capacity to use *majadas* therefore shape households grazing range.

Institutional interventions and external support (cross-scale interactions)

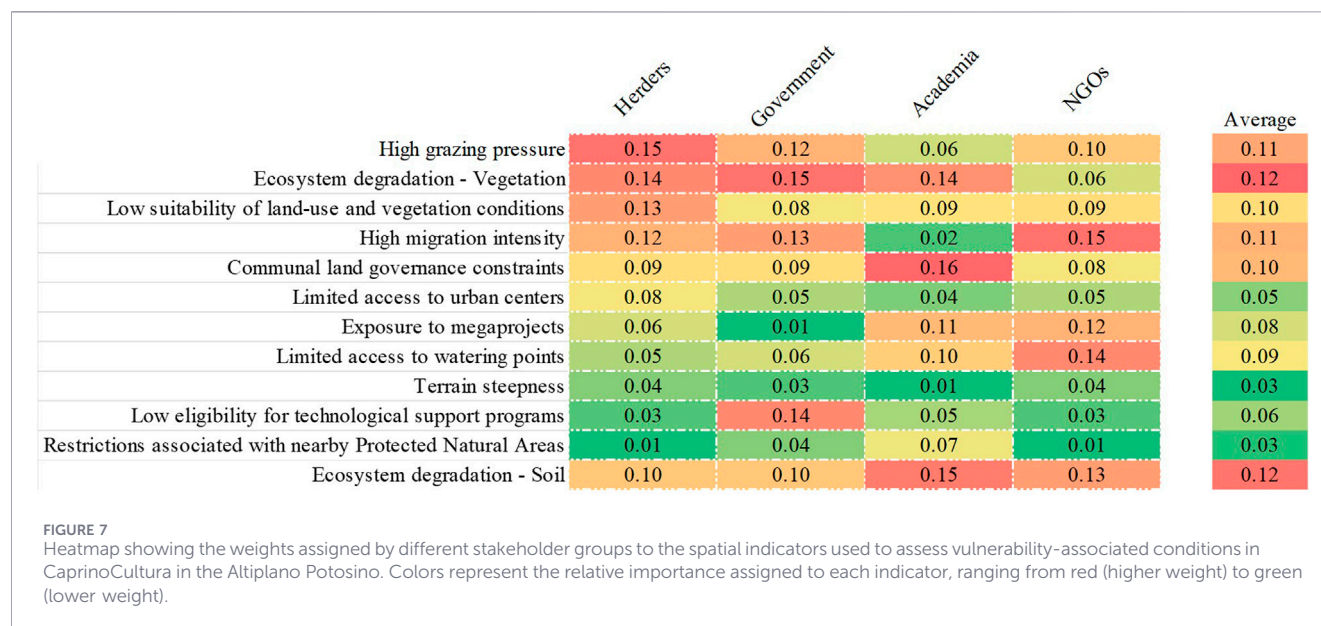
External interventions have strongly influenced CaprinoCultura across scales. Programs such as the Regional Goat Program (2016) and PROGAN (2003-2018) promoted technological adoption, improved breeding, infrastructure, and financial support. Participants acknowledge short-term benefits but identified a poor fit to local conditions, insufficient follow-up, and weak alignment with pastoral priorities. They emphasized that limited coordination among government agencies, academic institutions, and civil-society organizations undermined the long-term effectiveness of these interventions and their potential to strengthen adaptive capacity (Ríos-Rentería and Rivera, 2017).

In parallel, initiatives promoted by producer organizations and academic institutions, such as those supported by the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) and the Universidad Autónoma de San Luis Potosí (UASLP), contributed with alternatives to address livestock feed shortages, animal health, and infrastructure for production (Echavarría and Gómez-Ruiz, 2013; Anzaldo Montoya, 2024). However, poor alignment with local needs and limited continuity constrained their longer-term benefits (Anzaldo Montoya, 2024). These findings suggest that external interventions strengthen adaptive capacity when they respond to territorial, institutional, and household conditions of pastoral systems.

Overall, these findings suggest that the effects of environmental variability are mediated by processes operating across scales. Similar environmental conditions did not necessarily translate into similar pastoral conditions across the Altiplano Potosino. Rather, their effects were differentiated through interactions among territorial configuration, local governance, household organization and adaptive practices. These cross-scale interactions provide context for interpreting the spatial differentiation of vulnerability-associated conditions explored in Phase 2.

Phase 2: multi-stakeholder prioritization of vulnerability conditions of CaprinoCultura

Throughout the participatory characterization, stakeholders identified and discussed the principal socioenvironmental factors affecting the development and long-term sustainability of



CaprinoCultura. Analysis and triangulation across interviews, participatory mapping, Rivers of Life, and multi-stakeholder workshops revealed a range of perceived vulnerability-associated conditions that informed the development of the 12 criteria used in the spatial assessment.

Herders highlighted declining precipitation, overgrazing and soil degradation as their main challenges. Recent droughts (2020, 2022 and 2023) forced reductions in herd size and changes in grazing routes. Rangeland degradation is concentrated near communities, reflecting both historical grazing pressures from larger herds (Gómez-Ruiz et al., 2012) and declining use of remote grazing areas associated with livelihood diversification, the disuse of *majadas*, and mobility constraints among older herders. Herders identified weak regulation of communal grazing as a further contributor to overgrazing and soil degradation. They also acknowledged limited knowledge of rangelands' carrying capacity despite recognizing its importance for sustainable production. In some ejidos, stocking rates are nearly three times the recommended level of one Animal Unit (AU) per 17 ha, where one AU equals six productive goats (Barrera-Perales et al., 2018). Participants described changes in the ejido land use as slow and complex because they require collective decisions by the ejidatarios, many of whom live elsewhere or participate infrequently.

Government representatives identified prolonged rainfall deficits as a major constraint, even in areas served by earthen dams with a larger reservoir. They also emphasized limited access to milk collection and preservation technologies, linking these deficiencies to lower product quality and restricted market access (consistent with Potosí, 2013). They noted that effective technology adoption depends on the capacity and willingness to collaborate within each ejido. Soil degradation associated with livestock and other agricultural activities was another common concern.

Academic participants emphasized changes in land-tenure and management practices. They argued that, under certain conditions, a transition from communal to private tenure could encourage more sustainable rangeland management by strengthening ownership

incentives (similarly to Negrete-Sánchez et al., 2016). Nevertheless, they cautioned that land sales could enable acquisition by agribusinesses and mining companies, potentially reducing grazing areas and compromising water availability and quality, concerns also documented in previous studies (Oseguera Montiel et al., 2014; Mora-Ledesma, 2020; Ortega and Morán, 2020).

Civil society organizations also identified declining precipitation as a critical concern, but emphasized youth out-migration. Limited economic opportunities and adverse environmental conditions were perceived to threaten generational continuity, consistent with previous studies documenting the growing dependance of CaprinoCultura on older producers (Gómez-Ruiz et al., 2012; Oseguera Montiel et al., 2014; Trenti-Very et al., 2021).

These perceptions were reflected in the relative weights assigned to the 12 spatial indicators across stakeholder groups (Figure 7). Vegetation condition and soil degradation received the highest average weights (0.12 each), followed by grazing pressure and migration intensity (0.11 each). These averages highlight the overall prominence of rangeland conditions, grazing pressure, and demographic change in stakeholders' priorities.

Stakeholder priorities reflected their distinct role within the SES. Pastoralists emphasized day-to-day herd and rangeland management, government representatives focused on technological support and production constraints, academics highlighted governance and territorial processes, and civil society organizations stressed demographic continuity and resource access. Shared concerns about rangeland degradation and grazing pressure suggest opportunities for collaborative action. Stakeholder-specific weights were then incorporated into the Multi-Criteria Analysis (MCA) to assess how differences in priorities shaped the resulting spatial patterns.

Spatial patterns of vulnerability-associated conditions in CaprinoCultura

According to SIAP database, the largest numbers of registered livestock production units (LPUs) occur in Villa de Guadalupe ($n =$

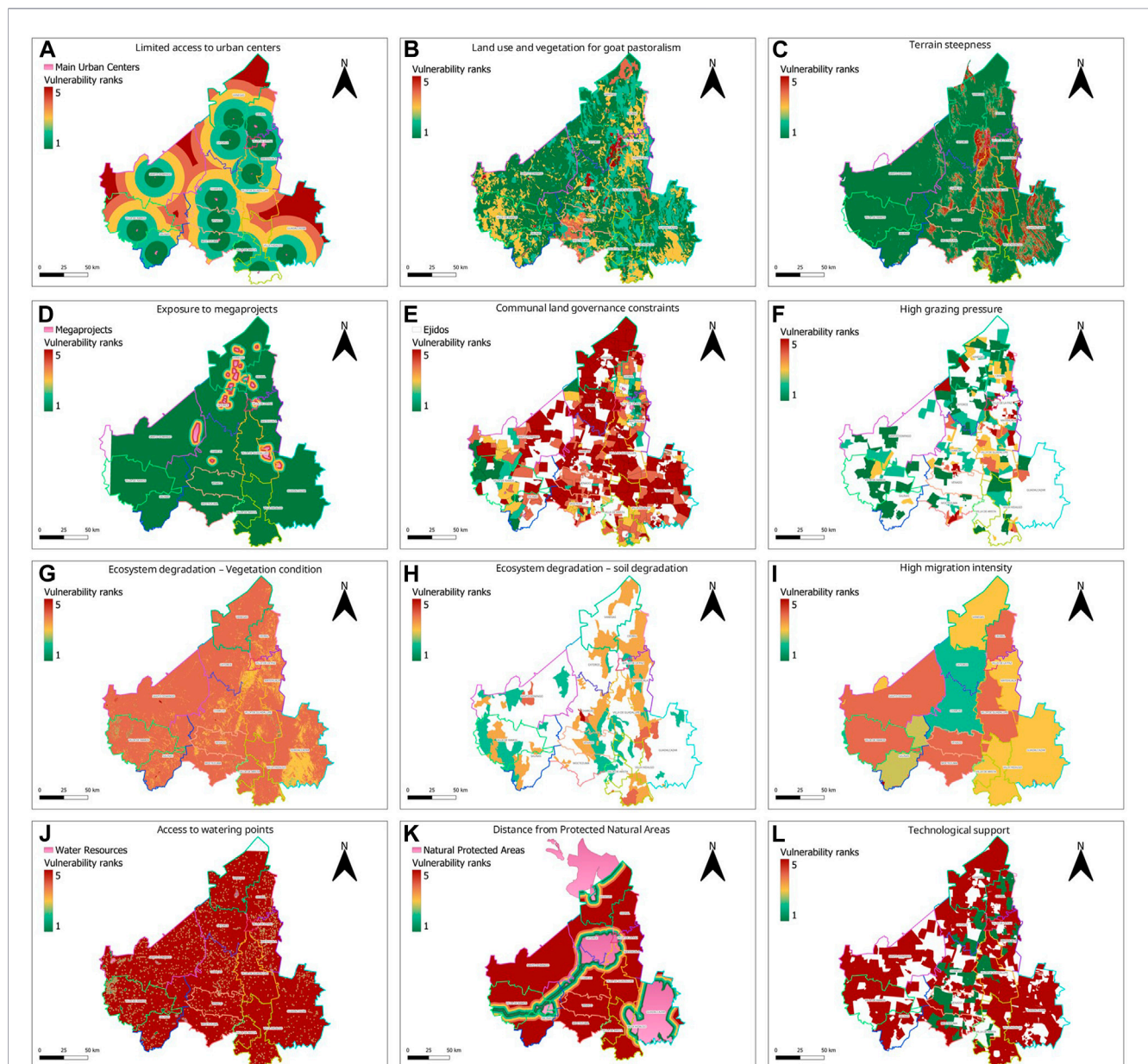


FIGURE 8

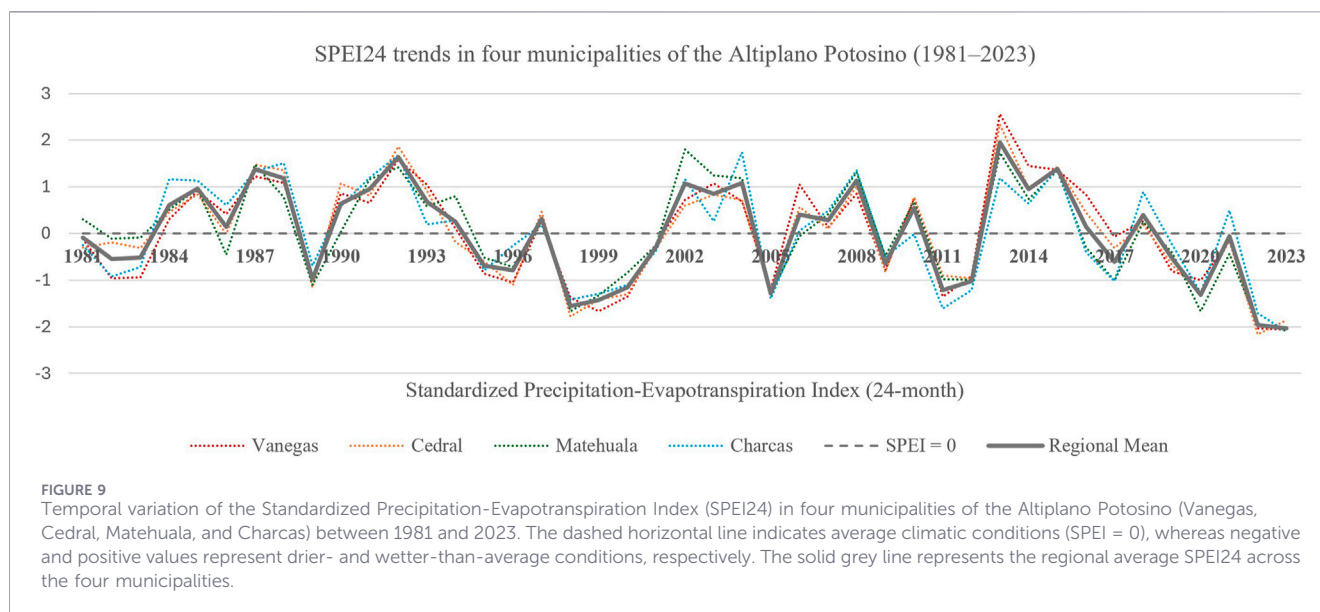
Spatial distribution of vulnerability-associated indicators for CaprinoCultura in the Altiplano Potosino: (A) Limited access to urban centers, (B) Low suitability of land-use and vegetation conditions for goat pastoralism, (C) Terrain steepness, (D) Exposure to megaprojects, (E) Communal land governance constraints, (F) High grazing pressure, (G) Ecosystem degradation - vegetation Condition, (H), Ecosystem degradation - soil degradation, (I) High migration intensity, (J) Limited access to watering points, (K) Distance to federal or state PNA, (L) Low eligibility for technological support.

336), Charcas ($n = 311$), Matehuala ($n = 273$), and Cedral ($n = 269$). Because many goat producers remain unregistered, the spatial assessment covered ejidos where CaprinoCultura is known to occur rather than relying on registered LPU locations. Each criterion was mapped independently to capture its specific spatial expression and relative contribution to pastoral vulnerability (Figure 8 panel).

Reduced annual precipitation: All stakeholder groups identified low rainfall as a major environmental stressor. The SPEI24 data indicated drought episodes across the Altiplano Potosino during 1998, 2000–2001, 2005, 2011, and 2022–2023 (Figure 9). Similar SPEI trends among municipalities indicate

that drought was a broadly shared regional stressor. Given its limited spatial differentiation at the scale of analysis, drought was retained as contextual information and excluded from the MCA and stakeholder weighting, as described in the Methods.

Limited access to urban centers: Distance to urban centers shapes access to markets and services. Matehuala, with 86,686 inhabitants, is the main regional market for goat meat and cheese. Remote herders face higher transportation costs and fewer opportunities to commercialize perishable products, often relying on local or informal markets with limited income opportunities. Animal movement across administrative



boundaries requires compliance with animal health standards, traceability and official permits (e.g., NOM-041-ZOO-1995 for brucellosis control in goats or the registers in SINIIGA) (Figure 8A).

Low suitability of land-use and vegetation conditions for goat pastoralism: Participants identified desert scrub vegetation and rainfed agriculture as the most favorable for goat production because they provide forage and crop residues. These land-cover types occupy much of the Altiplano Potosino, resulting in relatively low scores for this criterion across large areas. Higher scores occurred where vegetation and land were less suitable for pastoral production (Figure 8B).

Terrain steepness: Steep, rugged terrain constrains pastoral mobility. The highest scores occurred in the municipalities of Catorce, Villa de la Paz, Villa de Guadalupe, Charcas, Guadalcázar, and Villa Hidalgo (Figure 8C).

Exposure to megaprojects: Large-scale agricultural, mining, and energy developments were associated with rangeland fragmentation, restricted grazing areas, disrupted mobility routes, and reduced resource access. The highest vulnerability-associated conditions occurred in Vanegas, Villa de la Paz, Cedral, Santo Domingo, Villa de Guadalupe, Matehuala, and Charcas (Figure 8D). Although these developments may provide temporary employment, participants emphasized longer-term threats to pastoral livelihoods, consistent with previous studies (Mora-Ledesma, 2011; 2020; Urquijo Torres, 2017; Morán et al., 2023).

Communal land governance constraints: Scores varied across the region, with the highest values in Vanegas, Venado, Catorce, Charcas, Villa de Guadalupe, and Villa Hidalgo (Figure 8E). Participants described difficulties coordinating resource use, enforcing local agreements, and regulating grazing pressure. However, cases such as the ejido El Castañón illustrate how strong internal organization can support sustainable rangeland management (Negrete-Sánchez et al., 2016).

Ecosystem degradation and high grazing pressure: Cedral, Matehuala and Villa de Guadalupe, exhibited the highest grazing pressure, with stocking rates exceeding recommended

thresholds (Figure 8F). These municipalities together with Guadalcázar, also had the lowest SAVI values (Figure 8G). CONABIO data indicated moderate soil degradation across much of the region, with high to extreme degradation in Charcas, Villa de Guadalupe, Villa Hidalgo, and Guadalcázar (Figure 8H). The convergence of grazing pressure, reduced vegetation cover, and soil degradation was particularly evident in Villa de Guadalupe.

High migration intensity: Participants associated youth out-migration with reduced household labor and disrupted intergenerational knowledge transmission, leaving herding increasingly in the hands of older family members, often over 70 years of age. Reported consequences include smaller herds, shorter grazing routes, and reduced capacity to maintain labor-intensive practices. Migration was highest in Cedral, Santo Domingo, Villa de Ramos, Venado, Moctezuma, and Villa de Guadalupe (Figure 8I).

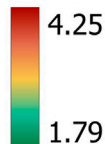
Limited access to watering points: Livestock water sources include seasonal ponds, small reservoirs (*bordos*), wells, and water-storage infrastructure. Water bodies suitable for livestock use occupied the largest portions of territory in Matehuala (0.71%), Santo Domingo (0.68%), and Vanegas (0.60%), and the smallest in Villa de la Paz (0.019%), Villa de Arista (0.025%), and Guadalcázar (0.04%) (Figure 8J). However, this measure does not fully capture effective access, as water sources may be unevenly distributed, seasonal, or restricted by land-tenure arrangements.

Restrictions associated with Protected Natural Areas: Sierra La Mojonera, Wirikuta, and the Guadalcázar State Reserve influence pastoral activities through land-use restrictions and opportunities for conservation support (Figure 8K). While these areas provide opportunities for conservation and restoration programs, may also restrict land use and grazing expansion. The highest levels of vulnerability-associated conditions occurred in Cedral, Matehuala, Villa de Guadalupe, Santo Domingo, Venado, Moctezuma, and Villa de Arista.

General Vulnerability

□ Ejidos

Vulnerability ranks



0 25 50 km

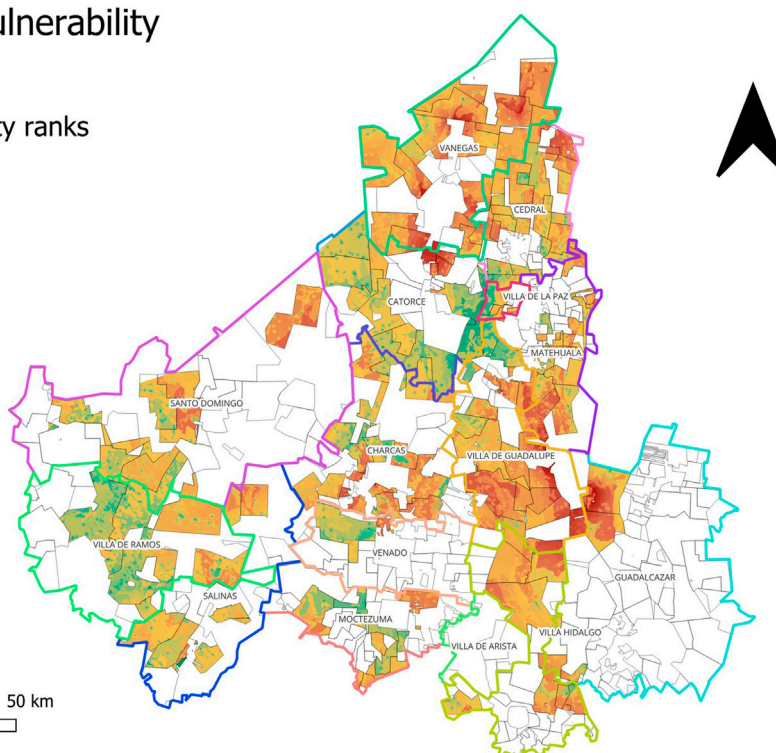


FIGURE 10

Composite spatial assessment of vulnerability-associated conditions across ejidos in the Altiplano Potosino derived from the multi-criteria analysis.

The gradient (1.79–4.25) represents relative levels of vulnerability-associated conditions, with higher values indicating areas where multiple conditions converge under the integrated weighting scheme. These areas may therefore represent potential priorities for further assessment and context-specific intervention. Only ejidos with available data and/or registered goat production units were included in the analysis; white areas indicate non-evaluated units.

Low eligibility for technological support programs: The Regional Goat Program, introduced in 2016, primarily benefited larger producers, particularly those managing more than 100 goats. Reported improvements in animal health and milk processing were limited by insufficient follow-up and technologies poorly suited to local production systems. Equipment underuse, discontinued practices and occasional conflicts over shared infrastructure further reduced program benefits. The highest levels of this vulnerability-associated condition occurred in Santo Domingo, Salinas, Villa de Ramos, Villa Hidalgo, Guadalcázar, and Vanegas (Figure 8L).

The integrated map, based on equally weighted stakeholder perspectives showed clear spatial variation in the convergence of vulnerability-associated conditions (Figure 10). Higher scores occurred in Vanegas, Cedral, Matehuala, Villa de Guadalupe, Guadalcázar, and Villa Hidalgo. Charcas, Catorce, Venado, Moctezuma, Santo Domingo, Villa de Ramos, and Salinas, exhibited lower and more heterogeneous scores. Contrasts among neighboring ejidos in Matehuala and Charcas also revealed within-municipality variation in grazing pressure, governance, vegetation condition, and resource access.

Stakeholder-specific maps showed broadly similar patterns, with substantial overlap in high-scoring areas in the central-eastern and northern Altiplano Potosino (Figure 11 panel). Differences in

stakeholder weighting nevertheless affected MCA score magnitude and distribution. Pastoralists' emphasis on grazing pressure and soil degradation produced higher scores near population centers, particularly in Matehuala, Villa de Guadalupe, Cedral, and Vanegas. Government priorities yielded a more homogeneous distribution of moderate-to-high scores, while academic priorities produced greater spatial differentiation. NGOs weight areas with high migration and limited access to resources and institutional support.

Sensitivity of spatial assessment results

Sensitivity analyses indicated that spatial MCA patterns were highly robust to moderate changes in criterion weights ($\pm 20\%$), with Spearman's ρ generally above 0.98. The leave-one-criterion-out analysis revealed that some criteria, particularly ecosystem degradation and overgrazing, had a stronger influence on the spatial organization of results, although their influence varied among stakeholder groups. Alternative stakeholder aggregation produced highly consistent spatial patterns, with equal- and sample-size-proportional weighting yielding high spatial agreement with the integrated assessment. Detailed sensitivity analysis results are provided in Supplementary Material S4.

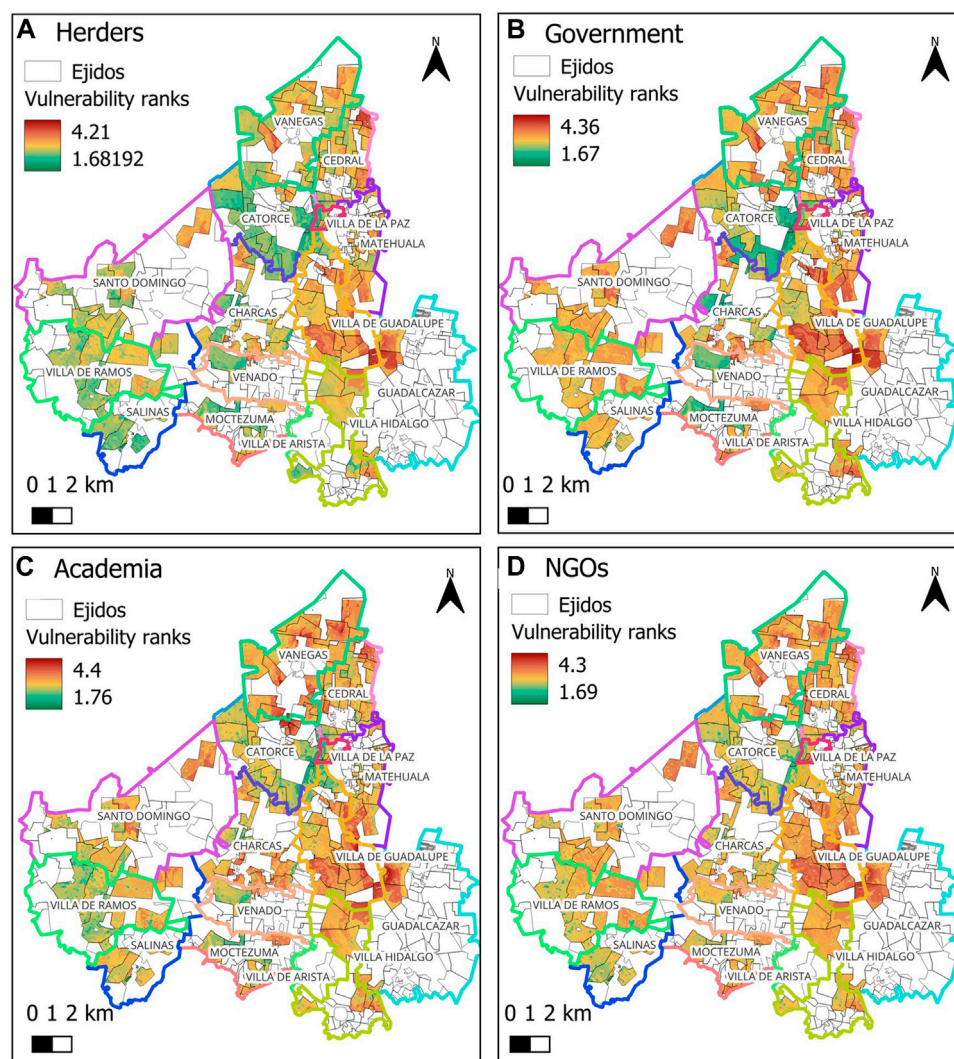


FIGURE 11
Stakeholder-specific spatial assessments of vulnerability-associated conditions across ejidos in the Altiplano Potosino, generated through Multi-Criteria Analysis (MCA) using stakeholder-specific weighting schemes. The maps represent the spatial configuration of relative vulnerability-associated conditions based on the priorities assigned by different stakeholder groups: (A) pastoralists, (B) government, (C) academia, and (D) NGOs.

Discussion

Pastoral vulnerability emerges from interactions among climatic variability, land degradation, governance, and socio-economic change across scales (Reid et al., 2021; Scoones, 2023). Social-ecological systems (SES) frameworks and spatial analyses help examine these interactions (de Sherbinin et al., 2019; Thiault et al., 2021; Balew et al., 2022; Yang et al., 2023); yet indicator selection and weighting remain largely researcher- or expert-driven, limiting stakeholders' influence over how vulnerability is assessed. Participation thus informed both what was assessed and how conditions were prioritized. This contribution complements GIS-based vulnerability assessments (de Sherbinin et al., 2019; Thiault et al., 2021; Balew et al., 2022; Yang et al., 2023) by making different stakeholder perspectives explicit, including concerns that may be overlooked in expert assessments but influence adaptation responses (Nelson et al., 2023).

Shared priorities can function as “theme bridges” among actors with different responsibilities and knowledge systems (Hernández-Valdez et al., 2025). Their value lies in providing a basis for dialogue and collective action without requiring agreement on all aspects of vulnerability (Seiferth et al., 2024). Such dialogue supports social learning while preserving differences among knowledge systems (Roux et al., 2017; Souza et al., 2020).

Multi-stakeholder learning platforms could sustain this dialogue beyond the assessment, enabling participants to interpret spatial priorities, monitor change and negotiate locally appropriate responses (Martínez-Tagüena et al., 2024). Although establishing these platforms is beyond the study's scope, the emergence of a multisectoral partnership following discussion of the results suggests potential for continued collaboration. Whether this partnership produces sustained collective action and strengthens adaptive governance remains to be assessed.

CaprinoCultura as a pastoral social-ecological system

The findings suggest that adaptive capacity in CaprinoCultura depends on conditions that allow households to put their knowledge and management strategies into practice. Pastoral households are embedded within broader territorial, institutional and ecological processes that shape their capacity to respond to socioenvironmental change (Linstädter et al., 2016; Tolera and Senbeta, 2020; Postigo, 2021).

Mobility illustrates this relationship: enables responses to variability in forage and water, but depends on ecological knowledge and arrangements governing access to grazing areas (Kakinuma et al., 2019; Turner and Schlecht, 2019; D'Abramo et al., 2021; Sharifian et al., 2023). In the Mexican ejido context, its adaptive value is therefore closely tied to communal resource governance. Territorial fragmentation and demographic change appear to constrain this capacity jointly. While privatization and competing land uses restrict accessible grazing areas, migration and population aging reduce the household labor available to use them. These processes have also been documented in other pastoral systems (Robinson and Flintan, 2022; Ntombela et al., 2024).

Local ecological knowledge is similarly dependent on opportunities for its continued use and transmission. It provides detailed information relevant to herd management and territorial planning, like forage quality, seasonal resource availability, grazing suitability, animal health, and production potential (León Villalobos et al., 2018; Sharifian et al., 2022), but its adaptive role may weaken when access to familiar grazing territories is lost or intergenerational participation declines. Participatory territorial planning offers one means of bringing this knowledge into dialogue with technical assessments and land-use decisions (Arteaga Aguilar et al., 2014). These findings shift attention from the presence of adaptive practices to the conditions that sustain them. Ejido governance is central to this distinction because collective rules and decisions shape whether households can access and manage the resources on which those practices depend.

Ejido governance as a key social-ecological process

Variation among ejidos suggests that communal tenure should not itself be interpreted as a vulnerability factor. Its implications depend on how collective institutions regulate grazing, negotiate resource access and enforce agreements. This interpretation is consistent with studies showing that collective institutions can support adaptive capacity through collective action and flexible resource management (Fernández-Giménez et al., 2015; Gongbuzeren et al., 2021; Pappagallo, 2024). The ejido is therefore a governance arena in which household interests, ecological variability, and external pressures are negotiated.

Robinson, (2019) similarly shows that pastoral tenure systems often involve flexible and overlapping arrangements of access and use that do not conform to conventional communal-private distinctions. Pappagallo, (2024) likewise shows how collective institutions can maintain connectivity and flexible access to heterogeneous resources across tenure arrangements. Together,

these studies suggest that the adaptive value of pastoral institutions depends less on formal tenure categories than on their capacity to maintain connectivity, negotiate access, and adjust resource-use arrangements under changing conditions.

Evidence from El Castañon associates rangeland parcelization with improved rangeland condition, livestock production, and individual stewardship (Negrete-Sánchez et al., 2016). Our findings do not rule out such benefits, but caution against attributing outcomes to tenure categories alone. Pastoral access arrangements often extend beyond communal-private distinctions, and their adaptive value depends on maintaining connectivity and negotiating access to heterogeneous resources (Robinson, 2019; Pappagallo, 2024). Strengthening local governance may therefore support adaptation without necessarily requiring changes in tenure.

This perspective favors support tailored to local institutional capacities over uniform prescriptions. Research across pastoral contexts worldwide highlights the importance of collaborative institutions and governance networks to coordinate communities, governments, and other actors under changing conditions like climate-related pressures (Tolera and Senbeta, 2023; Weng et al., 2023; Yang et al., 2023; Zhang, 2023). Thus, while institutional arrangements are various a common principle is that pastoral adaptive capacity depends partly on institutions' ability to maintain flexible and collectively negotiated access to heterogeneous resources while connecting local knowledge and decision-making with broader institutional support. In our study, we show that differences in local governance effectiveness become spatially differentiated across a pastoral landscape. For CaprinoCultura, this implies attending to how ejido rules operate in practice and whether households can participate in, negotiate, and implement collective decisions.

Household organization and the adaptive capacity of CaprinoCultura

The household is both a productive unit and a social setting through which labor, knowledge, resource management and production and risk are organized. This helps explain how pastoral families combine livelihood activities to respond to changing conditions, as documented in other pastoral and smallholder goat systems (Oseguera Montiel et al., 2014; Mairomi and Kimengsi, 2021). Livelihood diversification can buffer income fluctuations, but its adaptive benefits depend partly on whether households retain sufficient labor and knowledge to sustain pastoral practices. Migration and demographic aging may weaken these adaptive capacities (Ntombela et al., 2024).

Household continuity also has a sociocultural and territorial dimension. Herders' descriptions of grazing areas as places of family history and learning suggest that these territories sustain relationships beyond production and are rooted in memory, identity, and social meaning. This interpretation is consistent with research linking pastoral knowledge to landscapes, intergenerational transmission, and cultural identity and heritage (Sharifian et al., 2022; Chao et al., 2025). Consequently, migration and territorial fragmentation affect not only production but also relationships through which CaprinoCultura is maintained and renewed.

From vulnerability assessment to adaptive governance

The spatial assessment represents the relative convergence of selective vulnerability-associated conditions rather than an absolute measure of vulnerability. Its interpretation depends on the indicators, scale, and aggregation procedures used (de Sherbinin et al., 2019; Thiault et al., 2021). Mobility, livelihood diversification and household organization were identified through participatory activities but could not be consistently represented spatially. Their omission from the spatial model reflects methodological scope rather than the lack of relevance to adaptive capacity.

The maps should therefore guide further inquiry and locally negotiated responses rather than serve as definitive classifications of territories. Areas with higher scores warrant closer examination of how mapped conditions interact with capacities not captured by the indicators. Sensitivity analyses support the stability of spatial rankings under the tested weighting changes, but do not establish that the indicators capture all dimensions of vulnerability. This limitation also highlights a broader contribution of the study. Rather than treating vulnerability as a fixed territorial attribute, our results distinguish between the spatial distribution of selected vulnerability conditions and the broader processes shaping adaptive capacity.

Equal weighting balanced the contribution of stakeholder sectors to the integrated map but did not eliminate differences in representation within them, including the limited participation of women and younger generations. Spatial indicators also only partially capture the governance arrangements and adaptive practices identified through participatory research. Although sensitivity analyses supported the stability of spatial rankings under the tested scenarios, future research could examine how these patterns relate to observed livelihood outcomes and changes in pastoral continuity.

Stakeholder-specific maps also remain important alongside the integrated assessment. Although their broad patterns were similar, differences in priorities reveal distinct concerns that averaging can obscure. These differences provide information for deliberation rather than simply uncertainty to be eliminated (Findlater et al., 2022). Reading the maps together can support dialogue among complementary knowledge systems while preserving their distinct perspectives (similarly to Tengö et al., 2017; Fernández-Giménez, 2020; Reid-Shaw et al., 2021; Seiferth et al., 2024). In pastoral systems, collaborative research has similarly shown that co-production, integration of knowledges, social learning, networking, and collective action can strengthen connections between knowledge generation and governance (Reid et al., 2021).

Shared priorities may function as “theme bridges” around which stakeholders begin this dialogue (Hernández-Valdez et al., 2025). Our approach links co-produced criteria, stakeholder priorities, and spatial analysis to examine vulnerability-associated conditions within their local social-ecological contexts (as mentioned previously by Ayantunde et al., 2015; Yang et al., 2023). Beyond mapping these conditions, this integration can support joint learning,

priority setting, and dialogue to inform adaptive governance (Thiault et al., 2021).

Policy implications for place-based pastoral development

These findings support context-specific policies that coordinate actions across households, ejido authorities, government, academia, and civil society across various scales. Production-oriented interventions should account for the governance arrangements, household capacities, and resource constraints that shape their feasibility and adoption. This is particularly relevant where programs have incorporated pastoralists’ priorities and knowledge only to a limited extent (Anzaldo Montoya, 2024) and is consistent with calls for differentiated pastoral policies and coordination across scales (Zhang, 2023).

For territorial planning, stakeholder-informed assessments can complement existing information on environmental suitability, livestock production, infrastructure, land use, and resource availability. In Mexico, combining INEGI and SIAP datasets with participatory diagnosis could help distinguish biophysical suitability from the social-ecological conditions needed to sustain pastoral activities. This would inform decisions about which interventions are appropriate, where, and for whom.

At the ejido level, support should strengthen capacities to negotiate grazing access, regulate grazing pressure, resolve conflicts, and monitor rangelands. Communal tenure should not be treated as a constraint; attention should focus on how community-based institutions organize resource access and collective management, strengthening adaptive capacity through knowledge exchange, social capital, and collective action (Fernández-Giménez et al., 2015; Gongbuzeren et al., 2021; Pappagallo, 2024). At the household level, productive support should be accompanied by measures that enable women’s and younger generations’ participation, intergenerational learning and livelihood diversification.

At the regional level, the maps can identify areas requiring closer diagnosis. Where grazing pressure and ecosystem degradation converge, restoration and grazing management may warrant consideration; elsewhere, water access, institutional/technological support or demographic change may require different responses like infrastructure, mobility, market access, training, diversification, and generational strategies. These options should be evaluated locally, since the spatial assessment neither prescribes interventions nor implies an absence of adaptive capacity (Thiault et al., 2021; Balew et al., 2022). In this way, vulnerability assessment can contribute not only to territorial analysis, but also to dialogue, priority setting, and adaptive governance (Metcalf et al., 2015; Yang et al., 2023).

Monitoring vulnerability-associated conditions over time could strengthen the policy relevance of the assessment by tracking whether selected conditions improve, persist, or intensify. Such comparisons would require consistent methods and explicit attention to dataset reference years. Interpreting changes jointly with pastoralists, ejido authorities, and other stakeholders could connect monitoring with locally informed decisions without treating indicator trends as direct measures of changing vulnerability.

Conceptual contribution and broader implications

This study supports a relational understanding of pastoral vulnerability as an emergent, relational, and spatially differentiated property of social-ecological systems. In which environmental pressures acquire different implications through their interaction with resource access, governance, household organization and local knowledge (Turner et al., 2003; Yang et al., 2023). In CaprinoCultura, this directs attention to the social and institutional conditions that enable pastoralists to exercise adaptive capacity, rather than solely to the pressures they face.

The methodological contribution lies in connecting this contextual understanding with spatial assessment while distinguishing mapped conditions from adaptive processes that require qualitative interpretation. This is particularly relevant in pastoral systems, where mobility, livelihood diversification, household organization, and local knowledge may be central to adaptive capacity but difficult to consistently spatialize (Ayantunde et al., 2015; Thiault et al., 2021). The resulting framework identifies where selected conditions converge and how stakeholders prioritize them, providing a basis for further diagnosis and negotiation. Its broader relevance lies in supporting place-based decisions that sustain pastoralists' capacity to mobilize knowledge, labor, mobility, collective institutions, and external support in response to change (as described in (Wilmer et al., 2018; 2022; Reid et al., 2021).

Beyond its analytical contribution, participatory vulnerability assessment can create opportunities for dialogue by connecting spatial evidence with different knowledge systems and stakeholder priorities (as suggested by Reid et al., 2021; Seiferth et al., 2024). Its value therefore lies not only in identifying where vulnerability-associated conditions converge, but also in providing a shared basis for negotiating responses that sustain CaprinoCultura and the capacities of those who maintain it.

Data availability statement

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

Ethics statement

Ethical approval was not required for this study under applicable institutional and national guidelines. The Instituto Potosino de Investigación Científica y Tecnológica does not have an ethics committee, and the study involved non-invasive participatory methods, including interviews, participatory mapping, focus groups, workshops, and surveys. It did not involve experimental interventions or the collection of sensitive personal information. The research focused on documenting knowledge, perceptions, and experiences related to pastoral systems and was conducted in accordance with applicable local legislation and institutional requirements, respecting the principles of voluntary participation, confidentiality, respect for participants, and responsible use of information. Written informed consent for participation

was not obtained because literacy levels vary in rural pastoral communities and participants may be reluctant to sign formal documents. Instead, verbal informed consent was obtained before all research activities. Participants were informed about the study's objectives, the intended use of the information, their right to decline participation or withdraw at any time, and their right to withhold any information they preferred to keep confidential. Written consent for the publication of potentially identifiable images or data was also not obtained. Before photographs were taken, participants were informed about their intended use, and verbal permission for photography and publication was requested during the multistakeholder workshops. The photographs included in the Supplementary Material were taken during these workshops.

Author contributions

AG-M: Conceptualization, investigation, data analysis, interpretation, and manuscript writing. EH-S: Conceptualization, data analysis, interpretation, manuscript writing and supervision. RD-O: Data analysis and interpretation. NM-T: Conceptualization, manuscript review and editing, and supervision. FA: Conceptualization, manuscript review, and supervision. MM-L: Conceptualization, manuscript review, and supervision. MV-M: Conceptualization, manuscript review, and supervision. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was supported by a graduate scholarship granted by SECIHTI. Additional funding for the organization and implementation of the multisectoral meetings was provided by the Consejo Potosino de Ciencia y Tecnología (COPOCYT) through the 2023 "23871-Multas Electorales" call for proposal.

Acknowledgments

The authors sincerely thank the goat herders, academics, government representatives, and local stakeholders who participated in the interviews, workshops, surveys, and participatory mapping activities conducted throughout this research. We are especially grateful to the Federación de Caprinocultores del Altiplano Mexicano for their support and collaboration during the development of this study. We also acknowledge the valuable technical assistance provided by Alejandro Malagamba, as well as the contributions of the facilitators who supported the multistakeholder workshops: Roberto I. Márquez Hernández, Luis D. Cruz González, Gerardo Esquivel Arriaga, Esmeralda N. López Lozano, Marcela Corpus Hernández, and Fidel I. García Chávez. Finally, we acknowledge the institutional and logistical support provided by the Instituto Potosino de Investigación Científica y Tecnológica (IPICYT) and

the Consejo Potosino de Ciencia y Tecnología (COPOCYT), whose collaboration contributed significantly to the development of this research.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative artificial intelligence (AI) tools were used

to support language editing and improve the clarity of the manuscript. However, all scientific content, data analysis, interpretation of results, and conclusions were developed by the authors, who take full responsibility for the integrity and accuracy of the work.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontierspartnerships.org/articles/10.3389/past.2026.17175/full#supplementary-material>

References

- Amiri, F., bin Mohamed Shariff, A. R., Tabatabaie, T., and Pradhan, B. (2014). A geospatial model for the optimization grazing management in semi-arid rangeland of Iran. *Arabian J. Geosciences* 7, 1101–1114. doi: 10.1007/s12517-013-0840-6
- Amsidder, L., Alary, V., and Sraïri, T. M. (2021). An empirical approach of past and present mobility management in the desert societies of camel breeders in south eastern Morocco. *J. Arid. Environ.* 189, 104501. doi: 10.1016/j.jaridenv.2021.104501
- Anzaldo Montoya, M. (2024). Oportunidades perdidas para el uso social del conocimiento científico en la política agroalimentaria en la escala subnacional. *Rev. El Col. San Luis* 14, 1–36. doi: 10.21696/rcsl142520241523
- Arteaga Aguilar, M., Ayala Arcipreste, M., and Isaac Márquez, R. (2014). Ordenamiento territorial comunitario, participación social y uso del suelo: experiencias en el sureste de México. *Perspect. Geográfica* 19 (2), 289–308. doi: 10.19053/01233769.4100
- Atkinson, R., and Flint, J. (2001). Accessing hidden and hard-to-reach populations: snowball research strategies. *Soc. Research Update* 33, 1–4. Available online at: <https://sru.soc.surrey.ac.uk/SRU33.html>
- Ayantunde, A. A., Turner, M. D., and Kalilou, A. (2015). Participatory analysis of vulnerability to drought in three agro-pastoral communities in the west African Sahel. *Pastoralism* 5, 13. doi: 10.1186/s13570-015-0033-x
- Balew, A., Legese, B., Kunbushu, D., Nega, W., Alebel, W., Kerbesh, A., et al. (2022). Identification of suitable land for livestock production using GIS-based multicriteria decision analysis and remote sensing in the bale lowlands, Ethiopia. *Int. J. Ecol.* 2022, 1–17. doi: 10.1155/2022/9585552
- Basupi, L. V., Quinn, C. H., and Dougill, A. J. (2017). Using participatory mapping and a participatory geographic information system in pastoral land use investigation: impacts of rangeland policy in Botswana. *Land use policy* 64, 363–373. doi: 10.1016/j.landusepol.2017.03.007
- Barrera-Perales, O., Villegas, L. M. S., González, J. M. S., Rodríguez, J. A. L., and Laval, R. S. (2018). Economic and financial viability of extensive caprine livestock in San Luis Potosí, Mexico. *Mundo Agrar*. 19, e077. doi: 10.24215/15155994e077
- Bennett, N. J., Blythe, J., Tyler, S., and Ban, N. C. (2016). Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. *Reg. Environ. Change* 16, 907–926. doi: 10.1007/s10113-015-0839-5
- Bostedt, G., Knutsson, P., Muricho, D., Mureithi, S., Wredle, E., and Nyberg, G. (2023). Adaptive pastoralists—Insights into local and regional patterns in livelihood adaptation choices among pastoralists in Kenya. *Pastoralism* 13, 26. doi: 10.1186/s13570-023-00290-8
- Brondizio, E. S., Aumeeruddy-Thomas, Y., Bates, P., Carino, J., Fernández-Llamazares, Á., Ferrari, M. F., et al. (2021). Locally based, regionally manifested, and globally relevant: indigenous and local knowledge, values, and practices for nature. *Annu. Rev. Environ. Resour.* 46, 481–509. doi: 10.1146/annurev-environ-012220-012127
- Burk, R. C., and Nehring, R. M. (2023). An empirical comparison of rank-based surrogate weights in additive multiattribute decision analysis. *Decis. Anal.* 20, 55–72. doi: 10.1287/deca.2022.0456
- Chao, O., Li, X., and Reyes-García, V. (2025). Exploring the dynamic functions of pastoral traditional knowledge. *Ambio* 54, 932–946. doi: 10.1007/s13280-025-02131-x
- Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S., and Von Maltitz, G. (2018). *World Atlas of Desertification*, 26. Luxembourg: Publications Office of the European Union. Available online at: <https://wad.jrc.ec.europa.eu/download>
- Cho, M. A., and Mutanga, O. (2021). Understanding participatory GIS application in rangeland use planning: a review of PGIS practice in Africa. *J. Land Use Sci.* 16, 174–187. doi: 10.1080/1747423X.2021.1882598
- CONAGUA (2023). *Información Estadística Climatológica (Periodo 1991-2023)*. Servicio Meteorológico Nacional. Available online at: <https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica>
- CONEVAL (2020). *Medición De La Pobreza*. Available online at: <https://www.coneval.org.mx/Medicion/MP/Paginas/Lineas-de-Pobreza-por-Ingresos.aspx>
- Coppock, D. L. (2016). Cast off the shackles of academia! use participatory approaches to tackle real-world problems with underserved populations. *Rangelands* 38, 5–13. doi: 10.1016/j.rala.2015.11.005
- De Sherbinin, A., Bukvic, A., Rohat, G., Gall, M., McCusker, B., Preston, B., et al. (2019). Climate vulnerability mapping: a systematic review and future prospects. *Wiley Interdiscip. Rev. Clim. Change* 10, e600. doi: 10.1002/wcc.600
- Depietri, Y. (2020). The social–ecological dimension of vulnerability and risk to natural hazards. *Sustain. Sci.* 15, 587–604. doi: 10.1007/s11625-019-00710-y
- D'Abramo, S. L., Gonzalez, P. N., Perez, S. I., and Bernal, V. (2021). Modelling the routes of seasonal transhumance movement in north Neuquén (patagonia). *Hum. Ecol.* 49, 415–428. doi: 10.1007/s10745-021-00246-9
- Echavarría, F. C., and Gómez-Ruiz, W. (2013). “Los Sistemas de Producción de Rumiantes Menores en México y sus Limitantes Productivas,” in *La Producción De Rumiantes Menores En Las Zonas Áridas De Latinoamérica*, 564.
- Echavarría-Cháirez, F., and Gómez-Ruiz, W. (2013). Los sistemas de producción de rumiantes menores en México y sus limitantes productivas. Available online at: www.icarda.org
- Fernández-Giménez, M. E. (2000). The role of Mongolian nomadic pastoralists' ecological knowledge in rangeland management. *Ecol. Appl.* 10, 1318–1326. doi: 10.1890/1051-0761(2000)010[1318:TROMNP]2.0.CO;2
- Fernández-Giménez, M. E. (2020). Co-Creating knowledge for action with women pastoralists in Spain. Food and Agriculture Organization of the United Nations (FAO). Available online at: <https://www.fao.org/agroecology/in-action/detail/co-creating-knowledge-for-action-with-women-pastoralists-in-spain/en> (Accessed October 12, 2026).
- Fernández-Giménez, M. E., and Estaque, F. F. (2012). Pyrenean pastoralists' ecological knowledge: documentation and application to natural resource management and adaptation. *Hum. Ecol.* 40, 287–300. doi: 10.1007/s10745-012-9463-x
- Fernández-Giménez, M. E., and Wilmer, H. (2025). Towards a theory of pastoralist and rancher identity: insights for understanding livestock systems in transformation. *Agric. Hum. Values* 42, 845–862. doi: 10.1007/s10460-024-10641-9
- Fernández-Giménez, M. E., Batkhashig, B., Batbuyan, B., and Ulambayar, T. (2015). Lessons from the dzud: community-based rangeland management increases the adaptive capacity of Mongolian herders to winter disasters. *World Dev.* 68, 48–65. doi: 10.1016/j.worlddev.2014.11.015
- Fernández-Giménez, M. E., El Aichi, A., El Aouni, O., Adrane, I., and El Aayadi, S. (2021). Ilemchane transhumant pastoralists' traditional ecological knowledge and adaptive strategies: continuity and change in morocco's high atlas Mountains. *Mt. Res. Dev.* 41 (4), R61–R73. doi: 10.1659/mrd-journal-d-21-00028.1
- Findlater, K., Kozak, R., and Hagerman, S. (2022). Difficult climate-adaptive decisions in forests as complex social–ecological systems. *Proc. Natl. Acad. Sci. U. S. A.* 119, e2108326119. doi: 10.1073/pnas.2108326119

- Frank, M., Easdale, M. H., and Kaufmann, B. (2018). Assessing a demonstration farm approach for technological innovations in pastoral livestock production systems of northern Patagonia: participants' perceptions of stakeholder roles and innovations. *Exp. Agric.* 54, 774–793. doi: 10.1017/S0014479717000448
- García, E. (2004). Modificaciones al sistema de clasificación climática de Köppen: Para adaptarlo a las condiciones de la República Mexicana (5.ª ed. corr. y aumentada). Ciudad de México, México: Universidad Nacional Autónoma de México, Instituto de Geografía.
- Gatew, S., and Guyo, N. (2024). Livelihood vulnerability of borana pastoralists to climate change and variability in southern Ethiopia. *Int. J. Clim. Chang. Strateg. Manag.* 16, 157–176. doi: 10.1108/IJCCSM-06-2023-0077
- Gómez-Ruiz, W. J., Pinos-Rodríguez, J. M., Aguirre-Rivera, J. R., and García-López, J. C. (2012). Analysis of a goat milk cheese industry in a desert rangeland of Mexico. *Pastoralism* 2, 1–11. doi: 10.1186/2041-7136-2-5
- Gongbuzeren, Zhang, J., Zhuang, M., Zhang, J., and Huntsinger, L. (2021). Mitigating the impacts of fragmented land tenure through community-based institutional innovations: two case study villages from guinan county of Qinghai province, China. *Ecol. Soc.* 26 (2), 15. doi: 10.5751/ES-12326-260215
- Gray, S. A., Gray, S., de Kok, J. L., Helfgott, A. E. R., O'Dwyer, B., Jordan, R., et al. (2015). Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. *Ecol. Soc.* 20, art11. doi: 10.5751/ES-07396-200211
- Guilherme, R. D. F., Lima, A. M. C., Alves, J. R. A., Costa, D. F. da, Pinheiro, R. R., Alves, F. S. F., et al. (2017). Characterization and typology of sheep and goat production systems in the state of Paraíba, a semi-arid region of northeastern Brazil. *Semin. Cienc. Agrar.* 38, 2163. doi: 10.5433/1679-0359.2017v38n4p2163
- Hernández-Valdez, S., Mata-Páez, R. I., Martínez-Tagüña, N., Huber-Sannwald, E., Lauterio-Martínez, C. L., Reyes-Gómez, V. M., et al. (2025). From diverse interests to collective action: a framework to identify 'theme bridges' as entry points to co-design multi-stakeholder partnerships in a shared multifunctional dryland context. *Sustain. Sci.* 20, 1809–1831. doi: 10.1007/s11625-025-01706-7
- Huber-Sannwald, E., Palacios, M. R., Moreno, J. T. A., Braasch, M., Peña, R. M. M., Verduzco, J. G. de A., et al. (2012). Navigating challenges and opportunities of land degradation and sustainable livelihood development in dryland social-ecological systems: a case study from Mexico. *Philosophical Trans. R. Soc. B Biol. Sci.* 367, 3158–3177. doi: 10.1098/rstb.2011.0349
- Instituto Nacional de Estadística y Geografía [INEGI] (2001). Conjunto de datos vectoriales Fisiográficos. *Continuo nacional serie I. Provincias fisiográficas. (Escala 1:1 000 000) [Conjunto de datos]*. INEGI. Available online at: <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=70282526755>.
- INEGI (2016). Diccionario de datos de uso potencial agrícola, pecuario y forestal. (Vectorial). Esc. 1: 250 000 y 1: 1 000 000. Instituto Nacional de Estadística y Geografía. Available online at: <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825224004> (Accessed October 12, 2026).
- Instituto Nacional de Estadística y Geografía [INEGI] (2018). Conjunto de datos vectoriales de uso del suelo y vegetación. Escala 1:250 000. Serie VII. Conjunto Nacional [Archivo electrónico]. INEGI. Available online at: <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=889463842781>.
- INIFAP. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (2020). *Tecnologías para el mejoramiento de la producción caprina extensiva en México* (Libro técnico núm. 5). Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Available online at: https://vun.inifap.gob.mx/VUN_MEDIA/BibliotecaWeb/_media/_librotecnico/14364_5125_Tecnolog%C3%ADas_para_el_Mejoramiento_de_la_Producci%C3%B3n_Caprina_Extensiva_en_M%C3%A9xico.pdf (Accessed October 12, 2026).
- Jamsranjav, C., Fernández-Giménez, M. E., Reid, R. S., and Adya, B. (2019). Opportunities to integrate herders' indicators into formal rangeland monitoring: an example from Mongolia. *Ecol. Appl.* 29, e01899. doi: 10.1002/eap.1899
- Jiménez-Castillo, P., García, J. L. S., and Moreno-Narganes, J. M. (2025). From flocks to fields: pastoralism in eastern al-Andalus during the 11th century. *Humans* 5, 4. doi: 10.3390/humans5010004
- Johansson, E. L., and Isgren, E. (2017). Local perceptions of land-use change: using participatory art to reveal direct and indirect socioenvironmental effects of land acquisitions in kilombero valley, Tanzania. *Ecol. Soc.* 22, art3. doi: 10.5751/ES-08986-220103
- Johnsen, K. I., Niamir-Fuller, M., Bensada, A., and Waters-Bayer, A. (2019). A case of benign neglect: knowledge gaps about sustainability in pastoralism and rangelands. Nairobi and Arendal: United Nations Environment Programme and GRID-Arendal. Available online at: www.grida.no (Accessed October 12, 2026).
- Kakinuma, K., Yanagawa, A., Sasaki, T., Rao, M. P., and Kanae, S. (2019). Socio-ecological interactions in a changing climate: a review of the Mongolian pastoral system. *Sustain. Switz.* 11, 1–17. doi: 10.3390/su11215883
- Kok, M., Lüdeke, M., Lucas, P., Sterzel, T., Walther, C., Janssen, P., et al. (2016). A new method for analysing socio-ecological patterns of vulnerability. *Reg. Environ. Change* 16, 229–243. doi: 10.1007/s10113-014-0746-1
- Lara-Juárez, P., Aguirre-Rivera, J. R., Castillo-Lara, P., and Reyes-Agüero, J. A. (2018). Recolección de pupas (escamoles) de liometopum apiculatum (hymenoptera, formicidae, dolichoderinae) en el altiplano de San Luis Potosí, México. *Interiencia Rev. Cienc. Tecnol. América* 43 (11), 763–769. Available online at: <https://dialnet.unirioja.es/servlet/articulo?codigo=6651671>.
- Lauterio-Martínez, C. L., Huber-Sannwald, E., Hernández Valdéz, S. D., Leyva Aguilera, J. C., Lucatello, S., Martínez Tagüña, N., et al. (2021). Collective methods to weave the pathway from desertification to sustainable development: Participatory social-ecological observatories. *Ecosistemas* 30, 2232. doi: 10.7818/ECOS.2232
- León Villalobos, J. M., Ojeda Trejo, E., Vázquez García, V., McCall, M. K., Arévalo Galarza, G., and Ortiz Olguín, M. (2018). Mapping political space and local knowledge: power and boundaries in a Hñahñu (Otomi) territory in Valle del Mezquital, Mexico, 1521–1574. *J. Hist. Geogr.* 60, 64–76. doi: 10.1016/j.jhg.2018.01.003
- Levin, S., Xepapadeas, T., Crépin, A. S., Norberg, J., De Zeeuw, A., Folke, C., et al. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environ. Dev. Econ.* 18, 111–132. doi: 10.1017/S1355770X12000460
- Li, G., He, S., Ma, W., Huang, Z., Peng, Y., and Ding, G. (2025). Assessing rural development vulnerability index: a spatio-temporal analysis of post-poverty alleviation areas in Hunan, China. *Sustain. Switz.* 17, 6033. doi: 10.3390/su17136033
- Linstädter, A., Kuhn, A., Naumann, C., Rasch, S., Sandhage-Hofmann, A., Amelung, W., et al. (2016). Assessing the resilience of a real-world social-ecological system: lessons from a multidisciplinary evaluation of a South African pastoral system. *Ecol. Soc.* 21, art35. doi: 10.5751/ES-08737-210335
- Long, J. W., and Steel, E. A. (2020). Shifting perspectives in assessing socio-environmental vulnerability. *Sustain. Switz.* 12, 2625. doi: 10.3390/su12072625
- Luna, J. C. Y., Martínez, L. D. T., and Pérez, L. P. P. (2021). ¿Las condiciones socioeconómicas tienen efectos en el desempeño económico? El caso de la región del altiplano de San Luis Potosí en México. *Contaduría Y Adm.* 66, 1–21. doi: 10.22201/fca.24488410e.2021.2405
- Mairomi, H. W., and Kimengsi, J. N. (2021). Community-based actors and participation in rangeland management. Lessons from the Western highlands of Cameroon. *Sustain. Switz.* 13, 1–22. doi: 10.3390/su13041700
- Manzano, P., Burgas, D., Cadahia, L., Eronen, J. T., Fernández-Llamazares, Á., Bencherif, S., et al. (2021). Toward a holistic understanding of pastoralism. *One Earth* 4, 651–665. doi: 10.1016/j.oneear.2021.04.012
- Martínez-Tagüña, N., Huber-Sannwald, E., Reyes Gómez, V. M., Lauterio Martínez, C. L., and Lucatello, S. (2024). Zonas áridas de México: construcción de comunidades de aprendizaje. *Inst. Investig. Dr. José María Luis Mora*. doi: 10.59950/IM.131
- Masterson, V. A., Stedman, R. C., Enqvist, J., Tengö, M., Giusti, M., Wahl, D., et al. (2017). The contribution of sense of place to social-ecological systems research: a review and research agenda. *Ecol. Soc.* 22, art49. doi: 10.5751/ES-08872-220149
- Mata-Páez, R. I., Huber-Sannwald, E., Martínez-Tagüña, N., Cázares-Reyes, R., Reyes-Gómez, V. M., López-Pardo, J. J., et al. (2025). Talking as friends: weaving local and scientific knowledge to co-produce an integrated index to assess rangeland multifunctionality in a dryland biosphere reserve in Mexico. *People Nat.* 7, 3036–3056. doi: 10.1002/pan3.70175
- Mellado, M. (1997). La cabra criolla en América Latina. 28 (4), 333–343.
- Mena, Y., Nahed, J., Ruiz, F. A., Sánchez-Muñoz, J. B., Ruiz-Rojas, J. L., and Castel, J. M. (2012). Evaluating Mountain goat dairy systems for conversion to the organic model, using a multicriteria method. *Animal* 6, 693–703. doi: 10.1017/S175173111100190X
- Metcalf, S. J., van Putten, E. I., Frusher, S., Marshall, N. A., Tull, M., Caputi, N., et al. (2015). Measuring the vulnerability of marine social-ecological systems: a prerequisite for the identification of climate change adaptations. *Ecol. Soc.* 20, art35. doi: 10.5751/ES-07509-200235
- Molnár, Z. (2017). "I see the grass through the mouths of my animals"—folk indicators of pasture plants used by traditional steppe herders. *J. Ethnobiol.* 37, 522–541. doi: 10.2993/0278-0771-37.3.522
- Montiel Torres, M. A. (2019). Globalización y producción campesina de alimentos en las zonas áridas de San Luis Potosí (México). *Revista de El Colegio de San Luis* 9 (20), 559–581. doi: 10.21696/rcsl92020191066
- Mora-Ledesma, I. (2011). "Vámonos con todo y chivas," in *Sistemas De Supervivencia En Las Culturas Ganaderas Del Norte De San Luis Potosí. Revista De El Colegio De San Luis* 1, 48–66. doi: 10.21696/rcsl012011479
- Mora-Ledesma, I. (2020). Saberes del sustento: pastoreo, territorio y conocimientos. La cultura alimentaria en el desierto., 1a edición. *San Luis Potosí El Col. San Luis*
- Morán, J., Cano, A., and Ortega, L. (2023). *Desiertos Del Norte Mexicano Formas De Investigación Sobre Los Desafíos Para El Sosténimiento De La Vida En Las Zonas Áridas Y Semiáridas*.
- Moussa, Z. (2009). Tips for Trainers: Rivers of life. Available online at: <https://www.iied.org/g02828>.
- Negrete, L. O. (2020). *Los Agostaderos Del Altiplano Potosino Y La Desertificación*. Instituto de Investigación de Zonas Desérticas, 10–15.
- Negrete-Sánchez, L. O., Aguirre-Rivera, J. R., Pinos-Rodríguez, J. M., and Reyes-Hernández, H. (2016). Beneficio de la parcelación de los agostaderos comunales del ejido "El Castañón". *Municipio Catorce, San Luis Potosí 1993-2013. Agrociencia* 50, 511–532. Available online at: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-31952016000400511&lng=es&nrm=iso.

- Niamir-Fuller, M. (1999). *Managing mobility in African rangelands: The legitimization of transhumance*. Intermediate Technology Publications; FAO; Beijer International Institute of Ecological Economics. doi: 10.3362/9781780442761.000
- Ntombela, K. P., Angula, M., Samuels, I., Cupido, C., Swarts, M., Menjono-Katjizeu, E., et al. (2024). Pastoral coping and adaptive management strategies to climate change in communal areas in Namibia and South Africa. *Pastor. Res. Policy Pract.* 14, 13548. doi: 10.3389/past.2024.13548
- Oba, G. (2013). "The sustainability of pastoral production in Africa," in *Pastoralism and Development in Africa* (London: Routledge), 29–36. doi: 10.4324/9780203105979-3
- Ortega, L., and Morán, J. (2020). "Forced modernization in drylands: socio-ecological system disruption in the altiplano of San Luis Potosí, Mexico," in *Stewardship of Future Drylands and Climate Change in the Global South*. Editors S. Lucatello, E. Huber-Sannwald, I. Espejel, and N. Martínez-Tagüeña (Cham: Springer International Publishing), 97–109. doi: 10.1007/978-3-030-22464-6
- Oseguera Montiel, D., Keilbach Baer, N. M., van der Zijpp, A., Sato, C., and Udo, H. (2014). It is better to herd than be herded: making a living with goats in the bajo region, Mexico. *Pastoralism* 4, 1–18. doi: 10.1186/s13570-014-0009-2
- Pappagallo, L. (2021). Recasting tenure and labour in non-equilibrium environments: making the case for "high-reliability" pastoral institutions. *Land Use Policy* 138, 107034. doi: 10.1016/j.landusepol.2023.107034
- Pappagallo, L., and Semplici, G. (2020). Editorial introduction methodological mess: doing research in contexts of high variability. *Nomad. People* 24, 179–194. doi: 10.3197/NP.2020.240201
- Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Serv. Res.* 34 (5 Pt2), 1189–1208. Available online at: <https://pubmed.ncbi.nlm.nih.gov/10591279/>.
- Pinos-Rodríguez, J. M., García-López, J. C., Aguirre-Rivera, J. R., and Reyes-Hernández, H. (2013). Participatory cartography in a traditional goat production system of a smallholder community in northern México. *Trop. Subtropical Agroecosyst.* 16, 215–222. doi: 10.56369/tsaes.1782
- Postigo, J. C. (2021). Navigating capitalist expansion and climate change in pastoral social-ecological systems: impacts, vulnerability and decision-making. *Curr. Opin. Environ. Sustain.* 52, 68–74. doi: 10.1016/j.cosust.2021.07.002
- Potosí, S. L. (2013). Universidad Autónoma de San Luis Potosí (UASLP). Repositorio Institucional UASLP. Available online at: <https://repositorioinstitucional.uaslp.mx/xmlui/handle/i/3676>.
- Rajala, K., and Soric, M. G. (2022). Sense of place on the range: landowner place meanings, place attachment, and well-being in the southern great plains. *Rangelands* 44, 353–367. doi: 10.1016/j.rala.2021.07.004
- Rajala, K., Soric, M. G., and Thomas, V. A. (2020). The meaning(s) of place: identifying the structure of sense of place across a social-ecological landscape. *People Nat.* 2, 718–733. doi: 10.1002/pan3.10112
- Rana, M. M. S. P., and Moniruzzaman, M. (2023). Potential application of GIS and remote sensing to evaluate suitable site for livestock production in northwestern part of Bangladesh. *Watershed Ecol. Environ.* 5, 161–172. doi: 10.1016/j.wsee.2023.07.001
- Reid, R. S., Hobbs, N. T., Galvin, K. A., and Ellis, J. E. (2008). *Fragmentation of Arid and Semi-arid Ecosystems: Implications for People and Animals*. doi: 10.1007/978-1-4020-4906-4_2
- Reid, R. S., Fernández-Giménez, M. E., and Galvin, K. A. (2014). Dynamics and resilience of rangelands and pastoral peoples around the globe. *Annu. Rev. Environ. Resour.* 39, 217–242. doi: 10.1146/annurev-environ-020713-163329
- Reid, R. S., Fernández-Giménez, M. E., Wilmer, H., Pickering, T., Kassam, K. A. S., Yasin, A., et al. (2021). Using research to support transformative impacts on complex, "Wicked Problems" with pastoral peoples in rangelands. *Front. Sustain. Food Syst.* 4, 1–24. doi: 10.3389/fsufs.2020.600689
- Reid-Shaw, I., Jargalsaihan, A., Reid, R. S., Jamsranjav, C., and Fernández-Giménez, M. E. (2021). Social-ecological change on the Mongolian steppe: herder perceptions of causes, impacts, and adaptive strategies. *Hum. Ecol.* 49, 631–648. doi: 10.1007/s10745-021-00256-7
- Ríos-Rentería, I., and Rivera, P. (2017). Impacto socioeconómico y ambiental del progan y el procampo en el municipio de El Oro, Durango. *Agric. Soc. Y Desarrollo* 17, 143–170. doi: 10.22231/asdy.v17i1.1326
- Rivera, J. R. A., Sánchez, L. O. N., and Rivera, R. C. (2020). Effects of 20 years of parceling on the condition of communal rangeland on a Mexican ejido. *Rev. Fac. Cienc. Agrar.* 52, 189–203. Available online at: https://www.scielo.org.ar/scielo.php?script=sci_arttext&pid=S1853-86652020000200017&lng=es&nrm=iso.
- Roberts, R., and Goodwin, P. (2002). Weight approximations in multi-attribute decision models. *J. Multi-Criteria Decis. Analysis* 11, 291–303. doi: 10.1002/mcda.320
- Robinson, L. W. (2019). Open property and complex mosaics: variants in tenure regimes across pastoralist social-ecological systems. *Int. J. Commons* 13, 804–826. doi: 10.18352/ijc.903
- Robinson, L., and Flintan, F. (2022). Can formalisation of pastoral land tenure overcome its paradoxes? Reflections from East Africa. *Pastoralism* 12, 34. doi: 10.1186/s13570-022-00250-8
- Roche, L. M. (2021). Grand challenges and transformative solutions for rangeland social-ecological systems – emphasizing the human dimensions. *Rangelands* 43, 151–158. doi: 10.1016/j.rala.2021.03.006
- Roux, D. J., Nel, J. L., Cundill, G., O'Farrell, P., and Fabricius, C. (2017). Transdisciplinary research for systemic change: who to learn with, what to learn about and how to learn. *Sustain. Sci.* 12, 711–726. doi: 10.1007/s11625-017-0446-0
- Rzedowski, J. (1961). *Vegetación Del Estado De San Luis Potosí*, México: Universidad Nacional Autónoma de México.
- Sader, S. (2021). Unidades de Producción Agropecuaria un Orgullo para México. Available online at: <https://www.gob.mx/agricultura/articulos/unidades-de-produccion-agropecuaria-son-un-orgullo-de-mexico> (Accessed October 12, 2026).
- Scoones, I., Bose, S., Gogineni, R., Maru, N., Mohamed, T., Nori, M., et al. (2023). Pastoralism, uncertainty and development. The institute of development studies and partner organisations. Monograph. Available online at: <https://hdl.handle.net/20.500.12413/18009>.
- Seiferth, C., Tengö, M., and Andersson, E. (2024). Designing for collective action: a knowledge co-production process to address water governance challenges on the island of Öland, Sweden. *Sustain. Sci.* 19, 1623–1640. doi: 10.1007/s11625-024-01531-4
- Semplici, G., Haider, L. J., Unks, R., Mohamed, T. S., Simula, G., Tsering, P., et al. (2024). Relational resilience: reflections from pastoralism across the world. *Ecosyst. People* 20, 2396928. doi: 10.1080/26395916.2024.2396928
- Sharifian, A., Fernández-Llamazares, Á., Wario, H. T., Molnár, Z., and Cabeza, M. (2022). Dynamics of pastoral traditional ecological knowledge: a global state-of-the-art review. *Ecol. Soc.* 27, art14. doi: 10.5751/ES-12918-270114
- Sharifian, A., Gantuya, B., Wario, H. T., Kotowski, M. A., Barani, H., Manzano, P., et al. (2023). Global principles in local traditional knowledge: a review of forage plant-livestock-herder interactions. *J. Environ. Manage.* 328, 116966. doi: 10.1016/j.jenvman.2022.116966
- SIAP (2022). *Producción Ganadera: Cierre De La Estadística Pecuaria 2022. Servicio De Información Agroalimentaria Y Pesquera*. Available online at: <https://www.gob.mx/agricultura/dgsiap/acciones-y-programas/produccion-pecuaria>.
- Singh, R., Sharma, R. K., Babu, S., and Bhatnagar, Y. V. (2020). Traditional ecological knowledge and contemporary changes in the agro-pastoral system of upper spiti landscape, Indian trans-himalayas. *Pastoralism* 10, 15. doi: 10.1186/s13570-020-00169-y
- Souza, D. T., Jacobi, P. R., and Wals, A. E. J. (2020). Overcoming socio-ecological vulnerability through community-based social learning: the case of lomba do pinheiro in Porto alegre, Brazil. *Local Environ.* 25, 179–201. doi: 10.1080/13549839.2020.1714569
- Stillwell, W. G., and Seaver, D. A. (1981). *A Comparison of Weight Approximation Techniques in Multiattribute Utility Decision Making*.
- Tajonar, K., Díaz, C. A. L., Ibarra, L. E. S., Chay-Canul, A. J., Gonzalez-Ronquillo, M., and Vargas-Bello-pérez, E. (2022). A brief update on the challenges and prospects for goat production in Mexico. *Animals* 12, 837. doi: 10.3390/ani12070837
- Tengö, M., Hill, R., Malmer, P., Raymond, C. M., Spierenburg, M., Danielsen, F., et al. (2017). Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. *Curr. Opin. Environ. Sustain.* 26 (27), 17–25. doi: 10.1016/j.cosust.2016.12.005
- Thiault, L., Jupiter, S. D., Johnson, J. E., Cinner, J. E., Jarvis, R. M., Heron, S. F., et al. (2021). Harnessing the potential of vulnerability assessments for managing social-ecological systems. *Ecol. Soc.* 26, art1. doi: 10.5751/ES-12167-260201
- Tolera, T., and Senbeta, F. (2020). Pastoral system in the face of climate variability: household adaptation strategies in Borana Rangelands, Southern Ethiopia. *Environ. Dev. Sustain.* 22, 3133–3157. doi: 10.1007/s10668-019-00339-y
- Tolera, T., and Senbeta, F. (2023). A social network analysis of collaborative rangelands governance: the case of borana rangelands, Southern Ethiopia. *Hum. Ecol.* 51, 429–437. doi: 10.1007/s10745-023-00418-9
- Trenti-Verly, L. C., González-Jácome, A., Landín López, A. L., Mariaca Méndez, R., Jiménez-Ferrer, G., and Nahed Toral, J. (2021). Caprinocultura, ambiente y economía campesina: Un análisis de los sistemas familiares ganaderos en el semidesierto potosino. *Rev. El Col. San Luis* 11, 0–22. doi: 10.21696/rcsl112220211313
- Turner, M. D., and Schlecht, E. (2019). Livestock mobility in Sub-Saharan Africa: a critical review. *Pastoralism* 9, 13. doi: 10.1186/s13570-019-0150-z
- Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., et al. (2003). A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci.* 100, 8074–8079. doi: 10.1073/pnas.1231335100
- Urquijo Torres, P. S. (2017). *Reseña del libro Los caminos de la trashumancia: Territorio, persistencia y representaciones de la ganadería pastoril en el Altiplano Potosino, coord. por I. Mora Ledesma*. Revista de El Colegio de San Luis, Nueva época, año VII, 300–304.
- Vargas, S. P., Hargreaves, M., Del Valle, J. P., Hodges, A., Beltrami, E., Toledo, M. F., et al. (2022). Coexistence in times of climate crisis: a participatory mapping to understanding conservation conflicts in the central andes of Chile. *Front. Conservation Sci.* 3, 731382. doi: 10.3389/fcsc.2022.731382
- Vilá, B., Arzamendia, Y., and Rojo, V. (2020). Environmental education as a means for valuing and conserving camelids and pastoralism in the argentinean altiplano of Jujuy. *Mt. Res. Dev.* 40, D39–D49. doi: 10.1659/MRD-JOURNAL-D-20-00009.1
- Wang, Z., Xue, Z., Zhang, X., Yan, H., and Liu, G. (2025). Adaptive capacity to climate change in pastoral areas. *Sustain. Switz.* 17, 1337. doi: 10.3390/su17031337

- Weng, C., Bai, Y., Chen, B., Hu, Y., Shu, J., Chen, Q., et al. (2023). Assessing the vulnerability to climate change of a semi-arid pastoral social-ecological system: a case study in Hulunbuir, China. *Ecol. Inf.* 76, 102139. doi: 10.1016/j.ecoinf.2023.102139
- Wilmer, H., Derner, J. D., Fernández-Giménez, M. E., Briske, D. D., Augustine, D. J., and Porensky, L. M. (2018). Collaborative adaptive rangeland management fosters management-science partnerships. *Rangel. Ecol. Manag.* 71, 646–657. doi: 10.1016/j.rama.2017.07.008
- Wilmer, H., Schulz, T., Fernández-Giménez, M. E., Derner, J. D., Porensky, L. M., Augustine, D. J., et al. (2022). Social learning lessons from Collaborative adaptive rangeland management. *Rangelands* 44, 316–326. doi: 10.1016/j.rala.2021.02.002
- Wurzinger, M., Escareño, L., Pastor, F., H., S., Iñiguez, L., and Sölkner, J. (2013). Design and implementation of a community-based breeding program for dairy goats in northern Mexico. *Trop. Subtropical Agroecosyst.* 16, 289–296. doi: 10.56369/tsaes.1528
- Yang, Z., Li, B., Nan, B., Dai, X., Peng, C., and Bi, X. (2023). A methodological framework for assessing pastoral socio-ecological system vulnerability: a case study of altay prefecture in central Asia. *Sci. Total Environ.* 862, 160828. doi: 10.1016/j.scitotenv.2022.160828
- Zhang, Q. (2023). Land use and adaptive governance under climate change: analysis of four cases in pastoral areas of China. *Front. Environ. Sci.* 11, 922417. doi: 10.3389/fenvs.2023.922417