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Mining expansion may reduce livestock but facilitate vicuñas recovery in tropical Puna of South America

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High-elevation tropical grasslands in South America are vital for sustaining the livelihoods of indigenous communities, particularly in the Central Andes where herding of both wild and domesticated camelids has been a primary socio-economic activity for centuries. However, these grasslands are facing challenges due to changes in land use, economic activities, and climate, posing threats to the sustainability of camelid herding. Here, we determine the intricate relationship between land use management and camelid populations of the highlands of Apolobamba National Park in Bolivia. We identified two critical milestones in land use management across the indigenous communities: the creation of the Tierra Comunitaria de Origen (TCO) in 1999 and the expansion of the National Park in 2000. These initiatives collectively resulted in the diversification of livelihood sources by increasing the number of mining concessions and facilitating the management of wild camelids for their wool and fibers, catering to international markets. We found that this diversification of livelihood sources was negatively related to the densities of domesticated camelids across the studied communities. In contrast, the densities of wild camelids populations increased with an increasing number of mining concessions, likely due to local conservation efforts and reduced competition with livestock. Our results indicate a potential shift in land use management strategies and suggest that mining activities encroach upon pastoralism practices within indigenous communities. Understanding the long-term effects of land use changes is essential for providing comprehensive and sustainable land use strategies that will support both grasslands and animal conservation while providing livelihood security in this ecologically sensitive region.

KEYWORDS

tropical grasslands, indigenous communities, camelid herding, wild camelids, mining concessions, land use strategies

Introduction

Pastoralism is the main traditional socio-economic livelihood in mountainous ecosystems in most of the world (Arzamendia et al., 2021). The livelihoods of many people, particularly in rural areas, depend on the provision of goods and services such as milk, meat, and wool, derived from livestock (Eldridge and Delgado-Baquerizo, 2017). However, current ongoing degradation of grassland ecosystems poses a threat to the livelihoods of local communities (Bengtsson et al., 2019). Sustainable land use approaches are therefore essential to balance grassland conservation and human well-being, especially in marginalized indigenous communities (Rolando et al., 2017). Developing policies that foster such a balance is particularly important in regions where livestock herding maintains the economy and cultural identity of local communities (Anderson et al., 2014).

In the Andes, tropical grasslands cover about 30% of the total area and it is estimated that the livelihoods of 40 million people depend on them (Becker and Bugmann, 2001; Tovar et al., 2013). The pastoral strategies employed vary significantly along the latitudinal gradient. In the northern Andes (high páramos), areas are often not designated for permanent settlement and livestock may graze without supervision (Molinillo and Monasterio, 2002). In contrast, the central and southern Andes (punas) have seen the emergence of permanent settlements by herders, who have tended to exert greater control over grazing patterns for approximately 5000 years (Wheeler, 2012; Mengoni Goñalons, 2008). Notably, herders in the punas have preserved the longstanding tradition of camelid herding, specifically involving domesticated llama (*Lama glama*) and alpaca (*Vicugna pacos*). This longstanding history of camelid herding management has enabled central and southern Andean herders to establish institutions, ecological knowledge, and sustainable management practices tailored to the challenging climatic conditions of the Andes (Lindner et al., 2017). Practices such as mobility and transhumance have played a crucial role in allowing pastoralists to adapt to changes in resource availability and climatic conditions, particularly during dry periods (Khazanov, 1994; Yacobaccio, 2014).

The traditional grazing management practices in the central Andean region have helped conserve native grasslands, which are typically characterized by medium-sized to short grasses (Seibert 1994; Sylvester et al., 2014). The conservation of these grasslands has facilitated the presence of the wild vicuña (*Vicugna vicugna*), one of the most important wild mammal species in the Andes (Karandikar et al., 2023). Indigenous communities have traditionally managed vicuña populations by extracting and selling the wool fiber, which is currently in high demand at international markets (Wildlife Conservation Society, 2023). Widespread declines in vicuña populations have been linked to the expansion of human populations (McLaren et al., 2018). In particular, uncontrolled hunting and increased competition with livestock are the main factors leading to reduced vicuña populations (Lichtenstein and Vila, 2003; Izquierdo et al., 2018). Recently, vicuña populations in the central Andes seem to have remained stable or increased, despite challenges like poaching, diseases and predation by sheepdogs and puma (Arzamendia et al., 2021). This can be attributed to factors including better control of hunting and reduced competition from livestock (Grau and Aide, 2007). Interestingly, competition for food between livestock and vicuñas can be mitigated, especially during the wet season, in grasslands with higher spatial heterogeneity and higher forage plant quality (Mosca Torres and Puig, 2010). However, the longer-term sustainability of vicuña population management might face challenges, because native central Andean grasslands are currently overgrazed by domesticated camelids, leaving less food for wild vicunas (León-Velarde and Quiroz, 2004; Muñoz et al., 2015; Duchicela et al., 2019).

Overgrazing of grasslands in the central Andes typically results on grazing-resistant plant species, which have become dominant as a consequence of intense livestock grazing combined with impacts of climate change and shifts in land use strategies other than grazing (Duchicela et al., 2019; Adams et al., 2022; Sandoval-Calderon et al., 2023). Land use intensification, particularly the abandonment of collective land tenure and traditional herding methods, limits farmers' capability to adapt camelid herding practices. Moreover, the expansion of open-pit gold mining has emerged as a significant activity within indigenous communities across large areas of the Andes region (Achtenberg, 2014; Arzamendia et al., 2014). Increases in mining activities are leading to various environmental impacts and social conflicts. First, mining operations contribute to the depletion of natural resources, notably lowering water quality and quantity upon which agricultural and livestock-based livelihoods depend (Brain, 2017). Second, they result in both population growth in mining communities and the displacement of local residents into cities, or from communal grazing lands onto smaller plots of land, limiting their ability to continue land-based livelihoods. Third, mining operations are introducing new forms of employment, offering temporary higher incomes. Additionally, these changes may enhance social stratification within the community, as some people may perceive wage labor in mining as more contemporary and advanced compared to traditional pastoralism (Brain, 2017; Arzamendia et al., 2021). As a result of these different impacts, increases in mining activities could lead to a decrease in livestock populations due to the depletion of natural resources, displacement of local residents and new forms of employment (Abeledo, 2017). The decrease in livestock populations with increasing mining activities could in turn benefit wild vicuñas populations due to reduced competition for food with livestock as seen in the Argentinean Puna (Izquierdo et al., 2018; Navarro et al., 2023).

Consequently, collective land tenure, traditional herding methods and traditional institutions are diminishing (Postigo et al., 2008). In most regions of the central Andes, it remains unclear whether these changes in land use management are still safeguarding indigenous livelihoods (Damonte et al., 2016). Recent studies indicate declines in water availability and quality, and in grassland productivity (Damonte et al., 2016), along with biotic homogenization of plant diversity (Sandoval-Calderon et al., 2023). These trends suggest that pastoralist societies may not be able to continue livestock production sustainably. More research detailing the state and impacts of land use strategies in local communities is needed to inform and support more sustainable management of Andean grasslands.

Here we analyze changes in land use practices and camelid population within eight indigenous communities located in the highlands of Apolobamba National Park in northwestern Bolivia. First, we identify critical milestones in land use management across the indigenous communities. Second, we determine changes in livestock and wild camelids densities as well as in the number of mining concessions over time. Third, we relate changes in domestic livestock and wild vicuña populations to the number of mining concessions.

Methodology

Study area

The eight indigenous communities are situated in the high mountains of Apolobamba National Park, located in the northwest Bolivian Andes (Figure 1). Ecologically, this region is classified as wet Puna, situated at elevations ranging from 3,700 to 4,300 m, and characterized by traditional grazing practices (Lentz, 2000). Established in 1972 and expanded in 2000, Apolobamba National Park was created to conserve high-mountain ecosystems and houses one of Bolivia's largest vicuña populations (Servicio Nacional de Áreas Protegidas SERNAP, 2006). Covering approximately 482,742 hectares, with a portion used for camelid herding, the park employs a rotational grazing system where domestic livestock graze in upland pastures during the rainy season and move to valleys and bofedales (wetlands) during the dry season to allow vegetation recovery in upland pastures. Six of the studied communities belong to the Tierra Comunitaria de Origen (TCO) Marka Cololo-Copacabana-Antaquilla (Figure 1) which was created by a constitutional reform in 1994 (Figure 2). This reform recognized indigenous communities' rights, i.e., communities employ autonomous management strategies, transitioning from communal-based to family-based management and are able to take decisions on land management within an official legal framework (Damonte et al., 2016). Conversely, two of the studied communities: Cañahuma and Medallani, maintain communal management strategies outside the TCO framework.

Over the last few decades, mining and its impacts have become increasingly prevalent throughout the Andes, particularly in the Apolobamba region. Individual mining concessions differ in their area, depending on factors such as age of the concession and intensity of the activity, however there is an estimation that 51,61% of the area is currently with active or approved mining activities (Wildlife Conservation Society, 2023). Socioeconomically, mining is vital as it generates development, creates new forms of employment, provides income, and improves the quality of life for families in mining regions (Servicio Nacional de Áreas Protegidas SERNAP, 2006). Consequently, mining has become a priority and a crucial livelihood activity for many families within Apolobamba. However, the

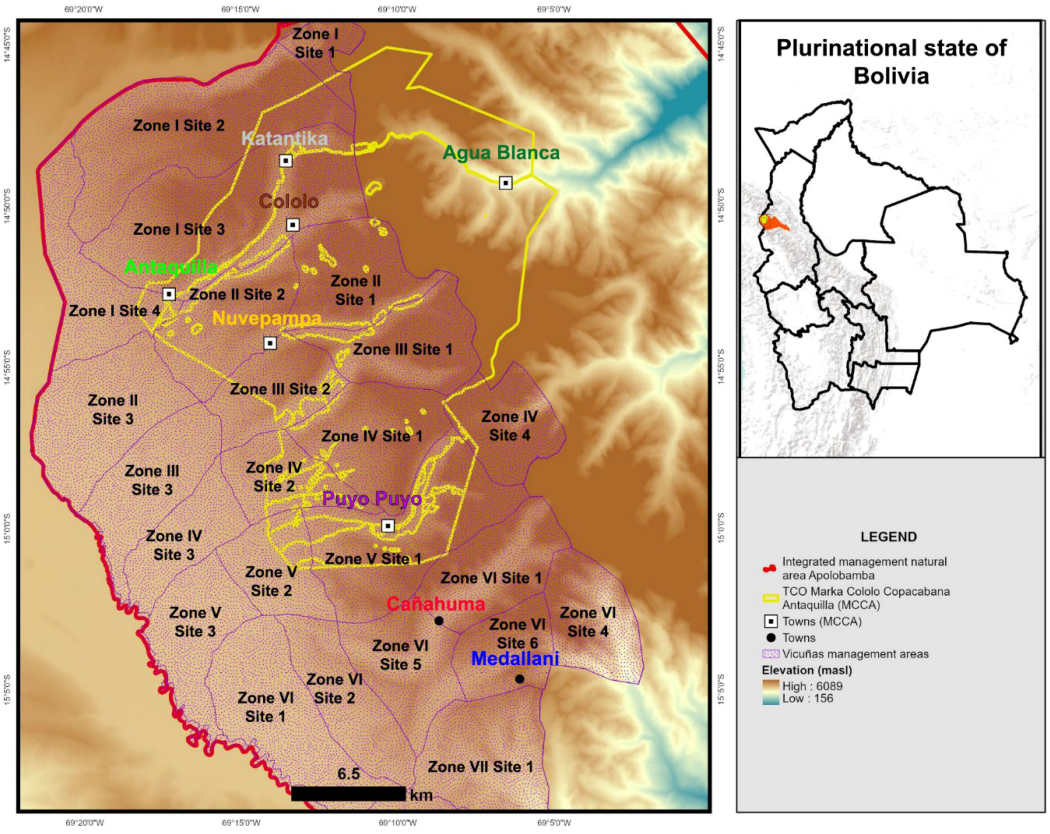

FIGURE 1
Location of the eight indigenous communities selected for the study. The center of the communities are represented with a squared or circle. Colors of the communities match colors in Table 1 and Figures 3, 4. The boundaries of the Tierra Comunitaria de Origen (TCO) Marka Cololo-Copacabana-Antaquilla within the National Park are outlined in yellow and the Vicuña census zones are delimited in purple.

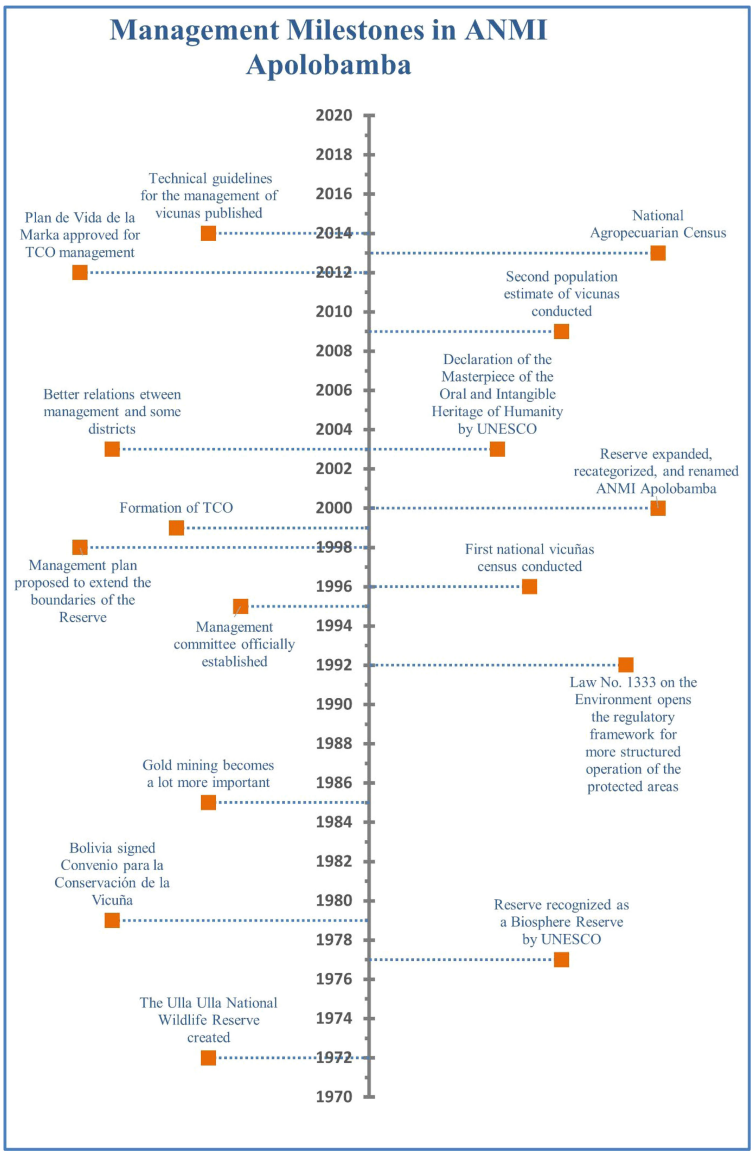

FIGURE 2
Timeline of important management events in Apolobamba National Park history. The most important events for our study regions occurred in the late 1990s and 2000. Information was synthesized from SERNAP (2016) and the management plan -TCO Marka Cololo Copacabana de Antaquilla (2012). TCO, Territorio Comunitaria de Origen, Community Territory; UNESCO, United Nations Educational, Scientific and Cultural Organization; ANMI, Área Natural de Manejo Integrado Apolobamba, Apolobamba Integrated Management Natural Area; SERNAP; Servicio Nacional de Áreas Protegidas, National Service of Protected Areas.

environmental consequences of mining are severe because rudimentary methods are often used. Most of the mining concessions are open-pit mining, which largely affect the grasslands in the area, while only a small percentage of them are located in rock edges. These impacts include landscape alteration, land degradation, water pollution, loss of flora and fauna, air pollution from heavy machinery and open mercury burning, and soil erosion (Servicio Nacional de Áreas Protegidas SERNAP, 2006). Beyond environmental damage, mining has led to other significant issues. The state struggles to control illegal mining activities, and population growth in mining communities has surged due to the return of former migrants. This population increase drives up the costs of goods, services, and basic necessities. Additionally, there are frequent conflicts over land use between communal landholders and mining rights holders, as well as between pastoralists and miners, due to the detrimental effects on grasslands, water sources, and bofedales (Servicio Nacional de Áreas Protegidas SERNAP, 2006).

Data collection

Land use strategies

To identify critical milestones in land use management across the indigenous communities, we conducted one participatory workshop in each of the eight indigenous communities between February and April 2019. These workshops provided insights into

the main events regarding livestock management and land use strategies, helping us contextualize and understand the varying land use strategies over time. Ethical approval was not required for the studies involving humans because our study was authorized by the local authorities (Benjamín Callancho, Casilla Jilir Apu Mallku Pukina Nation) and the head of protection of ANMI Apolobamba (René Romer Llaves Quisbert). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because the participants part of a training program provided by the Wildlife Conservation Society-Bolivia. This organization has established collaboration agreements that allow for the conduct of workshops and the use of information from monitoring reports.

Livestock and camelid populations and number of mining concessions

To determine changes over time in animal densities, number of mining concessions and relationships among them, we extracted spatio-temporal (2012-2022) data on livestock herd size and the number of mining concessions from monitoring reports provided by Wildlife Conservation Society in Bolivia (WCS-Bolivia) and data obtained from the national agricultural census in 2013. These reports were performed by field technicians from WCS-Bolivia using standardized interviews with farmers and authorities and focused on changes in livestock, vicuña and mining in the studied communities. WCS did not distinguish between active mines and those with paper approval. Similarly to livestock, we obtained data about wild camelid populations from the official *Vicugna vicugna* (vicuña) population census (2018-2022). These censuses were carried out by the Regional Association of Vicuña Management Communities Apolobamba (ARCMV Apolobamba) in collaboration with WCS-Bolivia. The census were performed in 18 delineated zones within Apolobamba National Park. We established which of these zones were located within each of the studied indigenous communities and extracted the number of animals for each community (Figure 1). In some cases, one entire indigenous community was covered by two zones. To obtain wild camelid densities, we divided the total number of vicuñas by the grazing area of the census zone for each community for each year (animal unit/hectare).

Data analysis

First, to provide a visual representation of the temporal livestock management changes and key milestones, we constructed a vertical timeline using Vertex42.com (Figure 2), offering a concise overview of the evolving landscape. Then, we conducted a comprehensive spatio-temporal analysis to investigate changes in livestock density, wild vicuña population density, and the number of mining concessions spanning the period from 2012 to 2022. To identify significant changes, we employed an analysis of covariance (ANCOVA) for each response variable, with a focus on the temporal dimension. We conducted separate analyses for each indigenous community, treating time as the continuous explanatory variable and community as the categorical variable. Next, using linear mixed-effects models with the lme function (Pinheiro and Bates, 2000), we modeled bivariate relationships between livestock density and number of mining concessions and between vicuña population density and the number of mining concessions. We treated community as random effect, allowing both the intercepts and slopes to vary among sites if supported by model selection. All analyses were conducted in R version 4.1.3 (R Core Team, 2023).

Results

Management milestones and land use strategies at the Apolobamba national park

Several significant management events (Figure 2) occurred in our study area. Before the Agrarian reform, land was owned by large private landholders. The agrarian reform of 1953 initiated the division of communities into smaller units, forming agrarian unions to access land. In 1995, a formal management committee between communities and the National Service of Protected Areas (SERNAP) was established to foster a more inclusive and participatory management regime. The creation of the TCO (Territorio Comunitaria de Origen, Community Territory) Marka Cololo-Copacabana-Antaquilla occurred in 1999, followed by the park's expansion in 2000. The late 2000s marked the recognition of indigenous rights, prompting a delicate balance between acknowledging indigenous communities and fostering conditions for local actors' participation in management through management committees. Subsequently, management committees delineated management plans in 2006 and 2016, incorporating technical guidelines for the conservation of natural resources, with a specific emphasis on vicuña conservation. These committees consist of representatives selected by each community, ensuring that all community stakeholders are represented. In 2022, the communities of Puyo Puyo, Nuvepampa, Antaquilla, Cololo, Katantitka, and Agua Blanca decided to be reconstituted and form the TCO Marka Cololo-Copacabana-Antaquilla.

Management differences between the studied indigenous communities

Major management differences among the eight indigenous communities exist (Table 1). Cañahuma and Puyo Puyo have comparable numbers of land surface and inhabitants practicing livestock herding (246 and 251, respectively); yet, Cañahuma has the highest livestock density from all studied sites and Puyo Puyo one of the lowest. Furthermore, Puyo Puyo was identified to be an area with high vicuña grazing and mining pressure. Opposite to this, Cañahuma and Medallani are unaffected by mining and are considered to have preserved more of the "traditional" aspects of management compared to the other studied communities. More specifically, Cañahuma and Medallani make decisions at the collective level, while the other communities make decisions at

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TABLE 1 Management practices across all studied indigenous communities.

Community Name	Antaquilla	Nuvepampa	Puyo Puyo	Agua Blanca	Cololo	Katantika	Cañahuma	Medallani
Color Figures								
Land surface (ha)	2958	14660	13445	7355	8015	4793	10243	1368
Nr. inhabitants *	540	220	540	219	165	86	678	118
Inhabitants density (Inhabitants/ha) *	0.18	0.02	0.04	0.03	0.02	0.14	0.07	0.09
Nr. of inhabitants practicing livestock herding *	142	118	251	32	153	71	246	36
Livestock herd size **	2003	3833	1869	1183	4008	2533	9603*	2040*
Vicuña population size ***	386	1202	3938	NA	877	197	786	968
Livestock density (animals/ha)	0.98	0.55	0.25	0.27	0.66	0.86	1.52	0.96
Vicuña (animals/ha)	0.03	0.29	0.16	NA	0.11	0.07	0.32	0.16
Vicuña census zones	Zone II Site 2	Zone III Site 1-2/ Zone II Sites 1-2	Zone IV Site 1-2/Zone V Sites 1&2	NA	Zone II Sites 1-2	Zone I Sites 1-3	Zone VI Sites 1-5	Zone VI Site 6
Herd rotation & transhumance	No	Yes (reduced)	No	No	Yes (reduced)	No	Yes	Yes
Nr. mining concessions **	5	4	24	8	3	2	0	0
Historic data camelid herding (2012-2022)	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Historic data mining practices (2012-2022)	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Historic data vicuña census (2018-2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Data from the national Population & Agrarian Census 2013.
**Mean value 2012-2022.
***Mean values 2018-2022.
Colors match the colors of the communities reported in Figures 1, 3, and 4.

the family level. Next, Cañuhuma and Medallani maintain transhumance. Temporary houses are still common, especially in Cañahuma. The census conducted in 2013 suggests that far more camelids reside in Cañuhuma and Medallani compared to the rest of the study area, which results in more intensively grazed grasslands in these communities.

Spatio-temporal changes in livestock and wild camelid densities and number of mining concessions

We found that changes in livestock densities over time vary across different communities ($F_{(7,\ 72)} = 4.05$, $p < 0.001$). The indigenous communities of Antaquilla, Nuvepampa, and Puyo Puyo show a significant decline in livestock density between 2012 and 2022. In these communities, the livestock per hectare has roughly halved during the study period (Figure 3A). Conversely, no significant change in livestock densities over time was observed in the remaining five communities. We found a significant variability in the changes in vicuña population densities over the years across the different communities ($F_{(6,\ 14)} = 4.156$, $p = 0.01$). In the indigenous communities of Nuvepampa and Cololo, the number of vicuñas per hectare more than doubled (Figure 3B). In contrast, the community of Cañahuma experienced a substantial decrease in vicuña density during the same period. No significant changes in vicuña densities over time were found in the other five communities.

Finally, we found that the number of mining concessions over the years marginally varies across different communities ($F_{(5,\ 34)} = 2.0712$, $p = 0.09$). We observed a significant increase in the number of mining concessions from 2012 to 2022 in the indigenous

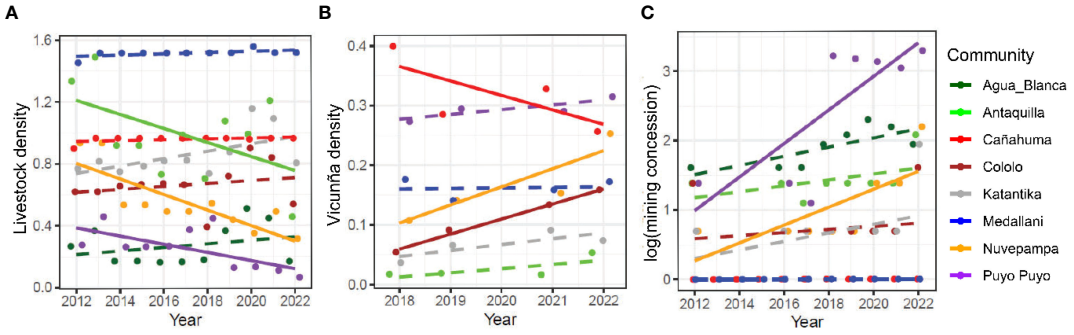

FIGURE 3
Spatio-temporal changes in livestock density (An/ha), vicuña density (An/ha) and number of mining concessions. **(A)** changes in livestock density in Puyo Puyo (slope and 95% CIs= -0.13, (-0.19, -0.08)), Nuvepampa (slope and 95% CIs= -0.07, (-0.13,-0.01)) and Antaquilla (slope and 95% CIs= -0.08, (-0.13,0.02)) **(B)** changes in vicuña densities in Cañahuma (slope and 95% CIs= -0.08, (-0.24,-0.10)), Nuvepampa (slope and 95% CIs= 0.18, (0.01,0.35)) and Cololo (slope and 95% CIs= 0.25, (0.07,0.42)), **(C)** Changes in number of mining concessions in Puyo Puyo (slope and 95% CIs= 0.24, (0.14,0.34)) and Nuvepampa (slope and 95% CIs= 0.13, (0.03, 0.23)). Dotted lines represent non-significant relationships.

communities of Puyo Puyo and Nuvepampa (Figure 3C). In the period 2012-2022, Puyo Puyo acquired or approved twenty-three new mining concessions, while Nuvepampa acquired or approved seven new mining concessions. No significant changes in the number of mining concessions over time were observed in the other six investigated communities.

Relationship between number of mining concessions and livestock densities and vicuña population densities

We found a positive relationship between vicuña densities and mining concessions across the studied communities (Figure 4A). Communities with the highest number of mining concessions have significantly higher vicuña population densities. In contrast we observed a significant decline in livestock densities with an increase in the number of mining concessions (Figure 4B). Livestock density in communities with the highest number of mining concessions (20-27 mining concessions) is around half of livestock densities compared with communities with lower number of mining concessions.

Discussion

We investigated the spatio-temporal dynamics of livestock density, vicuña density, and the number of mining concessions as indicators of shifts in management practices within the Apolobamba National Park. We found a shift away from camelid herding as the primary land use activity over the past decade in some of the studied indigenous communities. This shift was substantiated by the negative relationship between livestock density and the increasing mining activities. Furthermore, increasing vicuña density is positively related to the number of mining concessions. Our study suggests that communities experiencing decreases in domestic camelids were also those with significant increases in mining concessions, likely due to ongoing

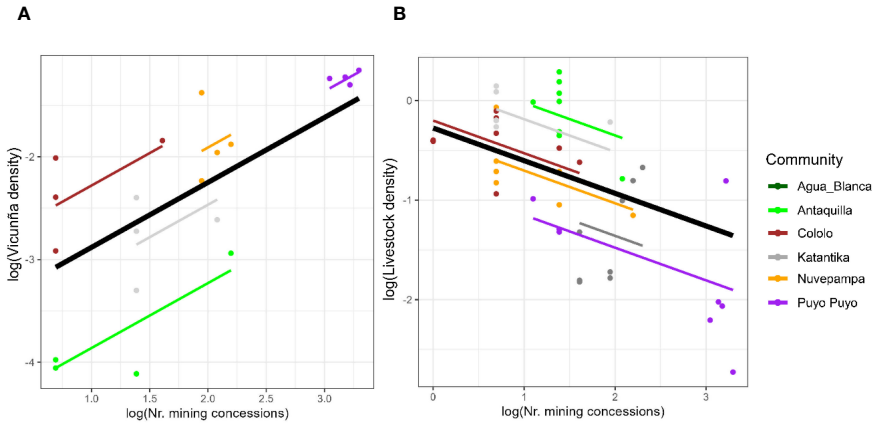

FIGURE 4
Relationship of the number of mining concessions with vicuña and livestock densities. **(A)** vicuña density (An/ha) and number of mining concessions (slope and 95% CIs= 0.63, (0.24-1.02)) **(B)** Livestock density (An/ha) and number of mining concessions (slope and 95% CIs= -0.33, (-0.53–0.12)).

mining on previous farming lands. Many households that previously relied on herding have possibly abandoned these practices to work in the mines. The rise in vicuña populations and their management offers a potential sustainable livelihood for the indigenous communities studied. However if not managed well, further expansions of mining concessions could lead to loss of native grasslands on a landscape scale. This is due to the conversion of livestock grazing areas into toxic environments caused by pollutants such as mercury. This situation could create conflicts over land use between communities, miners, and pastoralists.

Contrary to expectations, not all study sites experiencing increased mining activities showed declines in livestock densities. While livestock density notably decreased in three indigenous communities (Antaquilla, Puyo Puyo, and Nuvepampa), the continuity of camelid herding practices in most studied communities may be attributed to Andean pastoralists' capability to cope with environmental and economic changes through livelihood diversification (Mayer, 1989; López-i-Gelats et al., 2015). This suggests that indigenous communities in the central Andes prefer to not heavily rely on a single resource. For example, stakeholders in the National Park are prioritizing vicuña management, i.e., vicuña's wool extraction and commercialization of its fiber to international markets. It is currently preferred over livestock herding and mining expansion (Wildlife Conservation Society, 2023). This could contribute to the quality of life of communities, since vicuñas have one of the most valuable natural fibers in the world (Arzamendia and Vilá, 2015). However, our findings indicate that increases in vicuña populations were evident in only two of the studied indigenous communities and a significant decrease in another community without mining activity (Cañahuma). Thus, despite conservation efforts, vicuña population densities may not be significantly increasing in these regions. A potential explanation is the reported livestock-wildlife interactions in the Andes (Arzamendia and Vilá, 2015). Large livestock often outcompetes native herbivores, contributing to declines in wildlife populations (Laliberte and Ripple, 2004; Gordon et al., 2021). This is caused by a high dietary niche overlap, which augments a degraded state of the vegetation due to prolonged high grazing intensity (Milazzo et al., 2023). Additionally, shared bathing and drinking points increases the chance of disease transmission and could constrain populations of wild herbivores (McLaren et al., 2018). However, vicuñas are also known for persisting in highly segregated habitats suboptimal for livestock (Arzamendia and Vilá, 2015), which may explain their increasing populations in communities with significant decreases in livestock density, as seen in Nuvepampa.

We found that increases in mining activities were related to decreases in livestock densities across indigenous communities with active mining practices. Communities with the highest number of reported mining concessions had the lowest livestock density, suggesting that traditional pastoralism might eventually be replaced as the main productive activity in the studied area. This scenario is likely, given that cooperative-based (small-scale) mining, which is prevalent in Apolobamba, has increased more than fivefold in Bolivia since 2006 (Achtenberg, 2014). Peru and Ecuador have followed similar political-economic trajectories, with a notable rise in smaller-scale mines compared to larger, foreign-run operations (Law, 2012; Brain, 2017). Similar to our findings, in the northern Argentina Puna, a decrease in livestock herding has been associated with an increase in native wild herbivore populations (Navarro et al., 2023). This trend supports current policies to protect native wild herbivores, which could provide income to communities through wool extraction and commercialization. Thus, in Apolobamba National Park, increasing mining could lead to grasslands being grazed primarily by vicuñas, benefiting the grasslands and peatlands by reducing heavy livestock grazing pressure and promoting broader distribution of wild camelids (Navarro et al., 2023). However, the discontinuation of livestock herding could negatively impact biodiversity, as higher grazer diversity is typically linked to higher overall biodiversity.

Significant increases in mining concessions were observed in two indigenous communities, Puyo Puyo and Nuvepampa. This trend may be a response to the relatively low revenues from livestock farming compared to mining, highlighting the economic necessity of Andean farmers to diversify their income sources (Haggblade et al., 2010). Mining provides more jobs to local communities and facilitates the expansion of human settlements into previously untouched areas through the construction of new roads. These expansions positively contribute to the development of productive activities such as tourism, as observed in the Puna region of Argentina (Izquierdo et al., 2018; Navarro et al., 2023). However, mining expansion also poses significant long-term environmental risks. Mining disturbs water availability and contaminates it with mercury, creating inequalities in water distribution and access (Bebbington and Williams, 2008; Acosta et al., 2011; Bebbington et al., 2014; Velásquez-López et al., 2011). Studies in South America and Africa indicate that mercury pollution is rampant in small-scale mining communities (Wagner, 2021; Cordy et al., 2011). In Peru, mercury pollution has affected 48,000 people across 85,301 square kilometers (Fraser, 2016). Contamination of water bodies leads to biodiversity loss, removal of vegetation, soil depletion, and loss of farmland (Mensah and Tuokuu, 2023). Additionally, mining and farming activities often overlap geographically, demanding significant overlapping labor and land (Cuba et al., 2014). Many small-scale miners in the Global South operate informally without proper licenses (Veiga and Marshall, 2019). These illegal activities can cause long-term environmental degradation, as open pits are often not rehabilitated (Moyo Shoko and Mwitwa, 2015). For example, in Ghana, illegal mining, prior to its ban in 2017, degraded 4.4% of the total area of a natural reserve within five years (Boadi et al., 2016). To date, information on the impacts of cooperative mining on local livelihoods in our study area is scarce. Therefore, a comprehensive understanding of how mining affects local community members' livelihoods and well-being in the central Andes is critical for conserving native ecosystems and wildlife within Apolobamba National Park.

Our previous study on the influence of grazing intensity on grassland diversity in the study area indicates that sites with higher

livestock densities exhibit biotic homogenization, with cushion and short-type grasses dominating the functional groups (Sandoval-Calderon et al., 2023). Our current study further reveals that sites maintaining their livestock densities are located in indigenous communities without mining activities, where vicuña population densities are significantly decreasing. Consequently, these communities might struggle to sustain the current numbers of livestock and vicuñas in their grasslands. This situation may be attributed to a decline in rotational herding and transhumance, which is now limited to areas closer to the community due to a lack of quality forage. In contrast, grasslands in communities with an increasing number of mining concessions seem to support higher populations of vicuñas. However, rewilding may not benefit the diversity of plant and macroinvertebrate communities, as found in a study in Argentina (Navarro et al., 2023). In addition, as discussed, livelihood diversification through mining can have significant environmental consequences. Therefore, it is critical to assess alternative livelihood sources besides mining, such as vicuña wool production and management or eco-tourism, which could contribute to the sustainable management of grasslands and improve the quality of life for indigenous communities in Apolobamba National Park.

Changes in land use, particularly regarding mining activities, pose a sensitive issue for indigenous communities, marked by several challenges and nuances reported through participatory workshops. Significant discrepancies often arise between the number of concessions documented on paper and the tangible activities witnessed on the ground. The lack of distinction between active mines and those with only paper approval further complicates efforts to assess the true impact of mining operations. Additionally, the availability and consistency of time series data vary across different variables, making it difficult to establish uniform comparisons. Furthermore, some indigenous communities lack registries for livestock densities, complicating data collection. To understand fully the intricacies and gaps surrounding the interplay between sustainable herding practices in Andean grasslands, biodiversity, and indigenous livelihoods, collaborative studies involving governmental, non-governmental, and academic institutions are necessary.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found here: GitHub, https://github.com/AnapSandoval/Tropical-Puna-of-South-America.git.

Ethics statement

Ethical approval was not required for the studies involving humans because our study was authorized by the local authorities (Benjamín Callancho, Casilla Jilir Apu Mallku Pukina Nation) and the head of protection of ANMI Apolobamba (René Romer Llaves Quisbert). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because the participants part of a training program provided by the Wildlife Conservation Society-Bolivia. This organization has established collaboration agreements that allow for the conduct of workshops and the use of information from monitoring reports.

Author contributions

AS-C: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MV: Conceptualization, Formal analysis, Supervision, Writing – review & editing. YH: Formal analysis, Writing – review & editing. HA: Investigation, Methodology, Writing – review & editing. PV: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing.

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Conflict of interest

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

Publisher's note

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