

Pampa Galeras Vicuña Reserve a New Equilibrium State? Range Condition and Ecological Carrying Capacity

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Abstract:

The rangelands of the Pampa Galeras National Reserve (Peru) span 22,231 hectares (ha), of which 7,932 ha constitute the rigid zone—an area exclusively for vicuña (*Vicugna vicugna mensalis*) grazing—while the remaining 14,299 ha serve as a buffer zone for mixed vicuña–cattle grazing. Since the 1960s, this landscape has played a pivotal role in the recovery of the vicuña population from near extinction, offering a valuable opportunity for research on its ecology and management. Previous inventories indicated that the rangelands remained in poor conditions for vicuña grazing, despite relatively stable population densities. This study evaluated the ecological status and estimated the vicuña units (UV) that the rigid zone could support using an ecological site framework. Fifteen ecological sites were identified using geographic information systems and remote sensing, and each was assessed for floristic composition, rangeland condition, and trends. Results indicated that 86% of the sites were in poor conditions, and 35% exhibited a negative trend—evidenced by the presence of pedestalled plants, invasive species, and low litter—suggesting that many sites may have crossed abiotic thresholds and shifted into alternative stable states. The current ecological carrying capacity (C_k) of the rigid zone was estimated at 3,763 UV (0.47 UV/ha/year), which is below the potential carrying capacity (C_p) of 4,982 UV (0.60 UV/ha/year). Notably, when C_k was exceeded, vicuña numbers plummeted from 4,987 to 2,218 UV, indicating low resilience in the rangeland–vicuña system. Multiple limiting factors were identified, including interspecific competition, poor soil potential, harsh weather, and the lack of an adaptive rangeland–wildlife management strategy. Establishing an adaptive monitoring and management program based on key and reference areas is strongly recommended.

Keywords: Vicuña; Rangeland; Carrying Capacity; Condition; Resilience

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1. Introduction

The Pampa Galeras Bárbara D'Achille National Reserve (RNPG, for its acronym in Spanish) was established in 1966 as a part of a participatory strategy between the Peruvian government and local rural communities. Its objective was to serve as a knowledge hub for the conservation and sustainable management of natural ecosystems (Brack, 1980; Torres, 1983). The reserve encompasses a rigid zone of 7,932 ha and a buffer zone of 14,299 hectares, all under community ownership (SERNANP, 2023). Within this space, vicuñas (*Vicugna vicugna mensalis*) are managed under two systems: open man-

agement within the reserve boundaries and sustainable management modules (MUS) implemented within the communities (Lichtenstein et al., 2002). Both systems operate under the supervision and control of the National Service of Natural Protected Areas (SERNANP). The creation of natural protected areas for wild camelid conservation, alongside legal frameworks permitting vicuña fiber harvesting by local communities, has contributed to the reduced poaching and successful population recovery. Since the reserve's creation, the national vicuña population has increased from 5,000 to approximately 218,000 animals (MINAM, 2022).

Pampa Galeras, like other natural protected areas

(ANPs) dedicated to wild camelid conservation (e.g., Calipuy, Aguada Blanca, and Junín), has a Master Plan (MINAM, 2022). However, these plans generally lack components for rangeland inventories, site-specific management plans, and adaptive monitoring systems. Previous assessments of the rangeland's ecological status, based on range condition and forage productivity, have indicated that Pampa Galeras has remained in poor condition for decades, with an estimated carrying capacity of 0.2–0.8 UV/ha (Florez & Malpartida, 1980; Hofmann et al., 1983; Sotelo, 1980; Tuppia et al., 1997). This persistent degradation has led researchers to hypothesize that a combination of environmental constraints, low potential of rangeland sites, lack of soil conservation practices, and the absence of adaptive management and monitoring systems are principal drivers of environmental deterioration in the reserve (Zárate & Flores, 2023).

This study aimed to evaluate the ecological status of the rangelands in the Pampa Galeras Bárbara D'Achille National Reserve and to reconcile the economic carrying capacity — derived from historical grazing trials (Cordova et al., 1978) — with ecological carrying capacity estimates obtained using the logistic growth model (Begon et al., 2006; Bonacic, 2000; Mandujano, 2011; Shaw et al., 2012). An ecological site approach (Bestelmeyer et al., 2013) was employed to assess the rangeland conditions and trend indicators. Specifically, this research addressed the following questions:

- 1) How much does vegetation structure vary under the deteriorated rangeland conditions?
- 2) What is the conservation status of the reserve's rigid zone, and what are the drivers of its apparent deterioration?
- 3) How does the vicuña population fluctuate in relation to both ecological and economic carrying capacities?

2. Materials and Methods

2.1 Study Area

This study was conducted at the Pampa Galeras National Reserve (14°40'S, 74°24'W) located in the Lucanas province, Ayacucho region, Perú. The reserve spans 22,231 ha of natural pasture. Of this, 7,932 ha constitute a rigid zone designated exclusively for vicuña grazing under the supervision of the National Service of Natural Protected Areas (SERNANP). The remaining 14,299 ha form a buffer zone for the mixed vicuña–cattle grazing, managed by Puna herders and overseen by the National Forest and Wildlife Service (SERFOR). Two life zones are represented within the rigid zone: subtropical mountainous steppe and subtropical subalpine humid moorland. The vegetation is dominated by grasses interspersed with shrubs. The climate is dry and cold, with minimum temperatures reaching -8°C between April and September and maximum temperatures reaching 16°C during February and March. Annual precip-

itation averages 450 mm, falling mainly between January and March. Relative humidity ranges from 50% in the dry season to 90% in the wet season (MINAM, 2022). Soils are primarily shallow, stony, and superficial, formed by the slopes composed of alluvial deposits. The reserve is surrounded by the rural communities of Lucanas, Hualhua, San Cristóbal, Saisa, Santiago de Vado, and Ccochapata in the Ayacucho Region.

2.2 Determination of Site Groups

Rangeland sites were delineated through the superposition of data layers including geology, moisture regime, physiography, vegetation cover, slope, and ecological floor, following the conceptual model presented in (Figure 1). Once the sites were defined, a rapid assessment was conducted (Flores, 1991) to collect information on the vegetation type and characteristics, landscape context, topographic position, slope, and soil surface characteristics. This process enabled the identification of key areas within each site where indicators of ecological status were subsequently evaluated. The conceptual model served as a framework to guide the process estimation of the floristic composition, range conditions, trends, and carrying capacity for the reserve's rigid zone.

2.3 Ecological Status and Trends

The ecological status was assessed using rangeland conditions and trend indices (Figure 1). The condition was determined based on the relative abundance of desirable, less desirable, and undesirable plant species, along with vegetation cover and plant vigor (Zárate & Flores, 2023). Rangeland trend was estimated using indicators such as the presence of young seedlings, litter existence, signs of laminar erosion, pedestalled plants, and the vigor and diversity of perennial plants, as well as the abundance of weeds (Cox, 2005).

2.4 Population Dynamics and Carrying Capacity

The population dynamics were analyzed using data from the annual vicuña censuses conducted by SERNANP between 1994 and 2018. These data were used to estimate the population growth rate and the ecological carrying capacity (C_k) using a logistic growth model (Mandujano, 2011), which determines the number of vicuñas that the habitat supports under a condition of relative equilibrium (Pastor, 2008).

$$\frac{dN}{dT} = rN_t \frac{K - N_t}{K},$$

Where:

K : Carrying Capacity

r : Growth rate $\text{Ln} \left(\frac{N_t}{N_0} \right)$

N_0 : Initial population for the year 1994

N_t : Final population of the year 2018

dN : $N_t - N_0$

dT : $T_{2018} - T_{1994}$

The potential carrying capacity (C_p), expressed in Vicuña Units (UV = one adult mother, 38.5 kg; (Hof-

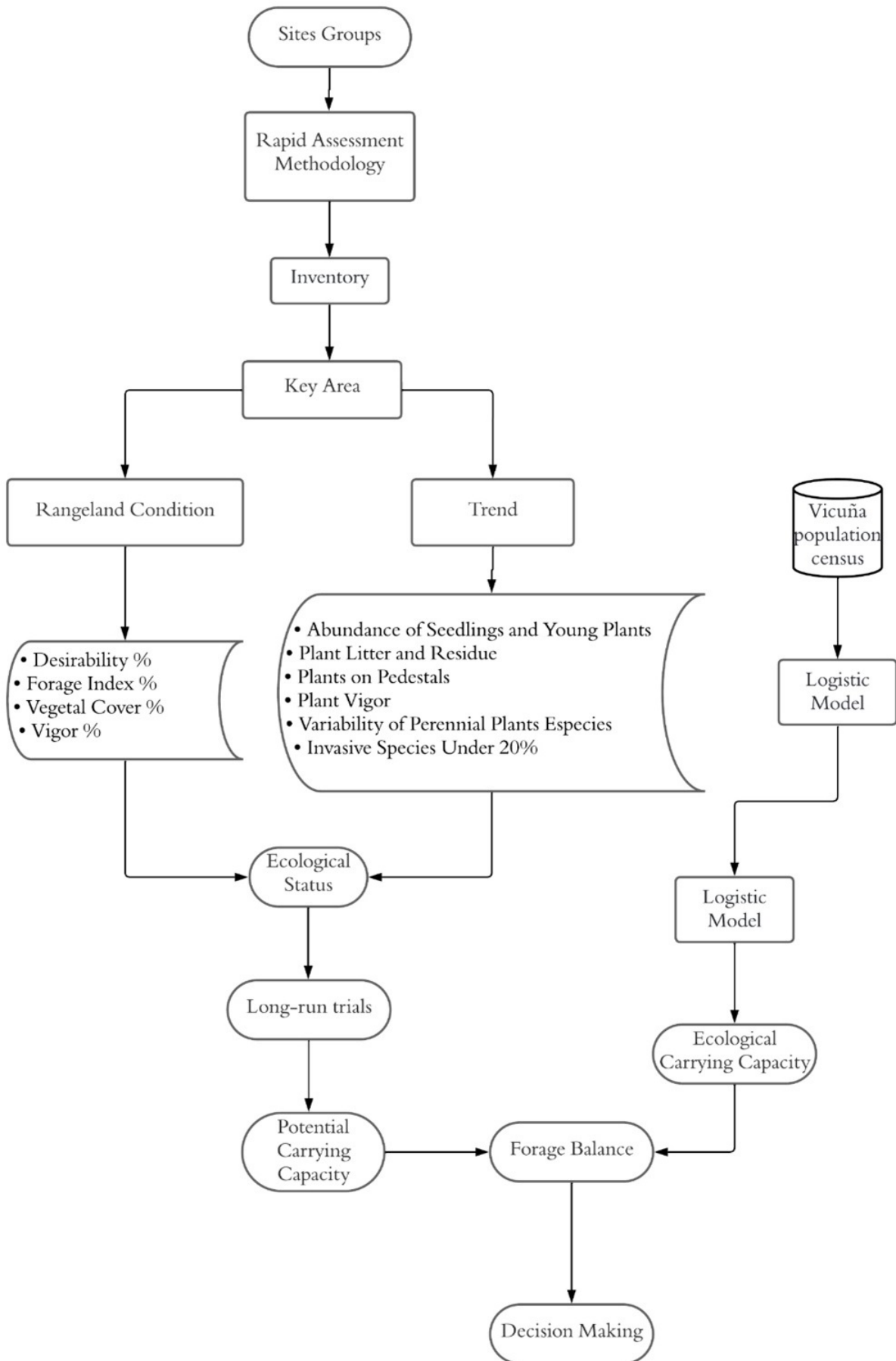


Figure 1. Conceptual model illustrating how the potential and ecological carrying capacities are estimated using a range condition-based approach.

mann et al., 1983)), was estimated based on data from long-term grazing and forage condition trials (Florez & Malpartida, 1980). For each site, C_p was determined at the intersection point between the animal productivity curve and the productivity per hectare response curve (Lubbering et al., 1991; Stuth & Sheffield, 1986), using site area as a weighting coefficient in the overall calculation. The forage balance was defined as the difference between the C_p and C_k , as illustrated in (Figure 1 & Figure 3).

3. Results

Grasses represented the dominant vegetation type, comprising 82.8% of the total cover, followed by shrubs (13.8%) and minor traces of native tree species (3.4%). The censuses allowed the registration of a total of 29 different species, mainly from the families Poaceae (69%), Asteraceae (10.3%), Rosaceae (6.9%), Caryophyllaceae (6.9%), Cyperaceae (3.4%), and Fabaceae (3.4%). From a functional group perspective, the census revealed 69% grasses, 13.8% shrubs, 10.3% forbs, 3.4% graminoids, and 3.4% trees (Table 1).

When changes in floristic composition associated with rangeland deterioration were analyzed, a marked increase was observed in the percentage of the Rosaceae and Asteraceae families. This was followed by a decrease in grass abundance and an increase in the percentage of herbs (e.g., *Aciachne acicularis*, *Aciachne pulvinata*, and *Pycnophyllum tetrastichum*) and shrubs (e.g., *Senecio spinosus*, *Tetraglochin cristata*, and *Baccharis tola*). These changes in botanical composition are recognized as indicators of rangeland degradation (Table 2), due to their low forage value (Tapia & Aguirre, 1982) and their limited occurrence in rangelands in good condition (Florez & Malpartida, 1980).

A more detailed analysis of the botanical composition, categorized by desirability for vicuñas, revealed that of the 29 species recorded, 31% were desirable, 34.5% less desirable, and 34.5% undesirable. Among them, *Festuca rigescens* (Griseb.) F. Rojas, *Calamagrostis vicunarium* (Wedd.) Pilg., and *Nassella mexicana* (Hitchc.) R.W. (SERFOR, 2022) (Table 3) were considered as key species due to their abundance and significant dietary importance for vicuñas (Capuñay, 2022).

Regarding the ecological status of the 15 identified rangeland sites, only one was in regular condition, representing 8.45% of the rigid zone. The majority—86.02%—were in poor condition, while 5.53% were in very poor condition. These classifications were based on key indicators of grazing condition for vicuñas, including the percentage of forage species, presence of desirable plants, vegetation cover, and the vigor of key species (Table 3). The rangeland trend remained stable in 45.74% of the sites, negative in 34.82%, and positive in the remaining 19.44% (Figure 2). Specifically, 60% of the sites contained young plants, 40% exhibited minimal litter cover, and 80% showed the presence of pedastalled plants, suggesting that most of

the sites may have surpassed their abiotic thresholds (Bestelmeyer et al., 2013). These findings indicate that the Pampa Galeras ecosystem may have entered a new equilibrium state. Accordingly, improving the reserve's ecological status will require a novel management approach based on a mixed model of equilibrium and non-equilibrium dynamics. This approach would help prevent adverse state transitions before ecological thresholds are crossed while enhancing the ecosystem's resilience (Sasaki, 2010).

The reserve's ecological carrying capacity was estimated at 0.47 UV/ha/year (Figure 3), which falls within the range reported by previous studies—0.4–0.8 UV/ha/year (Florez & Malpartida, 1980; Sotelo, 1980; Tuppia et al., 1997). These values also closely align with those reported by (Hofmann et al., 1983), 0.20–0.33 UV/ha/year, which are considered typical of mountain rangelands under arid and semi-arid climatic conditions (Sullivan & Rohde, 2002).

4. Discussion

The vegetation was dominated by species of the genera *Festuca*, *Jaraba*, and *Calamagrostis*, all members of the Poaceae family, with a smaller representation from the Asteraceae, Rosaceae, Caryophyllaceae, and Fabaceae families. This composition confirms that the area primarily consists of rangelands representative of the central arid Puna (Tovar, 1973; Tuppia et al., 1997; Zárate & Flores, 2023). The study area is characterized by high altitude, low temperatures, strongly negative water potentials, and nutrient-deficient soils—factors to which these species are clearly adapted (Bradford et al., 1987; Gutiérrez & Hernández, 1996). For instance, *Festuca rigescens* and *Calamagrostis vicunarium* are drought-resistant plants, possessing a competitive advantage over less-adapted species (Tito et al., 2024; Trillo et al., 2020). Given the minimal representation of the Asteraceae, Rosaceae, and Fabaceae families, it is suggested that these plants play a less relevant role in nutrient cycling and energy flow than grasses under the present study conditions (Tovar, 1973). This highlights the need for further research into their ecophysiological roles and potential contributions to the health and resilience of the Puna ecosystem.

In this study, key species from a grazing perspective, such as *Calamagrostis vicunarium* (Wedd.) Pilg. and *Festuca rigescens* (Griseb.) F. Rojas (Table 1), appeared to be declining, coinciding with an increased frequency of low-forage-value species such as *Aciachne pulvinata* and *Pycnophyllum molle*. The presence of these species indicates a loss of ecological status (Tapia & Aguirre, 1982). The reduced abundance of desirable forage species for vicuñas, notably *Calamagrostis vicunarium* and *Festuca rigescens* (Capuñay, 2022), is potentially associated with declining vegetative cover and increasing soil erosion, as evidenced by the presence of pedestal plants and displaced litter (Zárate & Flores, 2023). Litter displacement is an important factor in maintaining nutrient cycling and hydrological func-

Table 1. Names and degree of desirability of plant species for vicuñas.

Grasses	Desirability #
<i>Aciachne acicularis</i> Laegaard	U
<i>Aciachne pulvinata</i> Benth.	U
<i>Calamagrostis amoena</i> Pilg.	LD
<i>Calamagrostis heterophylla</i> (Wedd.) Pilg.	D
<i>Calamagrostis</i> sp.	LD
<i>Calamagrostis vicunarum</i> (Wedd.) Pilg.	D
<i>Festuca rigescens</i> (Griseb.) F. Rojas	D
<i>Festuca dolichophylla</i> J. Presl	LD
<i>Festuca humilior</i> Nees & Meyen	LD
<i>Festuca</i> sp.	LD
<i>Jarava leptostachya</i> (Griseb.) F. Rojas	LD
<i>Jarava pungens</i> (Nees & Meyen) Matthei	LD
<i>Jarava ichu</i>	LD
<i>Muhlenbergia fastigiata</i>	D
<i>Muhlenbergia ligularis</i> (Hack.) Hitchc.	D
<i>Muhlenbergia peruviana</i>	D
<i>Nassella brachyphylla</i> (Hitchc.) Barkworth	D
<i>Nassella mexicana</i> (Hitchc.) R.W. Pohl	LD
<i>Poa chamaeclinos</i> Pilg.	D
<i>Poa gymnantha</i> Pilg.	LD
Graminoids	
<i>Trichophorum rigidum</i> (Boeckeler) Goetgh., Muasya & D.A. Simpson	U
Forbs	
<i>Pycnophyllum molle</i> J. Rémy	U
<i>Pycnophyllum tetrastichum</i> J. Rémy	U
<i>Trifolium amabile</i> Kunth vel aff.	D
Shrubs	
<i>Baccharis tola</i> Phil. Subsp. Santelicens (Phil.) Joch. Mull. Var. <i>Incarum</i> (Wedd.) Joch. Mull	U
Var. <i>Incarum</i> (Wedd.) Joch. Mull	U
<i>Parastrephia quadrangularis</i> (Meyen) Cabrera	U
<i>Senecio spinosus</i> DC. vel aff.	U
<i>Tetraglochin cristata</i> (Britton) Rothm.	U
Trees	
<i>Polylepis tometella</i> Wedd.	U

D: desirable, LD: less desirable, U: undesirable

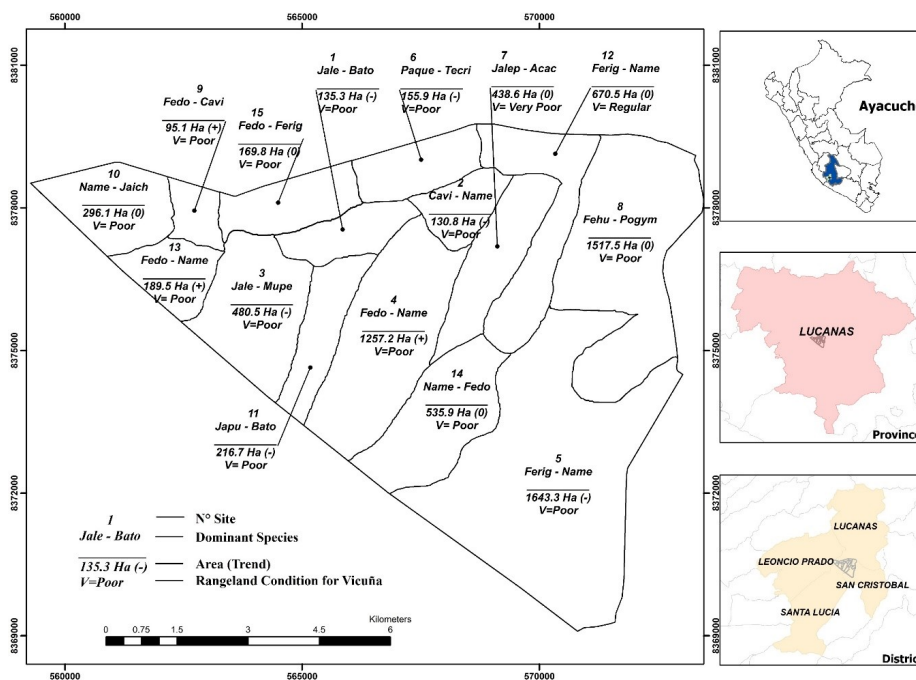


Figure 2. Range sites of Pampa Galeras.

Table 2. Basal cover percentage associated with the rangeland condition.

Basal Coverage (%)	Species Code	Rangeland Condition (%)		
		Regular	Poor	Very Poor
Grasses %				
<i>Aciachne acicularis</i>	Acac	0.0	4.2	17.7
<i>Aciachne pulvinata</i>	Acpu	0.0	2.6	4.8
<i>Calamagrostis amoena</i>	Caam	0.0	1.1	0.0
<i>Calamagrostis heterophylla</i>	Cahe	0.0	6.0	0.0
<i>Calamagrostis sp.</i>	Casp	0.0	1.8	0.0
<i>Calamagrostis vicunarum</i>	Cavi	18.2	8.1	6.5
<i>Festuca dolichophylla</i>	Fedo	4.5	6.3	6.5
<i>Festuca humilior</i>	Fehu	0.0	3.5	0.0
<i>Festuca rigescens</i>	Ferig	24.2	6.4	0.0
<i>Festuca sp.</i>	Fesp	0.0	0.4	0.0
<i>Jarava ichu</i>	Jaich	0.0	1.9	0.0
<i>Jarava leptostachya</i>	Jale	0.0	6.0	19.4
<i>Jarava pungens</i>	Japu	0.0	1.9	0.0
<i>Muhlenbergia fastigiata</i>	Mufa	0.0	0.7	0.0
<i>Muhlenbergia ligularis</i>	Muli	0.0	1.4	0.0
<i>Muhlenbergia peruviana</i>	Mupe	12.1	5.7	0.0
<i>Nassella brachyphylla</i>	Nabra	0.0	0.8	0.0
<i>Nassella mexicana</i>	Name	19.7	11.1	0.0
<i>Poa chamaeclinos</i>	Poch	3.0	0.8	0.0
<i>Poa gymnantha</i>	Pogym	0.0	1.4	0.0
Total		81.8	72.3	54.8
Graminoids, (grass-like) plants %				
<i>Trichophorum rigidum</i>	Triri	4.5	2.6	0.0
Forbs %				
<i>Pycnophyllum molle</i>	Pymo	0.0	3.1	12.9
<i>Pycnophyllum tetrastichum</i>	Pyte	10.6	5.2	16.1
<i>Trifolium amabile</i>	Triam	0.0	0.6	3.2
Total		10.6	8.8	32.3
Shrubs %				
<i>Baccharis tola</i>	Bato	0.0	6.5	1.6
<i>Parastrephia quadrangularis</i>	Paque	0.0	4.5	1.6
<i>Senecio spinosus</i>	Sespi	3.0	2.9	9.7
<i>Tetraglochin cristata</i>	Tecri	0.0	2.2	0.0
Total		3.0	16.2	12.9
Trees %				
<i>Polylepis tomentella</i>	Poto	0.0	0.1	0.0

Table 3. Dominant species, range condition and trend.

Range Condition	No. of Sites	Area Hectares	% Area	Dominant Species	Range Condition Indicators %				Trend	
					Desirable Plants	Forage Index	Basal Cover	Vigor	Category	%
Regular	1	670.5	8.45	<i>Festuca rigescens</i> <i>Nassella mexicana</i> <i>Calamagrostis vicunarum</i>	38	54	66	10	Stable	8.45
Poor	13	6823.6	86.02	<i>Festuca dolichophylla</i> <i>Nassella mexicana</i> <i>Calamagrostis heterophylla</i>	17.2	37.2	57.4	10.7	Positive Stable Negative	19.44 31.76 34.82
Very poor	1	438.6	5.53	<i>Jarava leptostachya</i> <i>Aciachne acicularis</i> <i>Pycnophyllum tetrastichum</i>	6	6	62	7.2	Stable	5.53

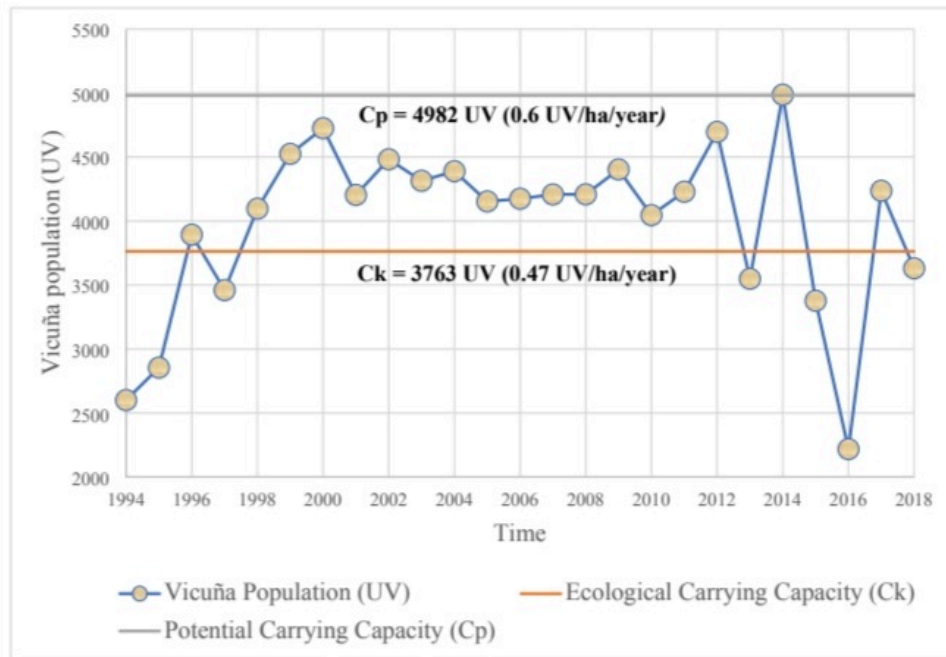


Figure 3. Range sites of Pampa Galeras.

tion (Flores et al., 2014; Lepak et al., 2024; Pyke et al., 2002) Historical rangeland inventories show that in the early 1970s, Pampa Galeras was dominated by Poaceae species such as *Festuca dolichophylla*, *Calamagrostis vicunaru*, *Stipa ichu*, and *Dissanthelium macusaniense*, with fewer species from the genera *Senecio*, *Parastrephia*, *Astragalus*, and *Nototriche* (Tovar, 1973). Currently, the dominant species also include *Jarava leptostachya*, *Nassella mexicana*, and *Festuca humilior*, which are considered less desirable for vicuñas and alpacas (Capuñay, 2022; Tapia & Aguirre, 1982).

Past inventories, from the early 1980s to date, consistently show the prevalence of poor-condition sites within the reserve. In fact, 90% of the ecological sites within the rigid zone were classified as being in poor condition and 10% in very poor condition (Florez & Malpartida, 1980), a status later corroborated by other researchers (Tuppia et al., 1997; Zárate & Flores, 2023). This condition suggests significant degradation of rangeland health in terms of biotic integrity, hydrological function, and site stability (Flores et al., 2014; Lepak et al., 2024; Pyke et al., 2002) Litter absence, limited vegetation cover, and the presence of pedestal plants in key areas within the sites indicate the disturbed rangeland conditions (Zárate & Flores, 2023). These findings highlight the need for rangeland conservation measures, such as the creation of forage-reserved areas, stricter control of domestic animal entry into the rigid zone, development of early warning systems, and potential adjustments to population structure and size (USDA, Department of Agriculture, Natural Resources Conservation Service, 2022). In addition, the application of soil conservation practices (Oscanoa & Flores, 2019), uni-

form incorporation of organic matter, and revegetation with native species (Tácuna et al., 2021) may further improve soil conditions and rangeland health.

The ecological carrying capacity is generally lower than its potential capacity due to limiting factors, including predation, mortality, disease, and competition, which regulate population dynamics (Shaw et al., 2012). In this study, the potential carrying capacity was estimated at 4,982 UV or 0.6 UV/ha/year (Figure 3), and the ecological carrying capacity at 3,763 UV or 0.45 UV/ha/year. These values fluctuated over time, occasionally exceeding the potential (notably in 2014), followed by a sharp decline and eventual stabilization after a four-year period (Figure 3). This pattern suggests a population that lacks resilience to stress arising from habitat degradation (Begon et al., 2006) —a pattern often observed in populations experiencing nutritional stress due to decreasing forage conditions and the increased presence of undesirable plants rich in structural anti-nutritional factors (Laca et al., 2001). These are characteristic of Puna tussocks, and may limit forage intake, reduce body condition, and impair the ability of vicuñas to store energy reserves necessary to withstand high-altitude environmental stress.

5. Conclusion

The reserve's rangelands have been in poor condition for several decades and the current vicuña carrying capacity remains below its potential. This underscores the need for an adaptive monitoring and management program that integrates the concepts of ecological sites, multiple equilibria, and key and reference areas. Ecological evidence—including degraded soil conditions,

the presence of pedestal plants and invasive species, and the scarcity of litter in numerous sites—supports the hypothesis that the ecosystem may have surpassed its abiotic threshold and reached a new equilibrium state. This hypothesis was further supported by shifts in the dominance relationships between key species and a marked increase in the frequency of less desirable species across several range sites. Consistent with habitat degradation, when the vicuña population exceeded the system's potential carrying capacity, the ecological carrying capacity declined sharply. This reduction suggests a loss of population resilience in response to stress from rangeland deterioration and high intraspecific competition.

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Authors contributions

All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The author states that there is no conflict of interest.

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