PERINATAL JOURNAL

Original Article

Perinatal Journal 2026; 34(2):492-498

https://doi.org/10.57239/prn.26.03420047

Demographic projection model applied to vicuña conservation in the Peruvian Andes

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Abstract

The vicuña (*Vicugna vicugna*) is an emblematic wild camelid of the Peruvian Andes, the conservation of which is crucial both for the equilibrium of High-Andean ecosystems and for the sustainable development of local communities through the sustainable use of its fiber. However, anthropogenic and environmental pressures necessitate the availability of tools capable of projecting its population dynamics. The objective of this research was to design a demographic projection model applied to vicuña conservation in the Peruvian Andes. A quantitative, projective methodology with a non-experimental design was employed, comparing theoretical and observed population data between 2012 and 2025. The results indicate that the observed population is growing at a compound annual rate of 2.8%, which is lower than the 4.8% projected by the theoretical trend; this generates a widening gap that reaches 85,448 individuals by 2025 (22.2% of the expected population). It is concluded that there exists a population gap characterized by a deceleration in growth.

Keywords: Model, Vicuña, Andes, Conservation, Demographic

Introduction

The camelid is the largest genetic and economic resource among the populations of the South American Andes. According to (Cali, 2021, p.1), among these, the vicuña produces quality fibers, with a price of 400 dollars on the international market. Every two years, an average of 250 grams of fiber per animal is obtained. However, camelids have managed to survive in extreme geographical areas because (Arraztoa & Carretro, 2021) they are adapted to areas with scarce forage and unfavorable climatic conditions, surviving at altitudes above 4000 meters above sea level. This is possible because they have physiologically adapted to use oxygen more efficiently (Jara, 2019, p.14). The vicuña (Vicugna vicugna) is the wild camelid with the greatest presence in Peru. Two subspecies of vicuña are described: Vicugna vicugna vicugna, found south of 18° South latitude, and Vicugna vicugna mensalis, found further north.

This Peruvian region presents a variable climate, (Capuñay, 2022) characterized by drier climates as it moves away from the equator; presenting two marked seasons, which, added to local factors, defines the distribution of the vegetation types where the vicuña inhabits, adapting its diet to these variations. However, climate change has introduced variations affecting the forage that feeds the species in the region, as explained by (Larios, 2025): climate change in the high Andean zone affects resources, livestock, productive and reproductive indices. Water stress due to glacier melting, severe droughts, prolonged snowfalls, and high solar radiation affect ecosystems.

This alters the grasslands, thus varying the diet of the vicuñas, causing changes in the coat, which is important for the economic sector. According to (Bravo, 2022), the vicuña has an average staple length at the mantle level of 32.8 mm in adult animals, with a range between 29.2 and 41.7 mm, and reaches staple lengths at the chest level of 18 to 20 cm. This species, according to (Quispe, 2023), belongs to the tylopod family. Peru currently harbors 76% of the world population, and the main characteristic of this species is its fiber, which is extracted without sacrificing the animal. This has allowed the region to have an economic activity through the extraction and sale of this fiber, becoming, according to (Tupayachy et al., 2022), an important economic activity in Peru for the textile industry throughout history, since the domestication of animals began.

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Other products derived from vicuñas (Freire, 2023) in recent years include manure as an alternative for fuel production. Regarding herd management, there are vicuñas in captivity, semi-captivity, and in the wild. Management by Andean communities (Lichtenstein & Cowan, 2021) is one of the few success stories in international conservation. The species was able to recover from the brink of extinction. The precious fleece of the vicuña has been both its greatest asset and its greatest downfall. Consequently, (Arzamendia & Baldo, 2024) in 1979 the "International Convention for the Conservation of the Vicuña" was signed between Peru, Bolivia, Chile, Argentina, and Ecuador. This convention agreed that the conservation of the vicuña constitutes an alternative for economic production for the benefit of local people.

One of the problems faced by the population according to (Quinta et al., 2023) is poaching, as this wildlife species has been hunted to the brink of extinction in Peru. However, thanks to repopulation programs and projects, its recovery has been achieved. But now, diseases threaten wild herds and those in semi-captivity; for example, (Hilares, 2023) in Apurímac, the agricultural sector lacks technologies for the control of watering holes and pastures, causing various types of parasitosis including nematodiasis and fasciolasis. According to (Hilares, 2023), fasciolasis is a parasitic disease caused by Fasciola hepatica, which is distributed worldwide, affecting mammals and humans. This parasitosis affects animals, reducing their meat, milk, and fiber production.

In addition to this disease, sarcoptic mange has been detected in vicuña populations (Arzamendia, 2022). It is a disease caused by the mite Sarcoptes scabiei, which affects vicuñas and other mammals, potentially causing the death of the animal and triggering epidemic outbreaks. In studies conducted by (Angulo et al., 2021) on 2,826 vicuñas, the occurrence of mange in wild conditions was 6.1% and in captivity 0.2%; among the cases, 85.1% corresponded to adult animals and 14.8% to juveniles, while 40.7% were males and 59.2% were females. Given the various factors impacting vicuña populations, this study aims to design a demographic projection model applied to the conservation of the vicuña in the Peruvian Andes. To this end, data on vicuña populations were taken from censuses published in the research advances on the vicuña (Vicugna vicugna) in Peru 2025.

Given that the vicuña constitutes a resource of great social, cultural, and economic importance in the Andean countries, particularly in Peru, where its sustainable management contributes both to the conservation of the species and to the development of high Andean communities according to the (Ministry of the Environment of Peru, 2025). The historical evolution of the vicuña population was specifically selected to observe the growth resulting from the conservation laws established in 1979. Within this scenario, the question arises: What will be the characteristics of the demographic projection model applied to the conservation of the vicuña in the Peruvian Andes? (Resques, n.d.) defines the demographic model as demographic projections understood as estimates about the future of a population, derived from the behavior of said population.

Methods

This study has a quantitative approach with a type of projective research defined by (Hurtado, 2000) as research that consists of developing a proposal, plan, program, or model as a solution to a problem or need, whether for a social group, institution, or geographic region, in a particular area of knowledge. Regarding the research design, it is documentary and non-experimental. The following phases were established for the algorithm design:

Library import phase to be executed in python

The model algorithm was designed with the Python programming language and the following libraries were used: Num Py (Harris, 2020) is the fundamental package for scientific computing in Python. It is a library that provides a multidimensional array object, various derived objects (such as masked arrays and matrices), and an assortment of routines for fast operations on arrays, including mathematical. Pandas (2026) is a library whose two-dimensional data structure can store data of different types (including characters, integers, floating point values, categorical data, and more) in columns. It is similar to a spreadsheet. And Matplotlib (Hunter, 2007) is a Python library specialized in creating two-dimensional graphs.

Data entry phase

The data were extracted from the population census published by the National Forestry and Wildlife Service SERFOR (2025). National Vicuña Census 2025, which recorded 300 thousand specimens, and from the research advances on the vicuña (Vicugna vicugna) in Peru 2025 with totals of 66,559 (1994), 103,161 (1997), 118,678 (2000), and 208,899 for (2012).

These represent observations P (t_i)
P= Vicuña population
(t_i)= Census years
Assumption phase of the exponential growth model
P (t) = $P_0(1+r)^t$
where:
P(t) = the population at time t
P_0= initial population
r = annual growth rate
t = number of elapsed years
This model is widely used in population ecology when the population is expanding.
Phase: Calculation of the historical growth rate
trend rate = (208899 / 118678) **(1/12) - 1
r = $(\frac{p_f}{P_i})^{\frac{1}{t}}$ - 1
P_f = final population
P_i = initial population
t = number of years
P_i = 118.678
P_f = 208.899
t = 12
r_{trend} = $(\frac{208.899}{118.678})^{\frac{1}{12}}$
R () =0.048
That is, 4.8% annually
Calculation phase for the most recent real rate.
real_rate = (300000 / 208899) **(1/13) – 1
The same formula
r = $(\frac{p_f}{P_i})^{\frac{1}{t}}$ - 1
P_i = 208.899
P_f = 300000
t = 13
R (real) =0.028
that is: 2.8% annually

Population projection phase

The model then projects the population using the exponential equation:

trend projection = initial population * (1 + trend rate) **(years - start year)

Mathematically

$P_{trend}(t)$ = P_0 $(1+\ P_{trend})^{\ t}$
Growth Gap Calculation Phase
Growth Gap = trend projection - real projection
Mathematically
B(t) = $P_{trend}(t)$ - $P_{real}(t)$

Results

Algorithm designed in Python to execute the demographic projection model

```
import pandas as pd
import num py as np
import mat plotlib.py plot as plt
# AESTHETIC CONFIGURATION
plt. rc Params. update ({
   "font. family": "serif",
   "font. size": 12,
   "axes. Title size": 16,
   "axes. Label size": 13,
   "legend. Font size": 11
})
# 1. Historical Census Data
data_hist = {
   'Year': [1994, 1997, 2000, 2012],
   'Population': [66559, 103161, 118678, 208899]
}
df_hist = pd. Data Frame(data_hist)
# 2. Projection Parameters
initial_ population = 208899
start year = 2012
end year = 2025
# historical trend rate
trend rate = (208899 / 118678) **(1/12) - 1
# real growth rate
real rate = (300000 / 208899) **(1/13) - 1
# 3. Population Evolution
years = np. Arrange (start year, end_year + 1)
trend projection = initial_population * (1 + trend_rate) **(years - start_year)
```

```
real_projection = initial_population * (1 + real_rate)
**(years - start year)
# 4. Create Data Frame
df_gap = pd. Data Frame({
   'Year': years,
   'Trend': trend_projection. As type (int),
   'Observed': real projection. A stype(int),
   'Growth_Gap': (trend_projection - real_projection).
A stype(int)
})
# 5. Main Plot
plt. figure (fig size= (12,7))
# trend line
plt. plot (
   df_gap['Year'],
   df_gap['Trend'],
   line style='--',
   color='red',
   linewidth=2.5,
   label='Theoretical Trend (Growth Inertia)'
)
# observed line
plt. plot (
   df_gap['Year'],
   df_gap['Observed'],
   color='blue',
   linewidth=3,
   label='Observed Population Growth'
)
# shaded gap
plt. fill_between(
   df_gap['Year'],
   df_gap['Trend'],
   df_gap['Observed'],
   color='orange',
   alpha=0.30,
   label='Growth Gap'
)
# visual details
plt. title ('Deceleration in the Vicuña Population
(2012–2025)')
plt. x label('Year')
plt. y label ('Total Population')
plt. legend ()
plt. grid (True, alpha=0.25)
# Export Image
plt. save fig (
   "vicuna_population_growth_gap.jpg",
   dpi=300,
   bbox_inches="tight",
   face color="white"
)
plt. show ()
print(df_gap.to_string(index=False))
```

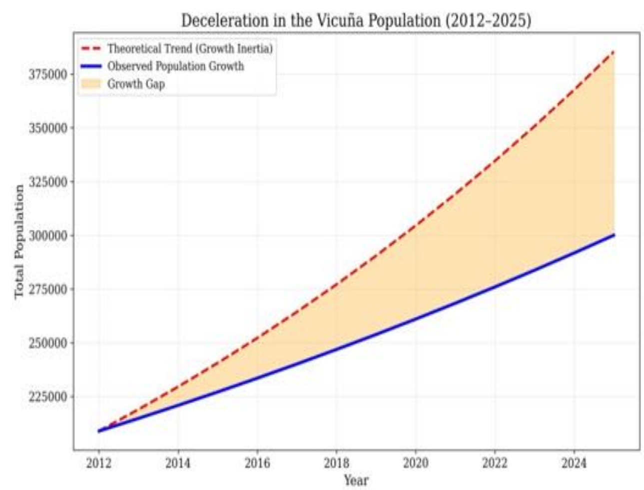

Figure 1. Demographic projection model of the vicuña in the Peruvian Andes
Source: Graph generated by the python algorithm

Theoretical trend line (inertial growth): Generally represented in one color (red). It illustrates how the population would grow if it followed an ideal growth rate, free from external constraints (based solely on optimal birth and survival rates).

Observed population line (actual): Represented in a different color (blue). It displays data whether estimated or actually tallied in the field reflecting the real-world conditions of the habitat and the threats present.

Gap area: This refers to the space formed between the two lines; this gap is quantified in the Growth Gap column. As the year's progress, this space widens.

Ecological interpretation of the model

The model shows $r_{trend} > r_{real}$
$P_{trend}(t) > P_{real}(t)$

This means that the population is growing more slowly than before. The rate decreases from 4.8% to 2.4%.

Table 1. Results obtained from demographic trends

Year	Trend	Observed	Growth_Gap
2012	208.899	208,899	0
2013	218.977	214,796	4,181
2014	229.542	220,86	8,682
2015	240.617	227,096	13,521
2016	252.227	233,507	18,719
2017	264.396	240,099	24,296
2018	277.152	246,878	30,274
2019	290.524	253,848	36,676
2020	304.541	261,015	43,526
2021	319.235	268,384	50,851
2022	334.637	275,961	58,676
2023	350.783	283.752	67,031
2024	367.707	291.762	75,944
2025	385.448	300.000	85,448

Note: Table prepared using data resulting from the execution of the model

Table 1 contains annual estimates of the vicuña population from 2012 to 2025, comparing a theoretical trend (expected inertial growth) with the observed values (real or estimated). From these data, the growth gap (difference between the theoretical and observed value) is calculated.

Year, Theoretical Trend, Observed Population, Gap (Theoretical-Observed)

The theoretical trend grows steadily, with a compound annual growth rate of 4.8% (from 208,899 in 2012 to 385,448 in 2025).

The observed population also increases, but at a lower rate: a compound rate of 2.8% (from 208,899 to 300,000 in the same period).

The gap progressively increases, going from 0 in 2012 to 85,448 individuals in 2025, which represents 22.2% of the theoretical population in that year.

The absolute difference grows each year, with an average increase in the gap of approximately 6,570 individuals per year.

Discussion

The divergence between the theoretical trend and the observed values indicates that the real vicuña population is growing below what would be expected under a scenario of inertial growth without limitations. This phenomenon may be due to multiple factors, among which the following should be highlighted:

Anthropogenic pressures: Poaching, competition with domestic livestock (sheep, llamas, alpacas) for grasslands, and habitat fragmentation due to human activities may be limiting population growth.

Effects of climate change: Variations in precipitation, glacier retreat, and changes in temperature affect the productivity of high Andean wetlands, a critical habitat for the vicuña.

Diseases and predation: Disease outbreaks transmitted by domestic livestock or the increase in natural predators (pumas, foxes) could be impacting mortality.

The growing gap (which goes from being practically non-existent in 2012 to more than 22% in 2025) suggests that the limiting factors not only persist but intensify over time. This could compromise long-term conservation objectives, especially if the observed trend continues to deviate from the expected one.

Implications for conservation

It is a priority to identify the specific causes of this deceleration in real growth through detailed population monitoring and habitat dynamics studies.

Projection models need to be reviewed and adjusted by incorporating variables such as carrying capacity, illegal extraction rates, and climatic effects, so that projections are more realistic and useful for decision-making.

Management strategies (such as the sustainable vicuña fiber harvesting scheme through chaccu) should be evaluated in light of these results, as they could be generating additional stress or not compensating for losses.

Strengthening surveillance and control of poaching, as well as promoting grassland management practices that benefit both the vicuña and local livestock, are key measures to reduce the gap.

The model has limitations as it does not incorporate ecological constraints; however, the population deceleration between the reported censuses can be observed.

Conclusion

The data show a worrying deviation between the theoretical and real growth of the vicuña population in the Peruvian Andes. This diagnosis should serve as a basis for redoubling efforts in applied research and adaptive management to ensure the sustainability of this emblematic species.

If the lines were together: It would mean that conservation strategies (such as chaccu, surveillance) are working perfectly and the ecosystem supports maximum growth. But in the model, the lines move apart: This visually indicates that pressure factors are winning. Nature (observed) cannot keep up with the pace that pure mathematics (theoretical) predicts.

Existing growth, but insufficient: The observed line is not flat (which would be a catastrophe); it rises. That is good: the vicuña is not in imminent extinction according to these data.

Ecological or anthropogenic brake: However, the "widening gap" between the lines suggests that something is holding back the potential of the Andes.

Unsustainability of the current trend: If this trend continues (the lines diverging), in a few more years, even if the observed population is high, it will be far below what the ecosystem could support if threats were eliminated.

Acknowledgment

We express our gratitude for the financial and logistical support provided by the project “Technological Innovation of the Vicuña Fiber Value Chain in the Camisea Gas Area and Andean Vicuña-Breeding Communities of the Huancavelica Region,” funded by FOCAM-UNH resources.

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