Cuadernos de Investigación Geográfica *Geographical Research Letters*	2025	Nº 51	pp. xx-xx	EISSN 1697-9540

http://doi.org/10.18172/cig.6451

ASSESSING THE DESIGN AND MANAGEMENT OF PROTECTED AREAS: LANDSCAPE GEOGRAPHY IN LOMAS AND TILLANDSIALES OF SOUTHWESTERN PERU

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ABSTRACT. Coastal desert ecosystems, such as the Lomas and Tillandsiales, are essential for the well-being of local populations, providing vital ecosystem goods and services, including climate regulation and water supply. These ecosystems are recognized as significant conservation areas at the national level. However, the Lomas and Tillandsiales in Tacna have been adversely affected and ecologically degraded due to uncontrolled population growth and inadequate regulation of human activities, such as agriculture, mining, and livestock grazing. Therefore, it is crucial to implement effective conservation strategies. Despite this need, when governmental entities delineate territories for potential protected areas, existing land use is often prioritized, leading to the exclusion of areas under current use rather than considering geographical criteria or ecological attributes of these vital ecosystems. This practice raises questions about the effectiveness of conservation efforts. To assess the proposed polygons for new protected areas by regional authorities, we compared these with natural ecosystem boundaries using various geographical tools. This comparison revealed substantial differences in geographical, ecological, and landscape metrics, indicating a decrease in ecological similarity and potentially lower effectiveness for conservation. We identified variations in geomorphological and morphometric diversity, with extreme cases showing coefficients of variability of 56% for the Gravelius index, 52% for the altitude index, and 43% for the morphometric protection index. These factors are critical as they strongly correlate with biodiversity, ecological processes, and the provision of ecosystem services, which are the main goals of conservation. Given these discrepancies, the newly proposed conservation area may inadequately fulfill its objectives. Once designated, the authorities should design and implement a management model that prioritizes expanding the protected areas to their natural limits, promoting restoration, and conducting ongoing monitoring of the metrics outlined in this research. Conservation should not merely involve declaring a spatial area as a reserve; it also requires defining these spaces based on tools and geographical knowledge to ensure the adequate protection and conservation of the Lomas and Tillandsiales ecosystems.

Evaluación del diseño y gestión de áreas protegidas: Geografía del paisaje en Lomas y Tillandsiales del Suroeste Peruano

RESUMEN. Los ecosistemas del desierto costero como las Lomas y Tillandsiales son fundamentales para el bienestar de las poblaciones locales, ya que proporcionan bienes y servicios ecosistémicos importantes, como la regulación climática o el suministro de agua entre otros, siendo considerados como importantes objetos de conservación a nivel nacional. A pesar de esto, en Tacna, estos ecosistemas vienen siendo impactados y degradados ecológicamente por el desordenado crecimiento poblacional y la poca regulación de actividades humanas, como la agricultura, minería y uso pecuario, por lo que es necesario implementar estrategias de conservación. Sin embargo, cuando las entidades del estado realizan la delimitación de territorios para futuras áreas protegidas, se prioriza el uso actual, se excluyen los derechos de aprovechamiento otorgados, y no se consideran los criterios geográficos o los atributos ecológicos de estos importantes ecosistemas, lo que pone en discusión su efectividad. Por ello, utilizando diversas herramientas geográficas, se evaluaron los polígonos propuestos por las autoridades regionales como nueva área protegida comparándolos con los del ecosistema natural, demostrándose diferencias entre los índices geográficos, ecológicos y las métricas del paisaje, evidenciándose una cada vez menor similitud ecológica y posiblemente una menor efectividad para su conservación. Se observó que existen variaciones entre sus rangos de diversidad geomorfológica y morfométrica que llegan en casos extremos hasta un 56% de coeficiente de variabilidad para el índice de Gravelius, 52% para el de altitud y el 43% para el del índice de protección morfométrica. Éstos son factores muy importantes que tienen una alta correlación con la biodiversidad, los procesos ecológicos y la provisión de servicios ecosistémicos, objetivos principales para la conservación. A partir de estas diferencias planteamos que esta nueva área de conservación sería deficiente en el cumplimiento de sus objetivos. Sin embargo, proponemos que, una vez declarada como tal, la entidad administradora deberá diseñar e implementar un modelo de gestión que contemple prioritariamente la ampliación hacia limites naturales, la implementación de medidas de restauración y el monitoreo permanente de las métricas presentadas en la presente investigación, bajo el principio de que la conservación no solo es la declaración de un ámbito espacial en la categoría de reserva, sino en la necesidad de definir dichos espacios en base a herramientas y conocimientos geográficos que garanticen la efectiva protección y conservación de los ecosistemas de Lomas y Tillandsiales.

Keywords: Ecology, conservation, fog oases, morphometry, geomorphology.

Palabras clave: Ecología, conservación, oasis de neblina, morfometría, geomorfología.

Received: 13 December 2024

Accepted: 12 June 2025

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1. Introduction

The Peruvian coast features a desert strip interrupted by valleys that rely on river flow from the Andean foothills, as well as patches of vegetation found in foothills and flat areas that depend on fog. Coastal Lomas are a type of ecosystem known as fog oases (Moat *et al.,* 2021; Tovar *et al.,* 2018). These ecosystems develop due to the capture of water droplets by shrub and tree vegetation situated between 100 and 1,000 meters above sea level. They typically arise in areas with complex topography where atmospheric humidity is driven by advection and meets steep slopes (Beresford-Jones *et al.,* 2015). The Lomas are characterized by a permanent formation of structure consisting of shrub and tree species that are well-adapted to arid conditions. During the foggy season (from August to September on the southern Peruvian coast), plant diversity increases significantly due to the emergence of various herbaceous species, which typically have seeds in diapause during the dry season (MINAM, 2019). Due to their association with specific topographic features, the Lomas exhibit a discontinuous distribution throughout the Sechura and Atacama Deserts, leading to a rich diversity of endemic species (Flores and Van Meerbeek, 2024). In flat or slightly sloping areas between 100 and 800 meters in altitude, where humidity meets the surface due to daily air mass movements caused by thermal variations and changes in density and pressure, Tillandsiales develop (Hesse, 2012). The Tillandsiales along the Peruvian coast comprise approximately five species of the genus Tillandsia, a group of Bromeliaceae that possess various physiological and anatomical adaptations, enabling them to absorb water and micronutrients from both soil (when available) and air (Rundel *et al.,* 1997; Belmonte *et al.,* 2022). Generally, each Tillandsial is dominated by one or a few species from the genus, resulting in lower specific and functional diversity compared to coastal Lomas (Stein *et al.,* 2023).

Currently, both formal and informal, as well as legal and illegal economic activities, threaten the conservation status of these ecosystems (Miyashiro and Ortiz, 2016). Activities such as mining and urban expansion can lead to direct ecosystem loss, replacing natural areas with land devoid of vegetation and generating permanent changes to the territorial landscape. Conversely, traditional practices such as camelid grazing have been conducted in the coastal Lomas since pre-Hispanic times without significant alteration (Baitzel and Rivera, 2019; Corcoran-Tadd, 2021). However, the introduction of more active species that consume plant material, including goats, since the colonial period has made the impacts of grazing activities much more harmful (Camel *et al.,* 2024). These direct human activities may interact with climate change, exacerbating their effects and diminishing the resilience of these ecosystems (Rau *et al.,* 2017; Tovar *et al.,* 2018). Evidence currently suggests a decline in the capacity of these ecosystems to provide essential services, such as habitat for important biodiversity and water resource capture (Ceballos, 2015; Madariaga, 2017).

Given the social and environmental risks, conservation proposals for the Lomas and Tillandsiales ecosystems in the Peruvian coastal desert are urgently needed, especially in areas facing rapid human pressures (Tovar *et al.,* 2018). However, it is crucial to have territorial planning documents that support this need, such as the Territorial Planning Plan of the Tacna Region (Gobierno Regional de Tacna, 2024). Upon the publication of the proposed polygon shapes for Regional Conservation Areas (RCAs) in El Peruano (2024), it has been noted that these boundaries are drawn on government-owned territories, excluding lands with preexisting rights. That evidence raises the question of whether these boundaries will effectively conserve such vital ecosystems and their biodiversity (Andrade, 2007). If the geographical landscape indices (topography, complexity, geomorphology, and surface) that underpin the ecological functioning of these ecosystems have been significantly altered from their natural state, ecological limitations for conservation are likely to arise (Olaya, 2009; Toivonen *et al.,* 2017).

This paper analyzes the differences in geomorphological and morphometric variability, as well as various landscape characterization indices, between the proposed polygons for regional conservation areas and the natural boundaries of the ecosystems intended for protection. The objective is to assess the extent to which the proposed areas preserve the ecosystem's spatial attributes, which are crucial for its sustainability. The questions we aim to address in this study are: (i) How does the geomorphological and morphometric variability of the ecosystem in the proposed areas for RCAs compare to the extent of the proposed protected ecosystem within their natural boundaries? (ii) What geographical tools can be used to measure the variation in landscape metrics between the compared polygons? (iii) Can the conservation of Lomas and Tillandsial ecosystems be effective without ensuring the preservation of their most significant geographical attributes?

2. Materials and methods

2.1. Study area

The study area is the coastal desert of the Tacna Region in southern Peru, from sea level to 2,000 meters above sea level. In this area, the Regional Government of Tacna has delimited five zones, proposing them as future conservation areas (Fig. 1), whose polygons were downloaded from the official statement

(RCA, El Peruano, 2024). These zones combine areas of seven large ecosystems characteristic of the coastal desert, including four Lomas: Chapolla, Tacahuay, Sama Grande, and Morro Sama. These Lomas represent a type of fog oasis formed by the interaction of masses of humidity from the Pacific Ocean carried eastward and intercepted by the coastal foothills. The three Tillandsiales, Intiorko, Yeseras, and Gallinazos, are large flat expanses covered by one of the most representative fog-dependent plant formations of the coastal desert, dominated by bromeliads of the genus Tillandsia. The total area of natural ecosystems is 619 km^2, and the space proposed for conservation only reaches 235 km^2 (Table 1).

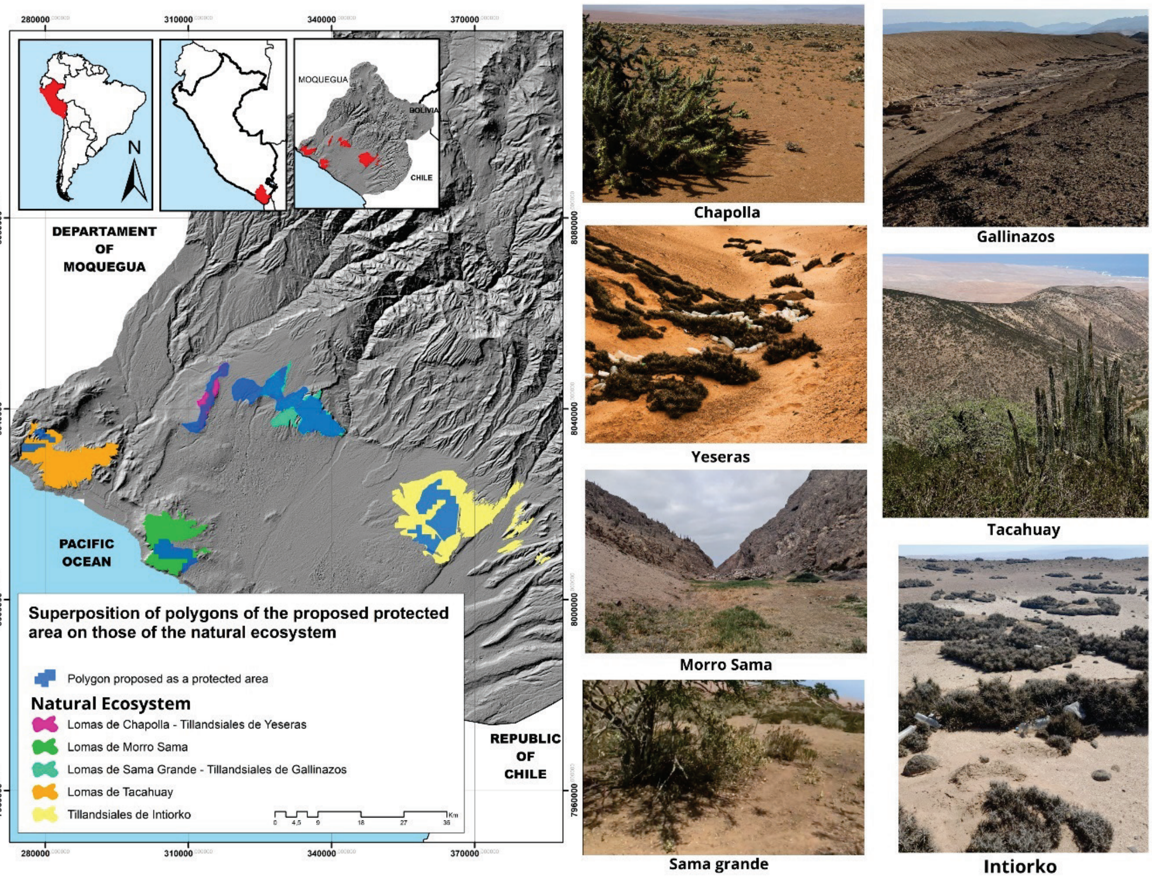

Figure 1. Geographical location of the study area, the coast of the department of Tacna, where the five zones that occupy the seven ecosystems of hills and coastal desert evaluated are presented in a color palette, together with the blue polygons that the Regional Government proposes as conservation areas, together with their respective panoramic photographs.

Table 1. Description of the hilly and coastal desert ecosystems of the department of Tacna

Ecosystem	Ecosystem area (Km^2)	Proposed area for RCA (Km^2)	Province
Lomas de Chapolla - Tillandsiales de Yeseras	22.1	24	Jorge Basadre
Lomas de Morro Sama	99.7	25	Tacna
Lomas de Sama Grande - Tillandsiales de Gallinazos	95.5	103.4	Tacna
Lomas de Tacahuay	128	11	Jorge Basadre
Tillandsiales de Intiorko	274	71.9	Tacna

The shapes representing the natural ecosystems were downloaded from the Peruvian Ecosystem Map (Ministerio del Ambiente, 2019), the National Vegetation Cover Map (Ministerio del Ambiente, 2015), and the Ecological and Economic Zonification of the Tacna Region (Gobierno Regional de Tacna, 2024). Subsequently, a manual correction of boundaries was made using high-resolution satellite images available on Google Earth (Google LLC, 2024) using QuickMapServices 0.19.36 in QGIS 3.40.0 (QGIS Development Team, 2024). Finally, the boundaries were adjusted based on primary information gathered during periodic field visits conducted between 2023 and 2024.

2.2. Geomorphologic, morphometric, and landscape analyses

To assess the geomorphological variability of natural Lomas and Tillandsiales ecosystems and the polygons proposed as new conservation areas, the Gravelius compactness index (Eq. 1) was used. This index measures the degree of compaction or geometric complexity of its territory, allowing the perimeter to be quantified per unit area and associated with edge effects, fragmentation, and connectivity.

$$K_g = \frac{P}{2\sqrt[2]{\pi \times A}} \quad (1)$$

where Kg is the Gravelius index, P es is the polygon perimeter in km, and A is its area in km^2.

For the morphometric analysis, the available 12.5-meter resolution Alos-Palsar digital elevation models (Alaska Satellite Facility, 2024) were downloaded. Altitude values were extracted from these models, and the slope, morphometric protection index (MPI), topographic wetness index (TWI), and Aspect (Table 2) for the natural ecosystems and proposed protected areas were estimated. These morphometric indices are quantitative tools used in landscape analysis to understand the physical characteristics of the Earth's surface, such as watersheds, and their geomorphological processes (Toivonen *et al.,* 2018). They are used to describe the shape, size, and distribution of landscape elements, as well as to identify drainage and relief patterns (Olaya, 2009). All the factors evaluated influence species distribution and habitat suitability. The slope determines factors such as the depth of the soil or its stability, MPI measures how well a location is protected from exposure by the surrounding relief, the TWI assesses the spatial distribution of moisture, and the Aspect determines how much radiation receives the land (Mander *et al.,* 2017). Based on the morphometry rasters, the mean values and the coefficient of variability (CV= sd/mean) were estimated for each study site, which helped compare vulnerability prioritize conservation that maximizes natural wetness and representativeness, as done by Doherty *et al.,* 2021, Harris and Baird 2019, Jeong *et al.,* 2024, Toivonen *et al.* 2018.

All the morphometric analyses were conducted using GIS packages such as spatialEco (Evans and Murphy, 2023), raster (Hijmans, 2024), and sp (Bivand *et al.,* 2013) in R 4.4.1 software (R Development Core Team, 2024). Like those done by Lipori and Martín (2022), Kondo *et al.* (2024), Faye and Ndiaye (2021), Bendjoudi and Hubert (2002).

To characterize each of the evaluated landscapes and compare the complexity and irregularity of the polygons proposed as future conservation areas about the boundaries of natural ecosystems, metrics or indices were calculated using Patch Analyst Tools v5.2 (Rempel *et al.,* 2012). Eight geographic indices were selected that represented the values of shape (3), edge (3), density-size (1), and area (1) (Table 3), in the same way as Ahmadzadeh *et al.,* 2023, Diktaş Bulut, 2023, Franco León *et al.,* 2024, Navarro *et al.,* 2021, Yu and Liu, 2025, developed in their respective investigations.

Table 2. Geomorphological and morphometric variables calculated for the study areas.

Variable	Description	Environmental importance
Gravelius compacity coefficient (K_g)	Relates the study site perimeter with the perimeter of a circumference with the same area	Inclusion of isolated habitats as headwaters or canyons, corridors and connectivity attributes
Altitude	Obtained directly from the Digital Elevation Model, is the altitude (in meters above sea level) for each cell in the raster	Temperature, radiation, clouds interception
Slope	Slope Angle in Degrees (°) estimated for a raster cell as the average with respect to its eight neighboring cells	Solar radiation exposure, soil accumulation, terrain stability, soil moisture
Aspect	The circular values of orientation (0 - 360°) corresponding to the cell on the slope	Solar radiation, summer-winter effects, day-night effects
Morphometric protection index	It analyzes the immediate vicinity of each cell up to a user-defined boundary, to assess how the relief protects that point. Starting from a particular cell, the algorithm evaluates in the directions of the 8 neighboring cells to calculate the vertical angle between the point of interest and its immediate range. The vertical angle values are iterated until the evaluation distance limit is reached, and then the average value of all angles obtained is estimated as the MPI value.	Hydrological condition, solar radiation exposure
Topographic wetness index	It consists of two parts: the hydrological contribution area per unit contour length (m2/m) called the area of the specific basin and the local slope in radians. This index developed for hydrological modeling is used to locate saturated areas that can generate runoff and to estimate the average aquifer level.	Soil moisture, flow accumulation zones

Table 3. Landscape metrics used to assess similarity between natural ecosystems and proposed polygons as RCAs.

Metric	**Name**	**Type**	**Description**
MSI	Average Shape Index	Shape	Equal to 1 when the patches tend to AWMSI circularity, the value increases when they tend to be irregular.
MPAR	Perimeter-to-Area Ratio Average	Shape	Estimate the regularity or complexity of the shape of the geographic polygon.
MPFD	Average of the fractal dimension	Shape	Calculate the degree of complexity of each fragment based on the relationship between area and perimeter. The AWMPFD index has theoretical limits that are between 1 and 2; Higher values indicate greater complexity and values close to 1 indicate simpler geometric shapes.
TE	Total edge	Edge	Total patch perimeter.
ED	Edge density	Edge	Amount of perimeter with respect to the total area of the landscape. It is the sum total of all edge lengths of a class (TE), divided by the total area of the landscape.
MPE	Edge Perimeter Average	Edge	Express the average perimeter length (TE) of the spaces for each type of class. It is calculated by dividing the total value of the class perimeter (TE) by the total number of spots (NumP).
MPS	Average Patch Size	Density	It represents the average area of patches contained in a class. It should be analyzed in conjunction with the standard deviation of patch size (PSSD)
CA	Class Area	Area	Landscape composition measures are the area of each class.

2.3. Effectiveness assessment for the proposed conservation areas

Based on the data obtained, the variability ranges between the boundaries of the proposed polygons as new protected areas and those of the Lomas and Tillandsiales. To do this, the ratio of the area represented by the RCA polygon to the boundaries of the natural ecosystems was estimated. Regarding the Gravelius compactness coefficient, the ratio of the value in kg of each area proposed for RCA to the kg of the polygons comprising the entire natural ecosystems was estimated. The same ratio was then estimated based on the coefficients of variability (CV) of each of the calculated morphometric variables (Eq. 2).

$$R_{A/N} = \frac{Obs_A}{Obs_N} \quad (2)$$

where $R_{A/N}$ is the ratio of values between the proposed RCA and the natural extent of each ecosystem, Obs_A is the value obtained for the RCA, and Obs_N is the value obtained for the Natural Extension of the ecosystem. The observed values can refer to the total surface area, Gravelius K_g, and coefficients of variation for altitude, slope, MPI, TWI, and Aspect.

Based on these ratios, nonlinear models were developed to evaluate the relationship between the proportion of area change versus the proportion of change in the geomorphological and morphometric parameters of the study polygons, similar to those carried out by El Jeitany *et al.* (2024), Lu *et al.* (2024), Macchioli *et al.* (2024), Speetjens *et al.* (2023), Wang *et al.* (2023), and Zhao *et al.* (2024) in their respective investigations.

Landscape parameters were analyzed by graphically representing positive or negative change by landscape metric, as well as by calculating a similarity index. Additionally, multivariate tests were conducted to assess the ecological similarity of the polygons based on landscape metrics for the extent of the natural ecosystem and the proposed RCA in each area of interest. For this, a principal components analysis (PCA) was applied, which allows for the reduction of the dimensionality of the data and shows how they are grouped according to the eight calculated variables (Warren *et al.,* 2008; Yu and Liu, 2025; Zhang *et al.,* 2025). All comparative analyses were conducted using R 4.4.1 (R Development Core Team, 2024).

3. Results

3.1. Geomorphological and morphometric differences

A comparison of the average data and the coefficient of variability (CV) for each geomorphological and morphometric parameter across five study areas reveals notable differences in their characteristic patterns (Table 4). Firstly, the most significant differences in the average CV between the RCA polygons and the natural ecosystems are observed in two variables: the Gravelius coefficient (Kg), which has an average CV of -0.37, and the distribution of altitude values, with an average CV of -0.16. In contrast, for the other four variables, the average CV values exceed -0.09 units, indicating that the average variability for these parameters is quite similar. Secondly, there is a notable variation in the size of the proposed RCA polygons when comparing the average CV change values across the five sites. The most extreme case is found in the Tacahuay Lomas, where the proposed RCA polygon represents only 8.6% of the natural ecosystem area (0.086). The average reduction in variability for all other evaluated parameters in this case is 20%. In the Intiorko Tillandsial, where the RCA polygon covers 26.2% of the natural ecosystem (0.262), the average reduction in geomorphological and morphometric variability relative to the natural limits is 35%. The Morro Sama Hill has a proposed RCA area that is 25% of the ecosystem area (0.25), resulting in an average 8% reduction in variability. In contrast, the RCA proposals that encompass Loma Chapolla and Tillandsial Yeseras, as well as Loma Sama Grande with Tillandsial Gallinazos, which cover nearly all the ecosystems (with the RCA being 1.08 times the ecosystem area in both instances), show negligible changes in variability for these parameters (1% and 2%, respectively).

Table 4. Average and coefficient of variation for the geomorphological and morphometric indexes estimated for the study sites.

	Proposed RCA / Natural Extent Ratio	Gravelius K_g		Altitude		Slope	
		Natural Extent	Proposed RCA	Natural Extent	Proposed RCA	Natural Extent	Proposed RCA
Tacahuay	0.086	3.14	2.23	605 (0.41)	782 (0.36)	17.7 (0.47)	21.2 (0.38)
Intiorko	0.262	5.94	2.63	963 (0.16)	914 (0.09)	6.32 (1.01)	4.14 (0.71)
Morro Sama	0.250	3.16	1.79	655 (0.29)	543 (0.14)	14.4 (0.60)	9.49 (0.73)
Chapoya - Yeseras	1.084	2.72	2.49	999 (0.07)	959 (0.10)	7.76 (0.63)	7.83 (0.61)
Sama Grande - Gallinazos	1.083	4.43	2.37	1010 (0.13)	1011 (0.11)	14.7 (0.62)	12.9 (0.72)

	MPI		TWI		Aspect	
	Natural Extent	Proposed RCA	Natural Extent	Proposed RCA	Natural Extent	Proposed RCA
Tacahuay	0.17 (0.44)	0.19 (0.34)	6.81 (0.28)	6.49 (0.25)	189.7 (0.42)	191.1 (0.33)
Intiorko	0.06 (0.81)	0.04 (0.46)	11.2 (0.26)	12.3 (0.18)	218.4 (0.36)	224.8 (0.34)
Morro Sama	0.12 (0.51)	0.09 (0.61)	7.36 (0.30)	8.58 (0.30)	183.6 (0.51)	171.1 (0.57)
Chapoya - Yeseras	0.06 (0.47)	0.06 (0.45)	8.77 (0.19)	8.68 (0.18)	171.1 (0.56)	182.1 (0.49)
Sama Grande - Gallinazos	0.13 (0.57)	0.12 (0.66)	7.38 (0.33)	8.00 (0.35)	204.3 (0.41)	213.3 (0.40)

Proposed RCA: proposed regional conservation area
Natural extent: natural extension of the ecosystem
Gravelius Kg: Gravelius compacity index
MPI: morphometric protection index
TWI: topographic wetness index
All values were represented as: average or average (coefficient of variation)

When correlating the $Factor_{RCA}/Factor_{Ecosystem}$ ratios with the proportion of the natural ecosystem area expected to be conserved under the RCA proposals (illustrated in Fig. 2), it is evident that each geomorphological or morphometric factor exhibits distinct variations. The variation in altitude ranges, showing a coefficient of determination (R^2) of 0.47, demonstrates the strongest correlation with spatial representativeness. The variations in the topographic humidity index and the morphometric protection index present moderate R^2 values of 0.27 and 0.20, respectively. For the remaining parameters, the R^2 values are all below 0.20, indicating that there is little significant difference in retaining the potential ranges of variability.

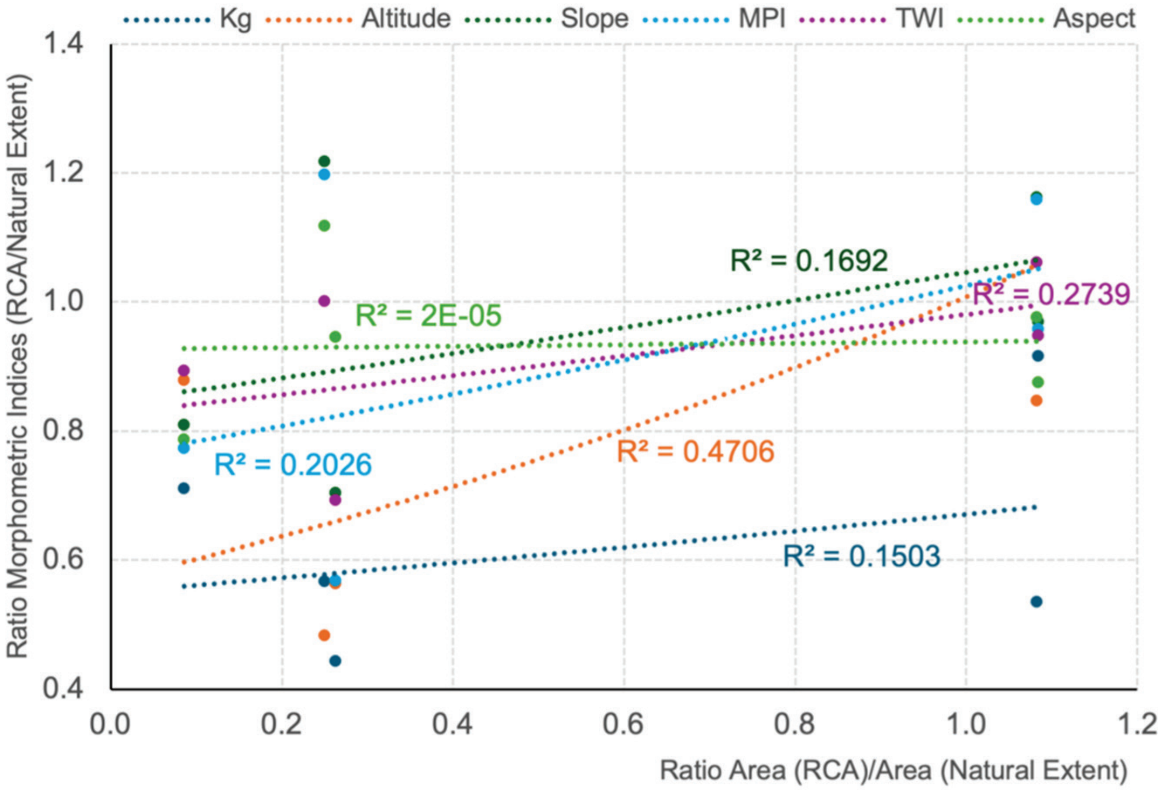

Figure 2. Nonlinear fit and coefficient of determination (R^2) comparing the RCA/Natural surface area ratio (x – axis) versus the variability (CV) ratio of each geomorphological and morphometric variables (y -axis) estimated for the study areas.

3.2. Landscape metrics

By superimposing the polygons representing the natural boundaries of the ecosystem with those proposed for the new protected natural area (Fig. 1), significant geographical differences become apparent. These differences are evident not only in size but also in the linearity of their shapes, the reduction of their areas, and the increase in their edges. These factors are key indicators of ecological health, which are essential for conserving biodiversity.

A review of the landscape metrics for the eight indices used reveals significant variability in both landscapes (see Fig. 3a). This variability, both positive and negative, raises questions about the effectiveness of these metrics for conservation, given what each landscape metric represents (Table 3). Among the areas analyzed, the Lomas of Tacahuay, Morro Sama, and the Tillandsial of Intiorko exhibited the most significant variation, as indicated by the number of metrics that changed, influencing their ecological structure; these areas had seven, seven, and eight changing metrics, respectively (see Table 5).

Table 5. Landscape metrics calculated by polygon and study areas

<table>
<tr><th rowspan="2">Study area</th><th rowspan="2">Polygon</th><th colspan="3">Shape</th><th colspan="3">Edge</th><th>Density</th><th>Area</th></tr>
<tr><th>MSI</th><th>MPAR</th><th>MPFD</th><th>TE</th><th>ED</th><th>MPE</th><th>MPS</th><th>CA</th></tr>
<tr><td rowspan="4">Lomas de Chapolla - Tillandsiales de Yeseras</td><td>Natural Ecosistem</td><td>2.72</td><td>20.50</td><td>1.27</td><td>45369.03</td><td>0.73</td><td>45369.03</td><td>2208.07</td><td>2208.07</td></tr>
<tr><td>RCA proposal</td><td>2.49</td><td>18.10</td><td>1.26</td><td>43240.53</td><td>1.84</td><td>43240.53</td><td>2393.49</td><td>2393.49</td></tr>
<tr><td>% Change</td><td>-8.46</td><td>-11.71</td><td>-0.92</td><td>-4.69</td><td>151.06</td><td>-4.69</td><td>8.40</td><td>8.40</td></tr>
<tr><td>Ecological condition</td><td colspan="8">Territory fragmentation leads to a loss of irregularity, with more regular shapes (squares, circles), severely impacting biodiversity by reducing ecosystem complexity and favoring generalist species. Additionally, environmental conditions at edges change, decreasing core areas, and the increased number of fragments reduces the average perimeter, affecting ecological functionality.</td></tr>
<tr><td rowspan="4">Lomas de Morro Sama</td><td>Natural Ecosistem</td><td>3.16</td><td>11.20</td><td>1.26</td><td>111993.53</td><td>1.81</td><td>111993.53</td><td>9971.68</td><td>9971.68</td></tr>
<tr><td>RCA proposal</td><td>1.79</td><td>12.70</td><td>1.22</td><td>31589.50</td><td>1.34</td><td>31589.50</td><td>2491.59</td><td>2491.59</td></tr>
<tr><td>% Change</td><td>-43.57</td><td>13.39</td><td>-3.63</td><td>-71.79</td><td>-25.70</td><td>-71.79</td><td>-75.01</td><td>-75.01</td></tr>
<tr><td>Ecological condition</td><td colspan="8">The fragmentation of the territory leads to a loss of irregularity with more regular shapes (squares. circles). severely affecting biodiversity by reducing ecosystem complexity and favoring generalist species. Changes in edge conditions decrease core areas. reduce ecosystem connectivity. and increase the number of fragments with smaller perimeters. Fragment sizes shrink. offering fewer suitable conditions for species and ecological processes. along with lower resource availability due to area effects.</td></tr>
<tr><td rowspan="4">Lomas de Sama Grande - Tillandsiales de Gallinazos</td><td>Natural Ecosistem</td><td>4.43</td><td>16.10</td><td>1.30</td><td>153314.96</td><td>2.48</td><td>153314.96</td><td>9552.17</td><td>9552.17</td></tr>
<tr><td>RCA proposal</td><td>2.37</td><td>8.20</td><td>1.23</td><td>85301.13</td><td>3.63</td><td>85301.13</td><td>10343.57</td><td>10343.57</td></tr>
<tr><td>% Change</td><td>-46.53</td><td>-49.07</td><td>-5.32</td><td>-44.36</td><td>46.56</td><td>-44.36</td><td>8.28</td><td>8.28</td></tr>
<tr><td>Ecological condition</td><td colspan="8">Territory fragmentation results in a loss of irregularity. forming more regular shapes (e.g.. squares. circles). which severely impacts biodiversity. The ecosystem becomes less complex. favoring generalist species. while changes in edge conditions reduce core areas. Additionally. an increase in the number of fragments lowers the average perimeter of each fragment. further compromising ecological integrity.</td></tr>
<tr><td rowspan="4">Lomas de Tacahuay</td><td>Natural Ecosistem</td><td>3.14</td><td>9.80</td><td>1.26</td><td>125870.77</td><td>2.03</td><td>125870.77</td><td>12813.63</td><td>12813.63</td></tr>
<tr><td>RCA proposal</td><td>2.23</td><td>23.90</td><td>1.26</td><td>26202.75</td><td>1.11</td><td>26202.75</td><td>1098.32</td><td>1098.32</td></tr>
<tr><td>% Change</td><td>-28.90</td><td>143.88</td><td>-0.24</td><td>-79.18</td><td>-45.16</td><td>-79.18</td><td>-91.43</td><td>-91.43</td></tr>
<tr><td>Ecological condition</td><td colspan="8">Territory fragmentation leads to a loss of irregularity. forming regular shapes (e.g.. squares. circles). which severely affects biodiversity. Ecosystem complexity decreases. favoring generalist species. while changes at the edges reduce core areas. Connectivity between ecosystems is diminished. further harming biodiversity. An increase in the number of fragments reduces the average border perimeter. and smaller fragment sizes offer fewer suitable conditions for species and ecological processes. along with limited resource availability due to area effects.</td></tr>
<tr><td rowspan="4">Tillandsiales de Intiorko</td><td>Natural Ecosistem</td><td>5.92</td><td>12.70</td><td>1.31</td><td>347538.08</td><td>5.61</td><td>347538.08</td><td>27399.20</td><td>27399.20</td></tr>
<tr><td>RCA proposal</td><td>2.63</td><td>11.00</td><td>1.25</td><td>78925.49</td><td>3.36</td><td>78925.49</td><td>7189.15</td><td>7189.15</td></tr>
<tr><td>% Change</td><td>-55.67</td><td>-13.39</td><td>-5.08</td><td>-77.29</td><td>-40.18</td><td>-77.29</td><td>-73.76</td><td>-73.76</td></tr>
<tr><td>Ecological condition</td><td colspan="8">Territorial fragmentation results in the loss of irregularity. forming regular shapes (e.g.. squares. circles). which negatively impacts biodiversity. It reduces ecosystem complexity. favoring generalist species. while edge conditions diminish core areas. Ecosystem connectivity is weakened. increasing fragmentation with smaller fragments. lower perimeter-to-area ratios. and fewer suitable conditions for species and ecological processes. Resource availability also declines due to the area effect.</td></tr>
</table>

The ecological similarity index (Fig. 3b), based on inverse Euclidean distance, highlights the differences between the polygons representing natural ecosystems and those designated for conservation. This analysis highlights the importance of prioritizing effective conservation strategies. Notably, three proposed areas, the Morro Sama and Tacahuay Lomas and the Tillandsial Intiorko, exhibit significant deficiencies for conservation.

Additionally, the principal components analysis (PCA) produced two spatial dispersion graphs (see Fig. 4), illustrating how the polygons of the study areas cluster based on the eight evaluated variables. The upper graph reveals the ecological similarity of ecosystems within their natural boundaries, while the lower graph displays the proposed conservation polygons. This graph clearly shows a radical change between the areas, confirming the variability among the linear combinations of landscape metrics. In this PCA, the X-axis accounts for most of the data variance. At the same time, the Y-axis represents the second most significant portion of the variance, independent of the X-axis.

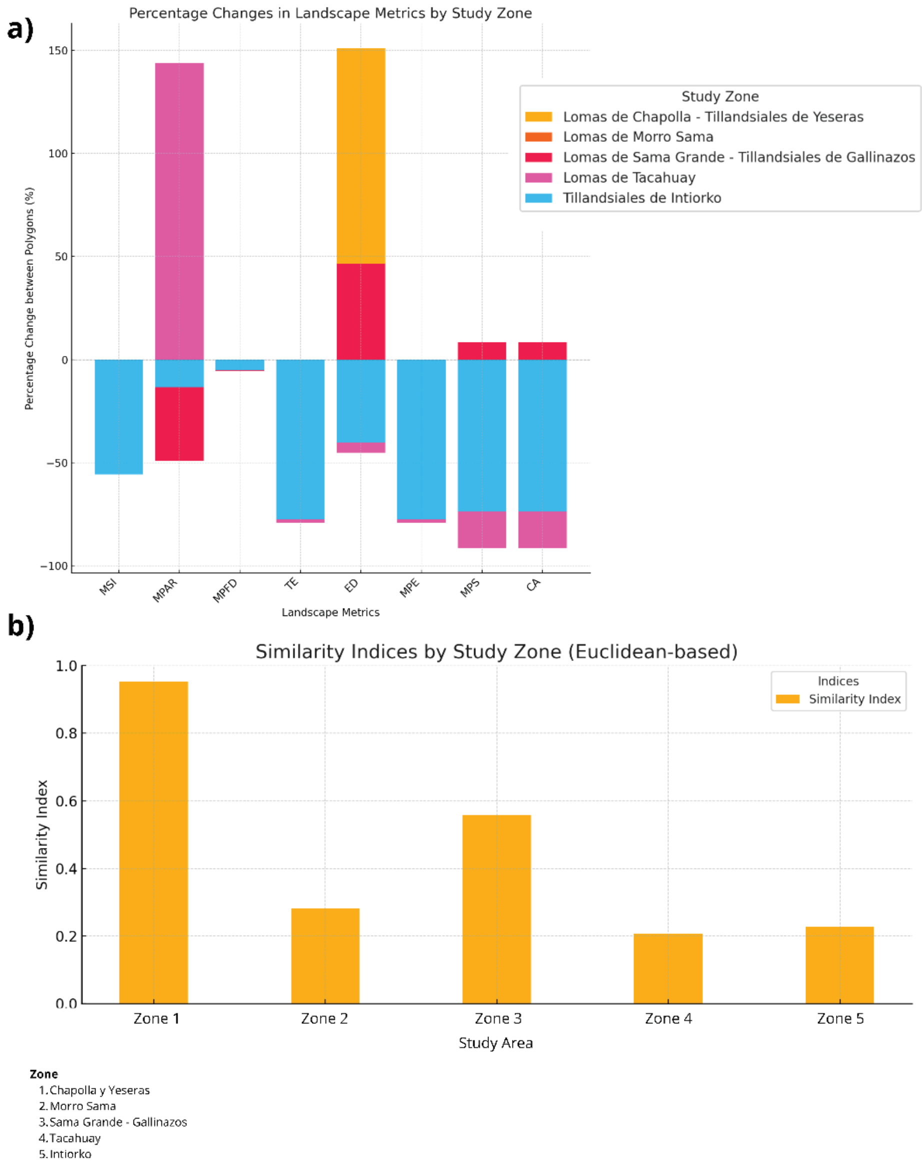

Figure 3. a) Efficiency graph according to the eight-landscape metrics evaluated, where positive and negative changes are observed. b) Bar graphs of the ecological similarity index by area, of the polygons of the natural ecosystem and their proposed conservation area.

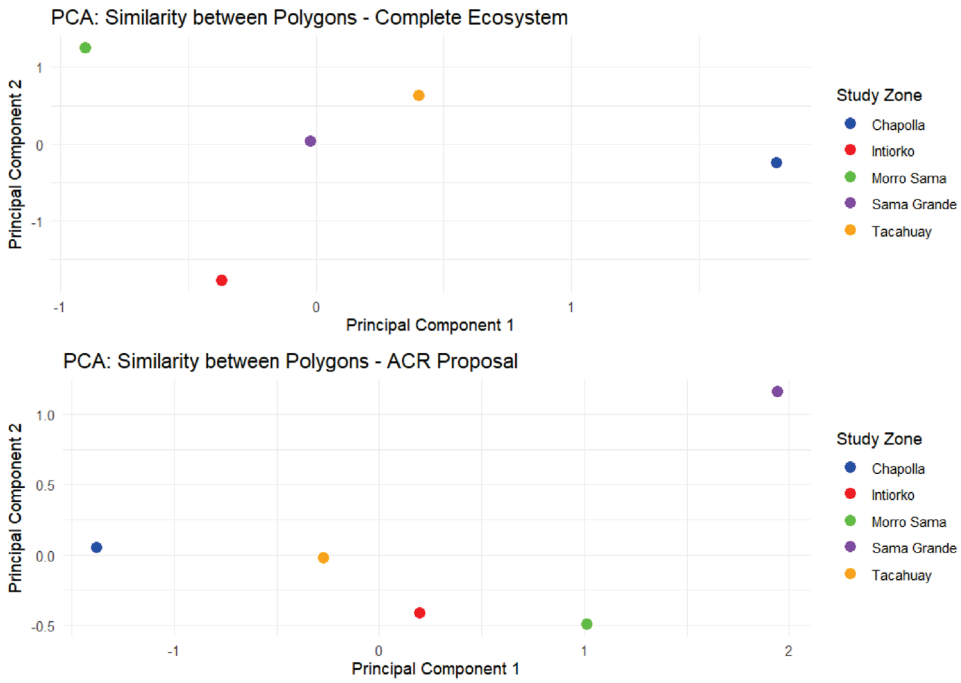

Figure 4. Spatial dispersion graphs as a result of principal component analysis (PCA), in the upper part the dispersion of natural ecosystems and in the lower part it is observed how their dispersion and similarity change when their landscape metrics vary in the process of delimitation as a conservation area.

4. Discussion

The relationship between geography and landscape ecology, along with its practical applications, plays a crucial role in addressing new challenges in the conservation of natural heritage. Technological tools have been integrated to facilitate the accurate identification and delineation of ecosystems, as well as to analyze areas designated for conservation, community management, and sustainable use. For instance, the use of geographic tools has enabled us to identify the most representative areas of Lomas and Tillandsiales along the coast of Tacna. Our findings align with those of Moat *et al.* (2021), which highlight the occupancy areas of natural fog oases in the Tarapacá Desert and their underrepresentation in the protected areas system. These tools are not only essential for identification and delineation but also facilitate statistical calculations based on landscape metrics such as shape, area, size, and edge. It is vital to assess the quality of the polygons that represent ecosystems or delineate conservation areas (Vila Subirós *et al.,* 2006) to determine their effectiveness for conservation efforts.

Additionally, these tools enable us to test fundamental ecological theories on biodiversity distribution, including the biogeographic island theory proposed by MacArthur and Wilson (1963, 1967) and the theory by Gascon *et al.* (1999). Both models emphasize the importance of connectivity and patch size, suggesting that intense fragmentation can lead to an increase in generalist species at the expense of specialist species. This raises concerns about conserving small, isolated, or regular areas, as is the case with the proposed RCAs for Lomas and Tillandsiales in Tacna, which cover less than 50% of the natural limits of the targeted ecosystems (see Fig. 3a).

Landscape metrics are partially derived from geomorphological and morphometric factors, as analyzed in this paper. Morphometry includes elements such as orientation (or Aspect), exposure to direct sunlight (measured by the Mean Potential Index, MPI), and relative position concerning areas with closer proximity to groundwater (expressed by the Topographic Wetness Index, TWI). These factors play a fundamental role in the distribution, extent, and complexity of ecosystems (Olaya, 2009). This significance is especially pronounced in arid environments, where strategies to reduce water consumption can be enhanced by terrain shapes that create optimal microclimates, thereby fostering extended periods of water availability (Elhag *et al.,* 2017). The ideal combination of these factors can promote greater species diversity, leading to the formation of areas that serve as biodiversity hotspots with high levels of complexity and richness, particularly in regions that are generally considered to be poor in biodiversity (Al-Rowaily *et al.,* 2012). In our observations, we find that specific parameters, such as the regularity of geographic polygons (kg) and the patterns of altitude distribution, demonstrate relatively high variability depending on the area in question. Other factors, such as topographic humidity and morphometric protection, which are closely associated with abrupt changes in altitude and slope, tend to exhibit medium variability. In contrast, slopes or aspects usually do not exhibit significant changes. Given the importance of factors that enhance water resource availability (or reduce water demand), it is crucial to consider these elements when delineating ecosystem protection areas, particularly in arid regions (Kadam *et al.,* 2017).

The results of the negative variation in landscape metrics indicate that those metrics related to the shape of polygons (see Fig. 3a), such as the Mean Shape Index (MSI) and the Perimeter-Area Ratio (PAR), reveal that the new conservation area for the Lomas and coastal desert in the Tacna Region, proposed by the government, has regular shapes. In contrast, the natural ecosystems exhibit more complex, fractal shapes. This difference is significant for conservation efforts because regular shapes can reduce species connectivity and increase the vulnerability of edges (With, 2019). More fractal shapes and complex geometries provide better conditions for biodiversity and enhance conservation opportunities, as evidenced by the decrease in the Mean Fractal Dimension (MPFD). Santos *et al.* (2006) highlight that if the edges of natural ecosystems are altered, perimeter bands with varying conditions for species will form. These modified edges often have lower ecological quality compared to the high-quality core areas.

Furthermore, greater total edge (TE) and average edge (MPE) measurements are associated with smaller core sizes due to variations in physical and biotic factors that can significantly impact population survival. In the proposed conservation area, the TE and MPE differ from the original ecosystem by approximately 70% in the Intiorko Tillandsia region. Therefore, it is crucial to protect core areas from surrounding zones.

Changes in landscape metrics have been shown to influence species distribution directly. In the Lomas and Tillandsiales, flora species such as *Tillandsia werdermanni* and *Carica candicans* are classified at various danger levels according to national and international standards (Decreto Supremo N° 043-2006-AG, 2006; Navarro *et al.,* 2020; IUCN, 2012). This necessitates an examination of the impacts that human activities have had over the years, as well as the changes in ecosystems related to shape, edge, size, and area. Verga *et al.* (2018) studied the relationship between fruit quality and seed abundance concerning area and edge, while Chacoff *et al.* (2006) observed a decrease in seed viability for *Acacia aroma* as fragment size diminished. Their findings also indicated lower predation indexes (less than 14%) in smaller fragments compared to larger ones, along with a 20% increase in the proportion of healthy seeds. These examples illustrate the consequences of fragmentation on the trophic chain, which likely affects all subsequent links. This phenomenon extends to other species in the community, which also experience population fluctuations based on the shapes, edges, areas, and sizes of the habitats they occupy. For instance, Tinajero and Rodríguez (2012) reported differences in bird records between fragmented and natural areas. This finding aligns with Wolff *et al.* (1997), who noted reduced movement in the grey-tailed field rodent. These dynamics suggest that the fauna of the Lomas and Tillandsiales regions will be adversely affected by changes in landscape metrics. For endangered lizard species, such as *Liolaemus poconchilensis* and *L. basadrei* (Valladares *et al.,* 2021), management strategies must account for their ecological niches and the landscape metrics that influence them. Studies conducted in nearby areas indicate that bird richness is significantly correlated with habitat area and size (Franco *et al.,* 2024).

Given the substantial scientific evidence showing little similarity between the landscape metrics—such as shape, edge, and area—of the natural ecosystem and the government's proposed conservation area, it is essential to provide comprehensive technical and scientific information regarding the limitations of this new protected zone. Table 5 outlines the ecological conditions of the polygon for each study area, drawing parallels with analyses by Saura and Pascual-Hortal (2007). It can be concluded that the design of the conservation proposal has not been optimal and will present ecological limitations (Andrade, 2007).

This research aims to assist in the development of an effective management model for the new conservation area, highlighting the ecological challenges it will encounter from the outset. It emphasizes the importance of using geographical tools and principles of landscape ecology, suggesting that management based solely on political criteria or land-use rights is no longer sustainable. Instead, the focus should shift to the role of science and research. Political decisions alone cannot create protected areas across different government levels; these efforts must be supported by substantial technical expertise, which academia can uniquely provide, though it is often undervalued in conservation management processes. Moreover, this presents an opportunity to incorporate new methodologies into regional planning processes and strategies. An ecosystem approach, among others, can bolster regional efforts to combat climate change, conserve biodiversity, and address desertification and drought, thus significantly enhancing territorial management and development.

5. Conclusion

The deficiencies of the proposed new conservation area for conserving the Lomas and Tillandsial ecosystems in the Tacna Region have been demonstrated. The shape, border, size, and area of the area indicate that the methods used to delimit its polygons (technical land use criteria and consideration of the limits of preexisting rights) are inadequate and that conservation will not be effective. This highlights the need to develop a suite of geographic tools to enhance the design of protected areas. These tools have been used to evaluate their effectiveness.

Given these geographic limitations and the fact that the creation process is progressing slowly with the competent national authority, it is proposed that this protected area have a specific management model aimed at addressing the deficiencies identified. Its management must be regulated within the context of landscape ecology and its leading conservation indicators and objectives: restoring irregularity, complexity, and connectivity with the natural ecosystem. This is undoubtedly a complex task for its administrator and strategic partners and one in which technical considerations prevail over political criteria.

Research institutions, such as universities and specialized institutes, are excellent sources of scientific information. They can help ensure the conservation of the Lomas and Tillandsiales of the coastal desert. However, they must be articulated and considered in the management committees of protected areas or in the mechanisms of administration contracts. The results of their research must be increasingly linked to the decisions made by public entities.

Acknowledgments

The authors would like to acknowledge the Programa Nacional de Investigación Científica y Estudios Avanzados – PROCIENCIA of the Consejo Nacional de Ciencia y Tecnología - CONCYTEC for funding the research project "Conservation status of Lomas and coastal desert ecosystems and their importance in contributing to the sustainable development of the Department of Tacna" under Contract No° PE51082394-2023-PROCIENCIA. The authors also acknowledge the Universidad Privada de Tacna for its technical and administrative implementation of the project through Rectoral Resolution No. 1517-2023-UPT-R.

Furthermore, the development of the fieldwork and data collection was made possible thanks to the Authorization for Scientific Research purposes issued by the Servicio Nacional Forestal y de Fauna Silvestre – SERFOR through the Resolution Directorate N° 147-2023-MIDAGRI-SERFOR-DGGSPFFS-DGSPF.

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