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FRAGMENTATION, BIRDS, AND CONSERVATION OF THE *POLYLEPIS* FOREST IN SOUTHERN PERU

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ABSTRACT. In the southernmost Andean regions of Peru, Moquegua, and Tacna, close to Chile and Bolivia borders, large forest stands of *Polylepis* species are essential for the social, economic, and environmental functionality of six basins. However, the need for more knowledge about their ecology, limited conservation efforts, and insufficient technical capacities for territorial regulation could accelerate their structural and functioning deterioration. Using landscape ecology -interdisciplinary science shaped by geography and biology- we found that in four evaluated areas, the composition of birds (and therefore also the resources they use) is differentiated by the influence of landscape fragmentation. Only two protected areas were legally recognized in the region, but they were established to cover small and remote isolated territories, which makes it challenging to conserve them effectively. Due to the poverty conditions common among the local communities, extractive or pastoralist activities conducted in large areas can trigger higher forest fragmentation rates. Under these circumstances, the valuable ecosystem services in the study area would be permanently lost or maintained at high risk. Because of these risks, specific measures were proposed to improve the social-environmental management of the forest by implementing mechanisms aimed at generating sustainable economic benefits in a healthy environment and social peace.

Fragmentación, aves y conservación del bosque de Polylepis en el extremo sur de Perú

REUMEN. En los Andes del extremo sur peruano, Moquegua y Tacna, departamentos limítrofes con las Repúblicas de Chile y Bolivia, se distribuye un gran bosque de *Polylepis* importante para la funcionalidad social, económica y ambiental de seis cuencas hidrográficas. Sin embargo, su escaso conocimiento ecológico, los pocos esfuerzos para conservarlo y las insuficientes capacidades técnicas de regulación territorial podrían facilitar la degradación de su estructura y funcionamiento. Utilizando la ecología del paisaje -ciencia interdisciplinaria conformada por la geografía y la biología-, se ha demostrado que en cuatro zonas evaluadas la composición de aves (y por ende también de los recursos que ellas utilizan) es muy diferente por influencia directa de la fragmentación encontrada. Esta circunstancia se vuelve sumamente clave para lograr una adecuada conservación, ya que, si las actividades extractivas otorgadas en grandes extensiones o las comunidades campesinas, a causa de sus altos niveles de pobreza, fragmentaran el bosque, o peor aún, si se mantuvieran las dos áreas protegidas reconocidas de forma aislada y de tamaño insuficiente, la coyuntura sería crítica y los valiosos servicios ecosistémicos del área de estudio se encontrarían permanentemente en alto riesgo. Se proponen, pues, medidas para mejorar la gestión socioambiental del bosque implementando mecanismos orientados a generar beneficios económicos sostenibles en un entorno saludable y de paz social.

Keywords: Landscape ecology, protected areas, sustainable development, Moquegua, Tacna.

Palabras clave: Ecología del paisaje, áreas protegidas, desarrollo sostenible, Moquegua, Tacna.

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1. Introduction

Polylepis, a tree and shrub genus endemic to the South American Andes, is a unique entity. Its twenty-seven recorded species (Kessler and Schmidtlebuhn, 2006; Mendoza and Cano, 2011) form fragmented or relictual forests spanning Chile to Venezuela. These forests, found at altitudes ranging from 900 meters in Cordoba, Argentina, to over 5,000 meters in Sajama, Bolivia, and Tacna, Peru (Renison *et al.,* 2013; Franco *et al.,* 2021), boast the highest levels of diversification in Peru and Bolivia (CDC UNALM, 2006; Zutta and Rundel, 2017). However, due to their territorial overlap with diverse human populations, they have become one of the most threatened Andean ecosystems (Cuyckens *et al.,* 2016).

The southern Peruvian Andes tends towards aridity, corresponding to units 7, 8, and 9 of the regionalization of rainfall on the Pacific slopes with an accumulated annual rainfall below 400 mm according to the classification by Rau *et al.* (2017). These arid environments constitute the primary habitat for three of the nineteen identified at the national level (Mendoza and Cano, 2011). These are the more water-stress-resistant species belonging to the genus. Its mostly fragmented forests (Kessler, 2002 and Rada *et al.,* 2009) can play a significant water-regulation role within the basins declared in the water emergency from 2007 onwards, making them unique plant formations essential in the extreme southern Peruvian corridor (Moquegua and Tacna regions) bordering Chile and Bolivia. Regrettably, there are still gaps in information on its cultural, environmental, and economic values, as well as very few conservation efforts, reflecting weak environmental management and conservation regulations. That is particularly critical in a region that maintains high levels of extreme poverty, constituting a significant risk in implementing measures to ensure sustainable development.

Given the critical state of *Polylepis* forests and their potential impact on sustainable development, it is proposed to conduct a comprehensive evaluation. This evaluation will focus on the relationship between bird composition and *Polylepis* forest fragmentation, using the principles of landscape ecology. The study will be conducted in four different areas, and the state of conservation of these forests will be geographically evaluated. Public policies will be rigorously analyzed, and a series of changes will be proposed to ensure these ecosystems are properly managed and contribute to sustainable development.

2. Methodology

2.1. Delimitation of the study area

To delimit the study area, vector geographic layers were downloaded from various sources of information: i) the spatial coverage of the *Polylepis* forest (Franco *et al.,* 2021; MINAM, 2018; Pacheco *et al.,* 2019), ii) the cartographic representation of watersheds and human activity (Regional Government of Tacna, 2023), and iii) the polygons representing the boundaries of the Andean and Puna ecoregion of the departments of Moquegua and Tacna (CDC UNALN, 2006). All this information were all loaded and processed in the QGIS software (QGIS Development Team, 2023). With the cutting and editing tools, each fragment of the forest formed an evaluation zone, based on its geographical position and representation in one of the six watersheds or by its proximity to other larger fragments with which they could be interacting.

2.2. Calculation of fragmentation indices, bird composition and correlation

Each of the *Polylepis* forest zones, delimited within the study area, was individually subjected to the calculation of its fragmentation indices, using the Patch Analyst Tools v5.2 extension (Rempel *et al.,* 2012). This was initially programmed to perform the calculation at the level of each fragment and obtain the values of its areas, perimeters, shape indices (SI), perimeter-area ratio (PAR) and Fractal Dimension (FD), indicating their complexity and irregularity. With the results, a similarity analysis of each zone was performed using the R software (R Core Team, 2020).

Next, the Patch Analyst Tools were programmed to calculate the values of fifteen fragmentation indices at the landscape level (set of fragments that make up a delimited forest area). Of these, five indices represent the evaluation of the shape of the fragments: MSI (average of the shape index), MPAR (average of the perimeter-area ratio), MPFD (average of the Fractal Dimension), AWMSI (weighted average of the average of the mean of the shape) and AWMPFD (weighted average of the mean of the fractal dimension of the patches). Three are related to the edge: TE (total edge), ED (edge density), and MPE (average of the edge). Five are linked to size and density: MPS (mean fragment size), MedPS (median size), PScoV (coefficient of variation of fragment size), PSSD (standard deviation, fragment size). Finally, two indices are representative of the area: TLA (the index of the total area of the landscape) and CA (class area).

As a next step, it was necessary to determine the composition of birds in each of the delimited forest areas; for this, we used the ornithological sighting records, obtained in the field between 2018 and 2023, during the trips made by the research team. The technique of transects of at least one kilometer of walking per counting point and the corresponding photographic record were applied. At least five transects of ten (10) fixed counting points with a radius of 25 meters were used in each. All the birds observed in each area were recorded and with the help of a camera, tripod and binoculars, the respective geographical coordinates were also noted (Franco *et al.,* 2020). To complement the information on the ornithological composition, bird watching records were downloaded from the eBird platform and database between 2010 and 2022 (eBird, 2021). With the geographical coordinates of the records, they were uploaded together to the QGIS to be edited, cut, and grouped according to the forest area to which they correspond.

In order to evaluate the existence of a direct relationship between fragmentation and the ornithological composition of the forest, it was first necessary to analyze whether the fragmentation indices at the landscape scale have a statistically significant autocorrelation, by constructing a correlation graph with Pearson's values (Taiyun and Simko, 2021) using the R software (R Core Team, 2020). The result of this analysis allowed us to know and select those fragmentation indices that predominate in each delimited forest area. For this purpose, together with the results of their ornithological composition, a non-metric multidimensional scaling (NMDS) was carried out to represent in each forest area the proximity between its set of birds and the indices that influence them (Hothorn *et al.,* 2008; Oksanen *et al.,* 2022).

2.3. Assessment of the conservation situation of the Polylepis forest

To evaluate the situation of forest conservation, official geographic information was downloaded from various sources, mainly related to the current use of the territory: i) the cartography of protected areas and priority sites for conservation (SERNANP, n.d.) that indicated how much area is currently conserved and how much potential it has for the future; (ii) the mining and peasant community cadastre from the GEOCATMIN -Geological and Mining Cadastral Information System (Hanco, 2010)- with which it was possible to determine the forest territory that is involved in current and future mining operations and which peasant communities are the own large plots of land; and (iii) the Provincial and District Monetary Poverty Map 2018 (INEI, 2020), which has been an important and conditioning factor for the conservation of biodiversity (Fisher *et al.,* 2005). This cartography was subjected to a superposition process with that of the *Polylepis* forest using the QGIS software for calculations.

3. Results

The study area corresponding to the *Polylepis* forest of the departments of Moquegua and Tacna, in the extreme south of Peru, ecoregions of the central Andes and the puna, was delimited (Fig. 1a). Based on the geographical distribution of the six watersheds, four areas of *Polylepis* forest were delimited: the Tambo basin, the Ilo Moquegua basin, the Maure basin and, finally, an area formed by the grouping of forest fragments located in the three basins on the Pacific slope of the department of Tacna: Locumba, Sama and Caplina basins, called VPTCQ (Fig. 1b).

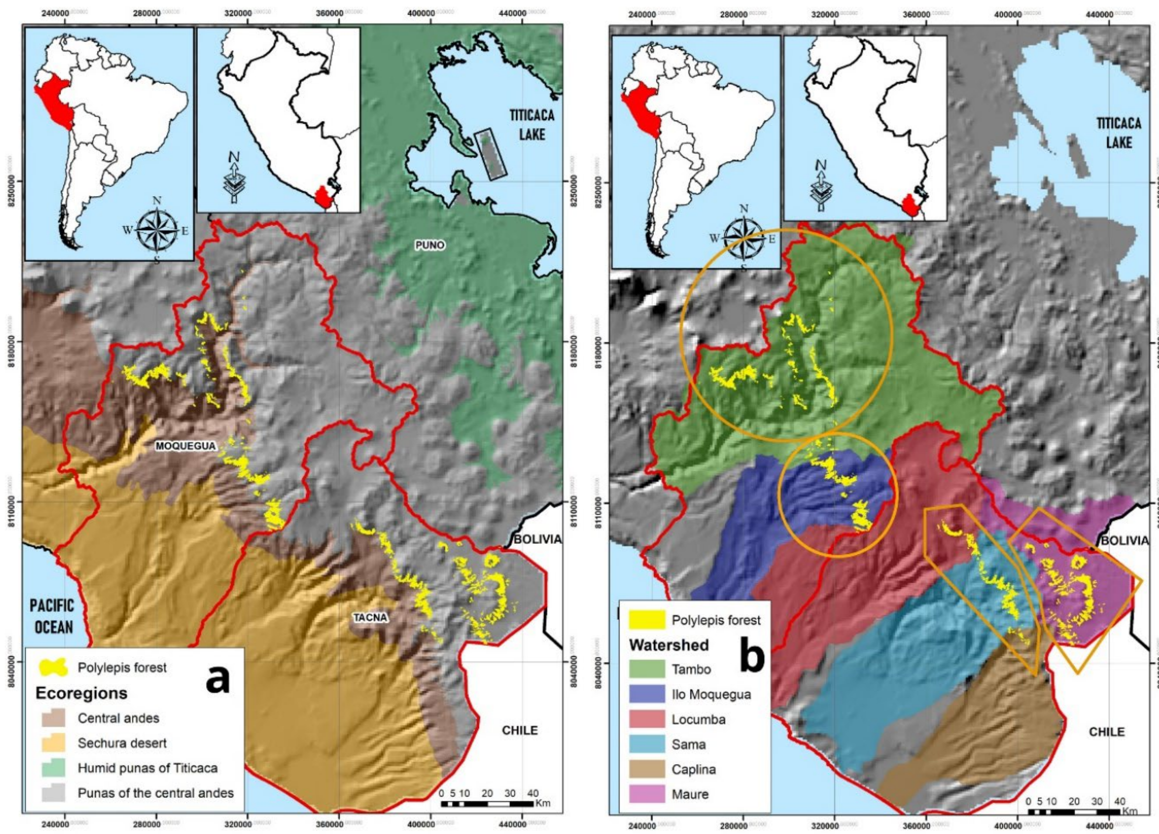

Figure 1. a) The yellow polygons represent the distribution of the Polylepis *forest in the Central Andes ecoregions and in its Punas; b) The large orange polygons show the four areas of* Polylepis *forest whose level of fragmentation and bird richness were determined in their respective watersheds (Source: CDC UNALM, 2006; El Peruano, 2013).*

Four indices (perimeter, PAR, SI and FD) were calculated for each of the forest fragments in their respective zone and the results of the statistical similarity analysis are presented in Figure 2, in which it is possible to observe that the area forest of the Tambo basin presents significant differences with the other areas studied in three of the four indices calculated: the perimeter (P) is larger, the shape index (SI) is larger, and the perimeter-to-area ratio (PAR) is similar to the others, indicating its fragments are larger and more irregular than the rest. However, at the level of fractal dimension (FD) (complexity) it is the fragments of the VPTCQ zone that show very significant differences: they are smaller than Tambo, similar to Ilo Moquegua and Maure, but with less complexity than all the others.

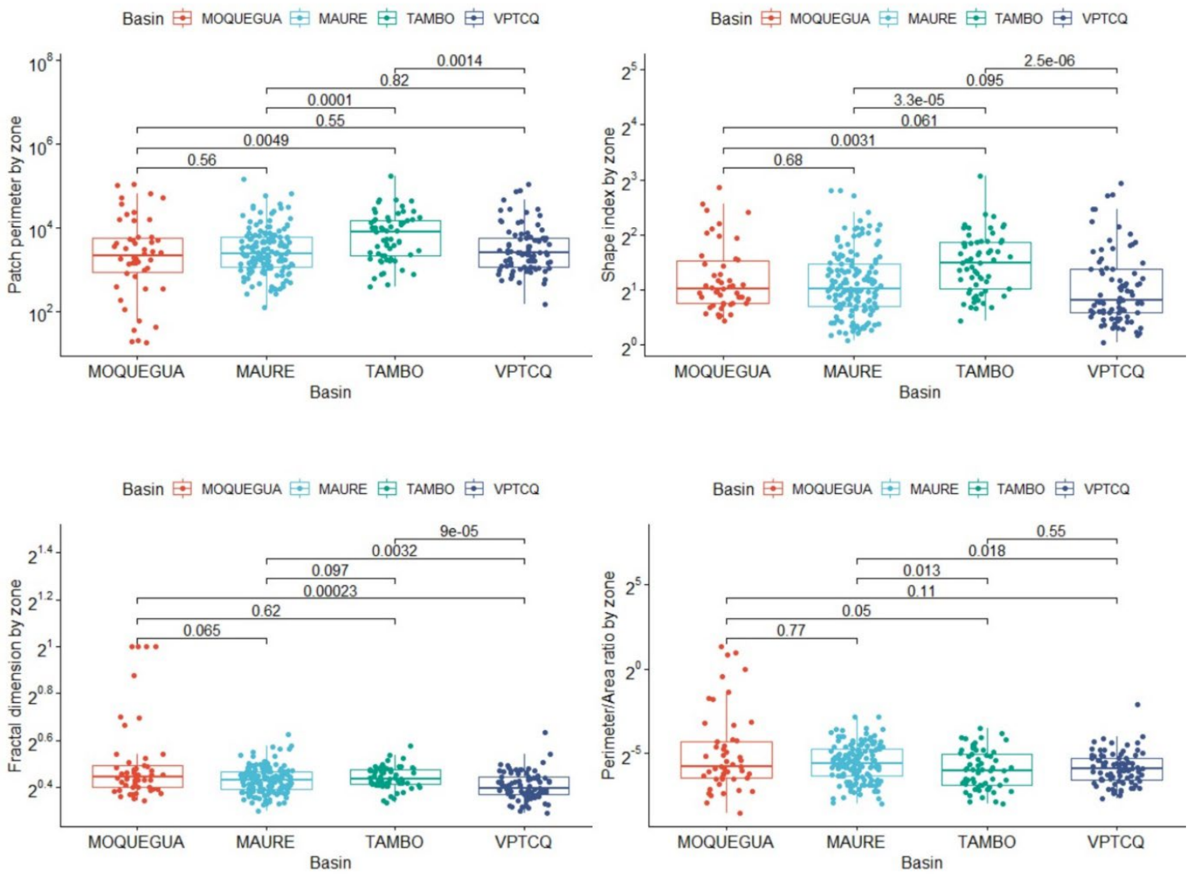

Figure 2. Statistical analysis of the shape of Polylepis *forest by each zone, comparing the existence of significant differences in the variables: Perimeter, Shape Index and Fractal Dimension.*

Table 1 also shows the values of the fifteen fragmentation indices calculated for each forest area, showing their differences and variations. These indices are multidimensional and lack the same unit of measurement but are related to the morphometric characteristics of the forest area studied.

Regarding the richness of bird species, according to Table 2, a total of 765 records were obtained, which were geographically distributed as follows: 432 records in the Ilo Moquegua basin, with 71 species, 64 records in the Tambo basin, with 33 species, 142 records in Maure, with 45 species, and 127 records in VPTCQ, with 50 species. Figure 3 presents the distribution map of bird species records within each *Polylepis* forest area, as well as some photographs of the most emblematic birds taken by the research team during field work.

Table 1. Landscape-level fragmentation indices of the four Polylepis *forest zones.*

TYPE	INDEX	PATCH			
		Tambo Basin	**Ilo Moquegua Basin**	**Maure Basin**	**VPTCQ Basins**
FORM	AWMSI	5.04	5.06	4.66	5.14
	MSI	2.99	2.53	2.38	2.30
	MPAR	218.71	2,008.77	281.53	225.09
	MPFD	1.36	1.43	1.35	1.33
	AWMPFD	1.35	1.35	1.35	1.36
EDGE	TEA	836,771.39	597,095.13	990,727.86	684,198.71
	ED	69.08	56.75	77.44	84.23
	MPE	13,717.56	11,941.90	6,880.05	8,446.90
DENSITY SIZE	MPS	198.59	210.42	88.84	100.28
	NumP	61.00	50.00	144.00	81.00
	MedPS	60.98	14.89	13.10	15.37
	PSCoV	240.91	264.32	378.66	261.10
	PSSD	478.42	556.17	336.41	261.82
AREA	TLA	12,113.83	10,520.79	12,793.29	8,122.61
	AC	12,113.83	10,520.79	12,793.29	8,122.61

Table 2. Official list of bird species recorded in the Polylepi*s forest patches according to our own records from 2018 to 2023 and those obtained in EBIRD from 2010 to 2022.*

Number scientific	IUCN-2023	SPECIES	IUCN-2023	SPECIES	IUCN-2023
Aeronautes andecolus	LC	*Geranoaetus melanoleucus*	LC	*Phalcoboenus megalopterus*	LC
Agriornis albicauda	VU	*Geospizopsis plebejus*	LC	*Polioxolmis rufipennis*	LC
Agriornis montanus	LC	*Geospizopsis unicolor*	LC	*Phrygilus atriceps*	LC
Anairetes flavirostris	LC	*Leptasthenura aegithaloides*	LC	*Phrygilus punensis*	LC
Anairetes reguloides	LC	*Leptasthenura striata*	LC	*Psilopsiagon aurifrons*	LC
Asthenes dorbignyi	LC	*Lessonia oreas*	LC	*Pygochelidon cyanoleuca*	LC
Asthenes modesta	LC	*Metallura phoebe*	LC	*Rhea pennata*	VU
Asthenes pudibunda	LC	*Metriopelia aymara*	LC	*Rhopospina fruticeti*	LC
Attagis gayi	LC	*Metriopelia ceciliae*	LC	*Saltator aurantiirostris*	LC
Cathartes Aura	LC	*Metriopelia melanoptera*	LC	*Sicalis lutea*	LC
Catamenia analysis	LC	*Muscisaxicola albifrons*	LC	*Sicalis olivascens*	LC
Catamenia inornata	LC	*Muscisaxicola capistratus*	LC	*Sicalis uropygialis*	LC
Cinclodes albiventris	LC	*Muscisaxicola cinereus*	LC	*Spinus atratus*	LC
Cinclodes atacamensis	LC	*Muscisaxicola flavinucha*	LC	*Spinus crassirostris*	LC
Circus cinereus	LC	*Muscisaxicola frontalis*	LC	*Spinus magellanicus*	LC
Colaptes rupicola	LC	*Muscisaxicola juninensis*	LC	*Spinus uropygialis*	LC
Hummingbird coruscans	LC	*Muscisaxicola maclovianus*	LC	*Systellura longirostris*	LC
Conirostrum binghami	NT	*Muscisaxicola maculirostris*	LC	*Thinocorus orbignyianus*	LC
Conirostrum cinereum	LC	*Muscisaxicola rufivertex*	LC	*Tinamotis pentlandii*	LC
Conirostrum tamarugense	LC	*Nothoprocta ornata*	LC	*Troglodytes aedon*	LC
Diglossa brunneiventris	LC	*Ochetorhynchus ruficaudus*	LC	*Turdus chiguanco*	LC
Falco femoralis	LC	*Ochthoeca leucophrys*	LC	*Upucerthia albigula*	LC
Falco peregrinus	LC	*Ochthoeca oenanthoides*	LC	*Upucerthia validirostris*	LC
Falco sparverius	LC	*Oreotrochilus estella*	LC	*Vultur gryphus*	VU
Geositta cunicularia	LC	*Orochelidon andecola*	LC	*Zenaida auriculata*	LC
Geositta punensis	LC	*Passer domesticus*	LC	*Zonotrichia capensis*	LC
Geositta tenuirostris	LC	*Patagioenas maculosa*	LC		
Geranoaetus polyosoma	LC	*Patagonian gigas*	LC		

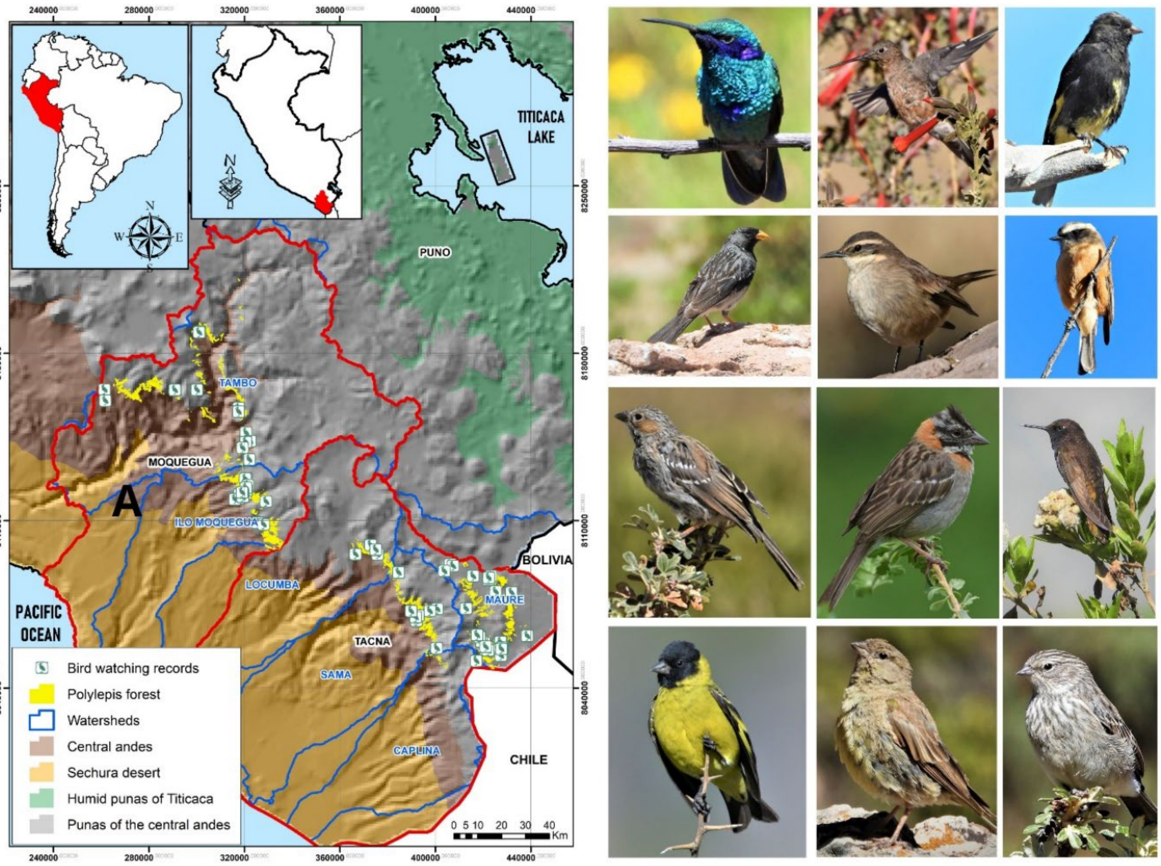

Figure 3. Geographic distribution of bird composition in the four evaluated areas of the Polylepis *forest in the extreme south of Peru. On the right, you can see emblematic birds photographed during the research team's excursions.*

The correlogram in Figure 4 represents the autocorrelation that exists between the fourteen fragmentation indices calculated for each zone, clarifying that in this analysis the CA or area class was not considered, because the research is based on a single vegetation class. The number of asterisks represents the level of correlation (high or low) and the intensity of the color, the sense of color, positive or negative values, which allowed us to select the MSI, MPAR, AWMPFD, TE, ED, MPS, NumP and MedMPS as the most representative.

With all these data, the bidirectional NMDS of Figure 5 was elaborated, in which the black dots and text represent the four evaluated forest areas, the green text indicates the most representative bird species of their composition, and the blue arrows and letters represent the intensity of the influence that the fragmentation indices have on the bird composition. This statistical distribution indicates differences in the composition in the four forest zones, with the Ilo Moquegua and VPTCQ (or VP Tacna) basins being similar to each other, with species that are repeated in their respective records, unlike Maure which has a different composition, where a single species, *Rhea pennata*, predominates, as well as Tambo, where *Circus cinereus* predominates. It is also possible to observe that the blue arrows represent the intensity of the influence of the fragmentation indices on the composition, whose numerical values are presented in Table 3. It is observed that one of the shape indicators, the MPAR, greatly influences the composition of birds in the forest of the Ilo Moquegua basin, while the AWMPFD is important in the basins of the Pacific slope of Tacna or VPTCQ. In the forest of the Maure basin, one of the indicators of fragment density, NumP, mainly influences bird composition, but it also shares with Tambo an important influence of the TE or total edge indicator. In Tambo, the influence of four indices is observed, but of different types: in the shape by the MSI, in the size by the MedMPS and the MPS, and partially in the border with the TE.

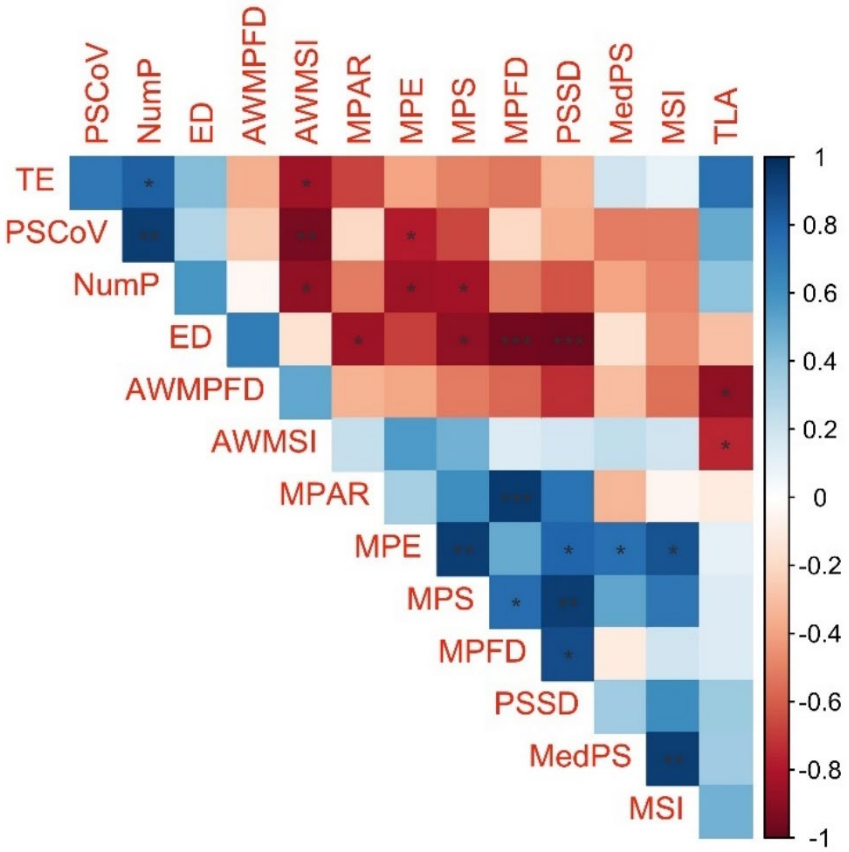

Figure 4. Correlogram developed to determine the autocorrelation of the fragmentation indices calculated for each forest area. The number of asterisks represents the correlation level that exists between the indices (high or low) and the color intensity characterizes the sense of correlation (positive or negative).

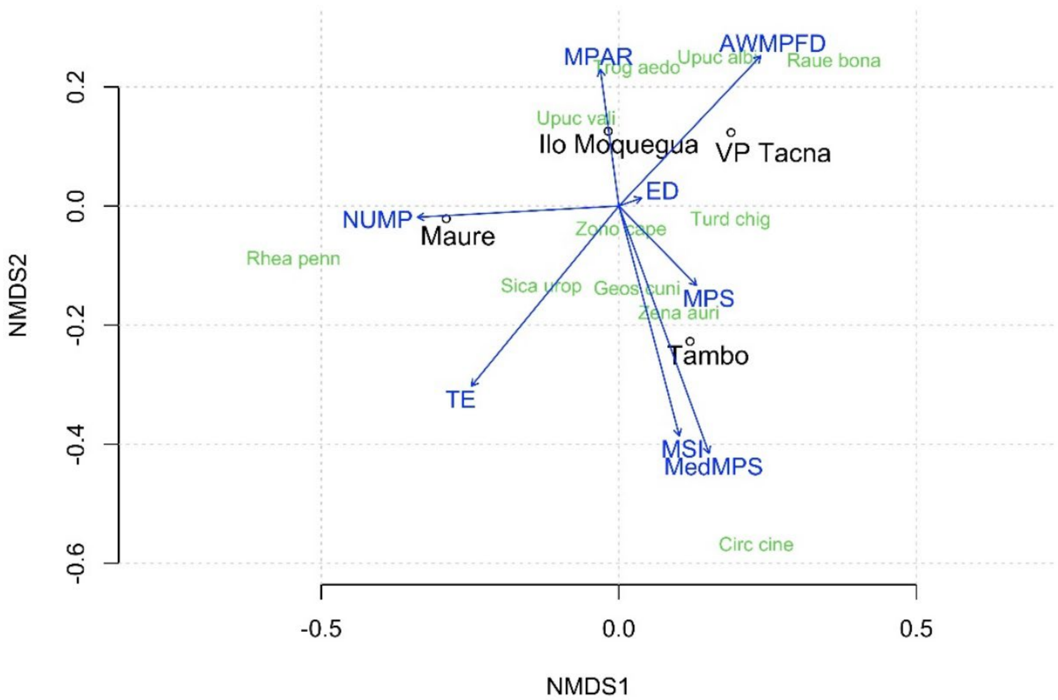

Figure 5. Bidirectional NMDS analysis regarding the influence of fragmentation indices (blue) on bird composition (green) by forest area assessed (black).

Table 3. Fragmentation indices together with the level of influence on bird composition in the Polylepis *forest.*

FRAGMENTATION INDEX	NMDS1	NMDS2
MSI	0.2547	-0.9670
MPAR	-0.1344	0.9909
AWMPFD	0.6872	0.7265
TEA	-0.6339	-0.7734
ED	0.9437	0.3308
MPS	0.6995	-0.7146
NUMP	-0.9985	-0.0556
MedMPS	0.3429	-0.9394

Table 4 shows how the *Polylepis* forest area in the extreme south of Peru has been occupied, clearly observing that only 3.09% is within a protected area administered by the governing body, SERNANP, through the Salinas and Aguada Blanca National Reserve and its buffer zone located in the Tambo basin. 10.88% is located within a Regional Conservation Area administered by the Regional Government of Tacna in the Maure basin. Thus, the preserved areas add up to approximately 14% of the total *Polylepis* forest. The remaining 86% corresponds to non-conserved territories with different types of use and tenure, as shown in Figure 6.

Table 4. Diagnosis of the current use of the territory of the Polylepis *forest.*

CONDITION	TYPE OF USE	OWNERSHIP	SURFACE (Km^2)	%
Not Preserved	Mining Operation Units	Public Land	1.62	0.37
		Land of Peasant Communities	1.55	0.36
	Livestock Activity	Of Peasant Communities	239.58	55.01
	Barren Lands	Public Land (no other vested rights have been assessed)	131.91	30.29
Preserved	ACR	Public and Peasant Communities	47.40	10.88
	ANP	Public and Peasant Communities	13.45	3.09
TOTAL			435.51	100.00

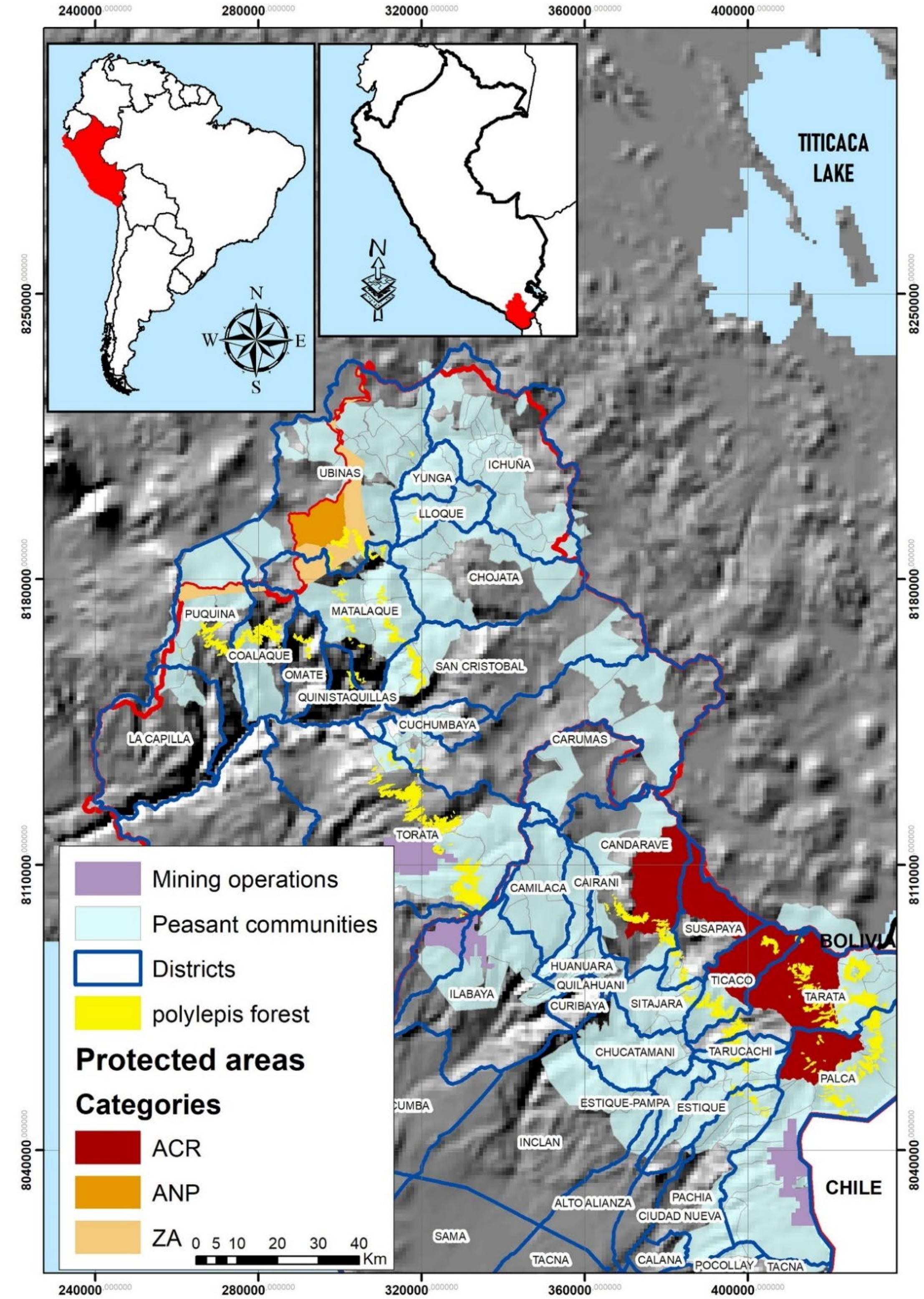

Figure 6. Geographical distribution of the Polylepis forest at the district level, peasant communities, mining operations and protected areas of different categories (national or regional).

Likewise, using the graphic base of the priority sites for conservation (SPC) of the regions of Moquegua and Tacna, represented in Figure 7, it is observed that there are eight large polygons (represented in fuchsia), which have been studied, delimited, and recognized -by its authorities and in their maximum territorial planning documents- as future protected areas. However, the technical processes for establishing an effective conservation modality have not been initiated for more than ten years. In these polygons, there are 192.53 km^2 of *Polylepis* forest, with enormous potential to be conserved and adequately managed, which would increase its surface within protected areas by more than 40%, as presented in Table 5.

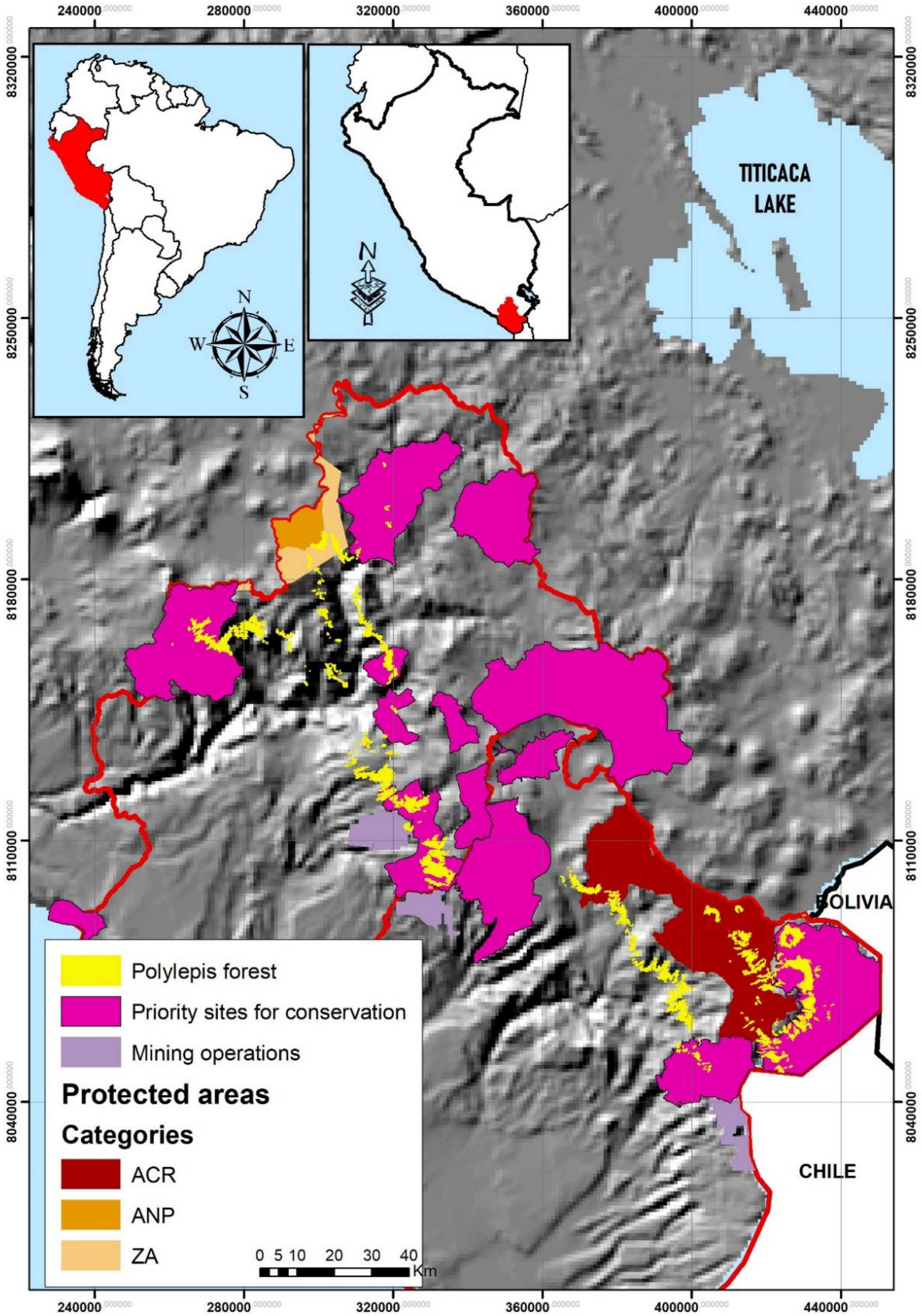

Figure 7. Distribution of priority sites for conservation projected and recognized by the regional governments of Moquegua and Tacna since 2013, but without technical processes initiated.

Table 5. Surface area and stakeholders that would be linked through future conservation modalities through the diagnosis of the Priority Sites for conservation recognized by the Regional Governments of Moquegua and Tacna since 2013.

Department	**Priority Site for Conservation**	**Actors**				**Area (Km^2)**	**% Conservation Potential**
		Interior of Mining Operations	Close to mining operations	Peasant communities	State		
Moquegua	Queñual de Muylaque	No	0.00	11.47	0.04	11.51	2.64
Moquegua	Chilata	No	0.00	4.35	17.52	21.87	5.02
Moquegua	Ticsani Valley	No	0.00	1.03	0.07	1.10	0.25
Moquegua	Upper Tambo Valley	No	0.00	2.29	0.00	2.29	0.53
Moquegua	Queñoal de Arondaya and Cuellar	Yes	1.68	38.38	25.66	65.72	15.09
Tacna	Upper Caplina Basin	Yes	0.00	4.35	0.00	4.35	1.00
Tacna	Bajo Candarave	Yes	0.00	0.02	0.00	0.02	0.01
Tacna	Upper Peru Tripartite	Yes	0.00	85.28	0.37	85.65	19.67
TOTAL			1.68	147.18	43.67	192.53	44.21

Finally, it was determined that the geographical distribution of human poverty is sectorized and extends to all the Andean and high Andean districts of the departments of Moquegua and Tacna, with a maximum percentage of 54.7% as shown in Figure 8. Overlapping with the areas of the *Polylepis* forest, high poverty values are obtained, such as those included in Table 6, making it clear that this natural wealth is found in the poorest districts of both departments, especially in the forests of the Maure basin. The same occurs in the other areas evaluated as illustrated in Figure 9.

Table 6. Status of human poverty and forest area of Polylepis for each area studied.

Maure		**Shelter**		**VPTCQ**		**ILO MOQ**	
% Poverty	Km^2	% Poverty	Km^2	% Poverty	Km^2	% Poverty	Km^2
44.1	6.94	17.3	4.64	32.1	3.85	8.3	2.29
37.7	54.39	11.1	4.91	20.4	4.34	8.1	0.15
43.8	66.61	23.6	51.06	33.8	18.78	11.2	5.08
		31.2	17.35	36.3	3.72	31.7	97.48
		35.3	1.17	37.7	15.93	35.3	0.21
		44	27.76	38.9	24.12		
		54.7	14.24	43.8	10.48		

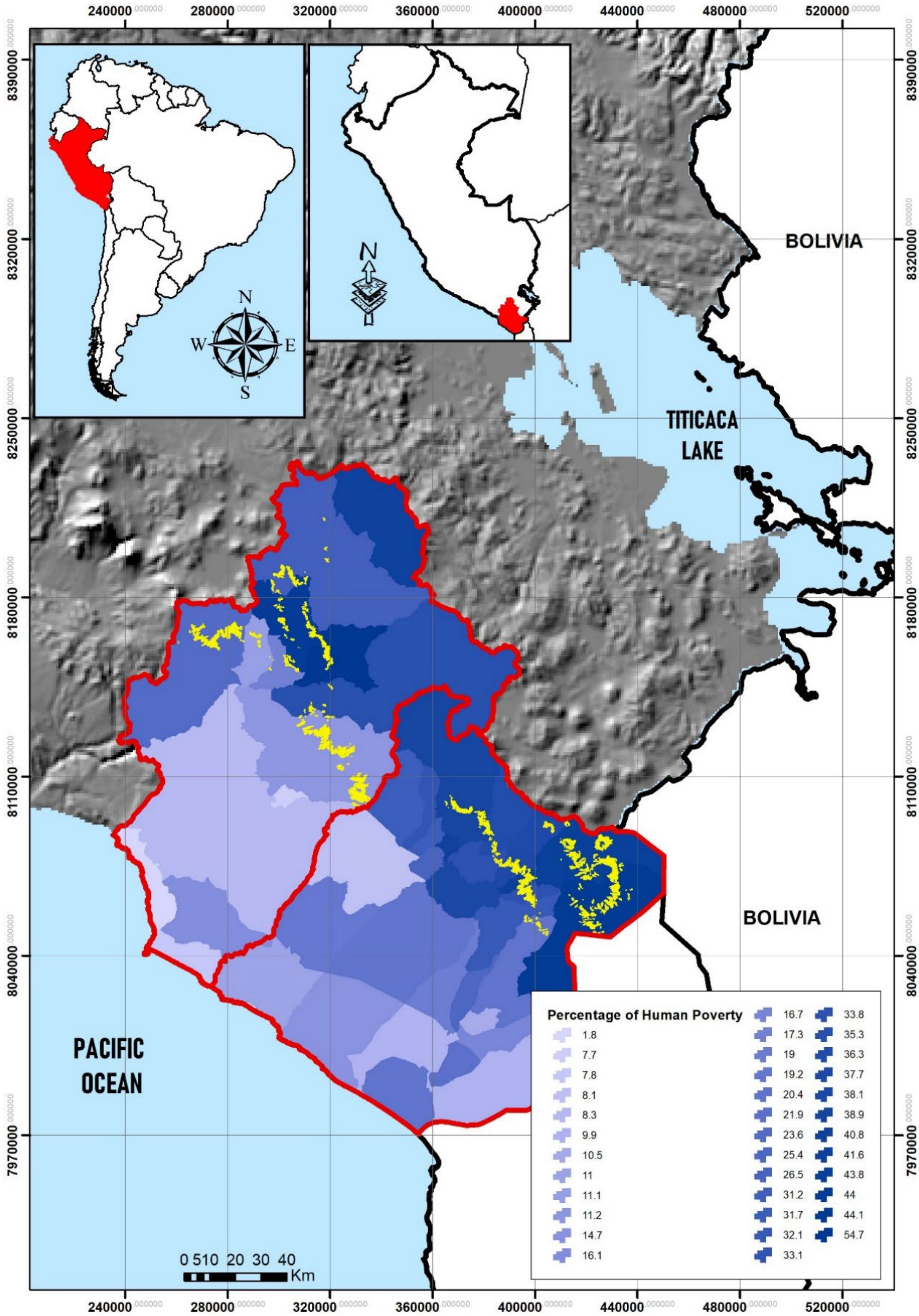

Figure 8. Map of the percentage distribution of human poverty by district and its overlap with the Polylepis *forest.*

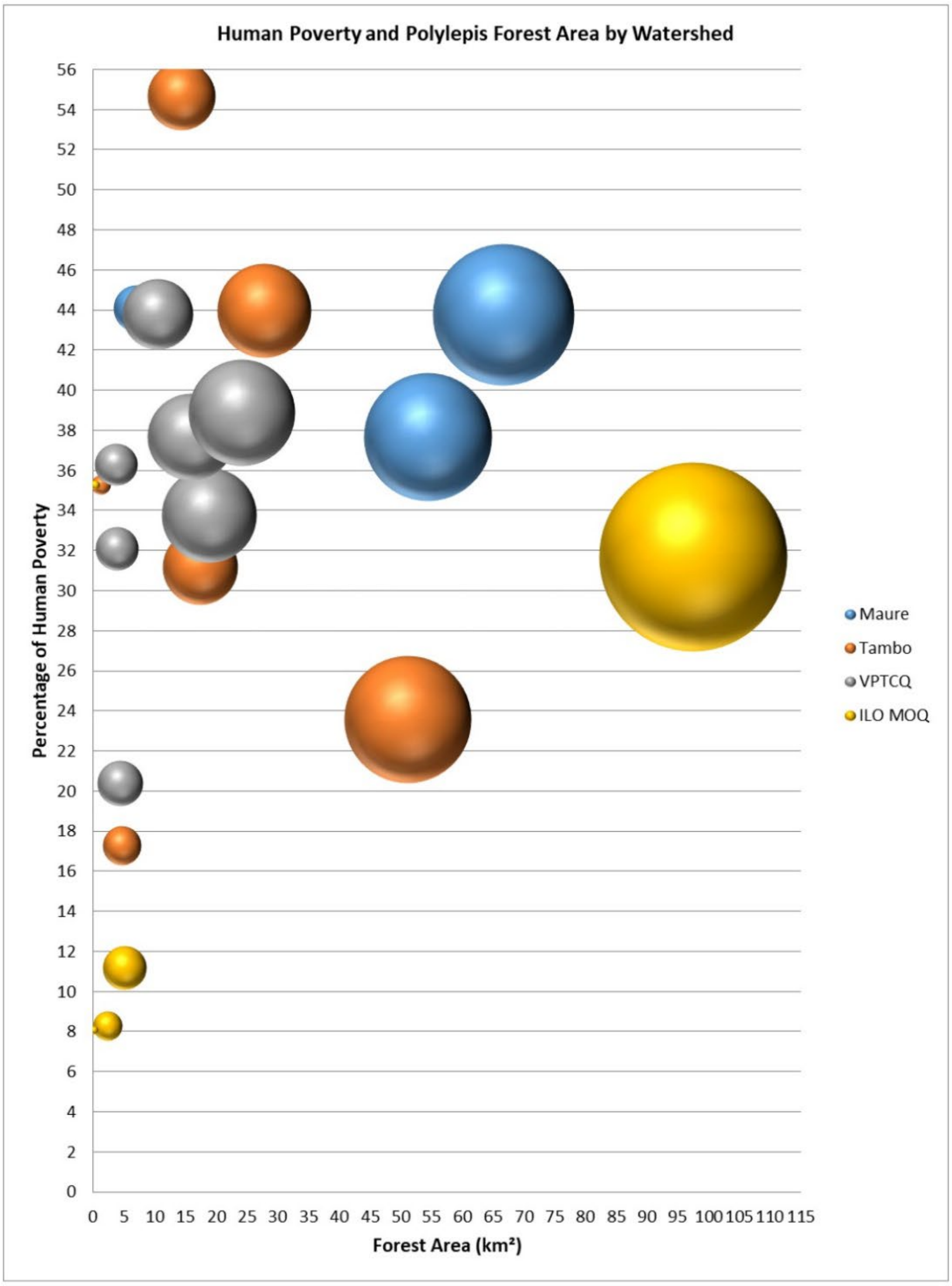

Figure 9. Distribution of the Polylepis forest according to the percentage of poverty in the evaluated areas, where the radii of the colored bubbles represent the area (km^2) of the Polylepis forest.

4. Discussion

At a global level, fragmentation is associated with processes that generate a negative impact on the natural vegetation cover and severe modifications in the structure of the landscape since it separates ecological units that have functioned efficiently for years and that become increasingly smaller and isolated with the transformation of their shape, edge, and areas (Fahrig, 2003; McGarigal and Cushman, 2002; Navarro *et al.,* 2021; Rodríguez-Etcheverry and Leiton, 2021; Shooshtari *et al,* 2018). The effects on ecosystems are adverse by endangering the normal development of the matter and energy flow, hydrological regimes, ecological processes, and abundant resources, among others (Uezu *et al.,* 2005; Kattan and Murcia, 2003). At the Latin American level, several researchers in native, dry, or tropical forests (Strap *et al.,* 2012; Lozano *et al.,* 2011; Mas and Correa, 2000) agree on the negative impact that fragmentation has had on their studied landscapes. However, fragmentation is an intrinsic condition for

Polylepis forests, also known as a relict, due to their natural dispersal (Simpson, 1979; Gareca *et al.,* 2010). Indeed, this will not be the same level for all *Polylepis* species and their corresponding forest formations. Where greater climatic and ecological stability have been generated over long periods, endemic and highly specialized species have developed, such as birds (Fjeldsa *et al.,* 2012).

Previous studies have considered these forests in Peru as a relict since, in most cases, the sizes of their fragments reach 0.02-0.03 km^2. Only in the central zone of Peru do they reach 0.5 km^2 (Simpson, 1986). The PSSD indicates that, in this part of the Peruvian territory, in the extreme south, bordering Chile and Bolivia, the smallest fragments are found, corresponding to the basins of the Pacific slope of Tacna. VPTCQ has a size of 261 m^2, the Maure basin 378 m^2, Tambo 478 m^2, and Ilo Moquegua 556 m^2. It is important to note that topographic relief plays a fundamental role in this type of distribution.

Despite the size of the forest fragments, each area evaluated has an essential and particular composition of birds that, as demonstrated by the statistical analysis, is influenced by forest fragmentation, especially by the eight indices presented in Table 3. Santos and Telleria (2006) also consider four fundamental factors in determining, calculating, or representing the fragmentation of natural ecosystems: MPS, NumP, ED, and TE. They also consider CA or class area, but this index has been removed from our analysis because the research has been based on evaluating a single vegetation class, the *Polylepis* forest.

This agrees with what was described by Valente and Betts (2019), who concluded that the composition of bird communities changes with a smaller fragment size. However, it cannot be generalized for the entire *Polylepis* forest analyzed. There are three marked compositions of birds in the four areas evaluated. The first is the forest area of the Ilo Moquegua basin and the VPTCQ basins, influenced by the shape indices of the fragments, representing regularity and complexity. The second composition is found in the forest of the Maure basin, influenced by the density indices of the fragments and partially by the edge indices. A third composition of birds is observed in the Tambo basin, influenced by size and shape indicators and moderately by edge indicators. For this reason, the forests of the extreme south of Peru are very particular, and their bird composition is based on the size of the fragments and the shape and edges.

These latter researchers recommend as a priority conserving the large forest fragments, which, applied to this study, should be those corresponding to the Tambo Ilo and Moquegua basins, as indicated in Figure 2. However, small and complex fragments, such as those of VPTCQ, should also be prioritized with conservation measures due to their particular ornithological composition or endemism (Fjeldsa, 2002; Renison *et al.,* 2018). The aim is to make its importance visible and improve its conservation level, as Sevillano et al. (2019) presented.

Therefore, it is essential to link geographical and statistical knowledge with the conservation of the biodiversity of the *Polylepis* forest in the extreme south of Peru. It is worrying that these forests are minimally represented within the Peruvian conservation system and that they contribute minimal territorial area to the total managed as protected natural areas (17%) and to the fulfillment of Aichi goal 11 by 2030, represented mainly by Amazon ecoregions (SERNANP, s.f.). As shown in Figure 5, the only two protected areas in our study area need to be increased. They are territorially isolated, not ecologically connected, and poorly articulated administratively, which would not guarantee efficient and effective conservation (Chassé *et al.,* 2021; Wiersma and Nudds, 2009). Furthermore, there is always the risk that anthropogenic activity can generate profound and irreversible impacts, for example, by constructing roads or highways that can increase their fragmentation and generate a biodiversity crisis (Rosselló and Lorenzo, 2017).

The need to implement innovative conservation management for the *Polylepis* forest is evident, with territorial connectivity between its areas through conservation corridors under different modalities (SERNANP, 2013), with different administrators, and with the political decision of its departmental authorities. The Regional Governments have not yet taken any decision or action in this regard despite having technical files of the priority sites for conservation that were prepared between 2011 and 2013 (Fig. 7). This could increase the conserved area by more than 40% and implement a decentralized, efficient, transparent, and sustainable conservation system (Azfar *et al.,* 2009).

Likewise, fragmentation must become a binding indicator in the management of *Polylepis* forests, which allows for regulating the environmental impact generated by constructing too linear or straight infrastructures. This modifies the MSI and other shape indices, causing the fragments to become more regular and harming biodiversity. Likewise, in forest areas where the composition of birds is primarily influenced by the size of the fragments, as is the case of the forest of the Tambo and Ilo and Moquegua basins, any work or infrastructure to be built must establish connectivity mechanisms to avoid ecological separation of the fragments and maintain their functioning as a single unit (Grilo *et al.,* 2011; Ministry of Agriculture, Food and Environment, 2015; Ministry of Environment and Rural and Marine Affairs, 2010). In short, these approaches establish essential ideas for the environmental management assumed by the Peruvian State and which are included in the current national legislation that regulates the evaluation of environmental impact based on qualitative study methods and which refer to fragmentation using as an indicator tangible the number of fragments or NumP (MINAM, 2011) and ignoring the other relevant indicators.

Paradoxically, in recent times, when essential territories are proposed to be declared protected areas, it is still a widespread practice to exclude areas under concession for mining and oil activities (with very linear forms) to avoid dialogue, authorizations, and consents between the sectors of the State. As a result, there are protected areas of linear polygons, very regular and with minimum sizes that, at first glance, could be more useful for adequate conservation management (Andrade, 2007). It is therefore necessary to change focus and adopt new concepts such as sustainable mining or productive extractive activities linked to conservation (ECLAC, 2019). It is also essential to question the technical information used to delimit current protected areas, such as the National Maps of Vegetation Cover and Ecosystems of Peru (MINAM, 2018; MINAM, 2015), which are not suitable for management at specific scales (Norgués, 2013).

Fragmentation not only limits forest conservation. The high poverty of the human populations that inhabit them (Fig. 7 and 8) also makes conservation options difficult (Fisher *et al.,* 2005). Therefore, Opportunities are required to develop their livelihoods and to transform the *Polylepis* forest into an effective tool for sustainable development, promoting close coordination between the multiple actors in the territory (Table 4). It is about achieving and replicating successful experiences (Álvarez and Shany, 2012; Amaya, 2020; Hernández *et al.,* 2018; Rivera *et al.,* 2008) through effective conservation mechanisms based on economic benefits, fragmentation, biodiversity, and ecosystem services. (Andrade, 2020, Secretariat of the Convention on Biological Diversity, 2004) with development opportunities for all public and private actors.

Therefore, within these innovative mechanisms, the establishment of modalities for using and conserving forest resources through concessions stands out (Law No. 29763, 2011). These will improve the forest conservation area and boost socio-economic development in the Andes and the Puna (Bergmann *et al.,* 2021; Saravia and Aguirre, 2019). However, some erroneous paradigms still need to allow us to understand the multifunctionality of forest heritage (Macdicken *et al.,* 2015). Forest zoning (ZF) is detained in the offices of the regional governments of the two departments. With it, it is still possible to grant forestry, conservation, ecotourism, and local municipal administration forest titles, among others. Likewise, the regional processes of identification and recognition of fragile ecosystems - other methods of ecosystem management that would help conserve the *Polylepis* forests of the extreme south of Peru - still need to be completed, paralyzed, or slowly managed.

5. Conclusions

The *Polylepis* forests in the departments of Moquegua and Tacna are essential to supporting the water stress of its six hydrographic basins caused by extreme climatic and geographical conditions. Although close to each other, the different areas of the forest present unequal fragmentation and avian composition. Inadequate conservation planning and management, added to extreme human poverty, are the main limitations that expose these forests to different pressures, threats, and permanent risks.

To guarantee forest conservation, increasing the surface area of protected areas is necessary, breaking with some erroneous paradigms that limit sustainable development and promoting new concepts and innovations that balance economic development and people's quality of life. In Chile, they achieved this by integrating betting activities into a healthy and protected natural environment. They built knowledge, concepts, and legal, technological, and social tools aimed at developing, for example, sustainable mining, achieving an articulated work of all productive sectors in favor of conservation.

In Peru, urgent regulatory changes and inter-institutional actions are required, but it is necessary to integrate conservation standards with mining procedures. Exploration and exploitation tasks must consider environmental management in their respective concession area. Many mining companies may oppose this because they need to gain experience in conservation. However, they can link up with specialized entities or associate with peasant communities that are already developing effective ecosystem conservation practices.

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