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Mammal Diversity on Conservation Islands in Protected Areas in Oaxaca, Mexico

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Abstract: Protected sites managed by indigenous people have been used for decades to conserve natural resources. These sites can be considered "conservation islands" and can maintain high biodiversity. This study explores the diversity and structure of medium and large mammals in (1) four protected natural areas in Oaxaca, Mexico, and (2) two different conservation strategies: one protected natural area (PNA) and three Voluntary Conservation Areas (VCAs). Data from 30 camera traps installed by community monitoring between 2013 and 2019 were used. A total of 29,304 camera days were accumulated in the Central Valleys and the Western Mountains and Valleys province. A total of 60,725 photographic records were analyzed, resulting in 13,471 independent events. Twenty-four species of wild mammals were documented, including endangered species. VCA showed higher species richness compared to PNA. *Odocoileus virginianus* was the most dominant in PNA, while *Dicotyles angulatus* was most dominant in VCA. We found differences in species richness between the four sites and between the two conservation strategies. Both conservation strategies are effective in maintaining mammal richness. We consider that these sites can serve as conservation islands that, in turn, can inter-connect landscapes and serve as potential biological corridors.

Keywords: Areas Destinadas Voluntariamente a la Conservación; camer traps; community-based monitoring; endangered species; jaguar; medium and large mammals

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1. Introduction

The accelerated transformation of forests in the American tropics has been a major concern both globally and locally for over three decades [1–4]. These ecosystems not only harbor a high diversity of species but also influence the climate through physical, chemical, and biological processes that affect the planet's hydrological and energy cycles, as well as atmospheric composition [5,6]. The destruction, degradation, and fragmentation of rainforests lead to the loss of various ecosystem services [7–9]. This negatively impacts the composition and structure of vegetation by disrupting the biological interactions that maintain their stability [10].

A key strategy to mitigate the impact on ecosystems and the loss of biodiversity has been the establishment of protected natural areas (PNAs), a measure used globally for decades and supported by federal official decrees [11,12]. However, despite the progress made, species extinction rates and habitat degradation continue at an alarming rate, especially in countries with high biodiversity like Mexico [13]. A more recent initiative for biodiversity conservation has been the establishment of Voluntary Conservation Areas (VCAs), which are considered goals within the Convention on Biological Diversity [14,15].

VCAs have been recorded in several countries worldwide [16,17]. In some Latin American countries, these areas are recognized and certified within governmental systems [18]; however, many of them face a lack of funding and information gaps regarding their management and operation [19].

In Mexico, particularly in the southern states of Oaxaca, Chiapas, and Guerrero, various rural and indigenous communities have chosen to voluntarily conservation areas of their territory to preserve ecosystem services and protect biodiversity [20]. This is performed through a mechanism called Areas Destinadas Voluntariamente a la Conservación (VCAs, Voluntary Conservation Areas), which allows landowners to certify their lands as conservation zones without the need for the state to acquire or expropriate them, thus promoting private and community participation in environmental protection [21].

The VCAs are not formally decreed nor managed by the federal government; their establishment and management depend on the commitment of the landowners. These areas are certified by the National Commission of Natural Protected Areas (CONANP), which provides them with institutional support and participation in broader conservation programs [22]. These initiatives cover variable forest extensions and aim to protect the most fragile natural environments. They are in areas that maintain high biological and cultural diversity, and it is common for them to host species that are classified under some risk category [23].

Particularly in the state of Oaxaca, the voluntary conservation of lands with official certification has grown significantly under the VCA conservation scheme, which complements the protection and conservation of natural resources outside the decreed PNAs. They are mainly distributed in the northern part of the state and in the Isthmus of Tehuantepec; however, they also exist in other areas such as the Pacific coast and the central region of the state [24,25]. Additionally, there are community conservation areas and rural reserves without official certification that serve the same function as the VCA [26]. As of 2023, Oaxaca had eight federally decreed PNAs, six state-level PNAs, and 158 VCAs, in addition to an undetermined number of Voluntary Conservation Areas without certification [24,27].

The VCAs have functioned as conservation islands that, collectively, could form archipelago-like reserves, as proposed by various authors [28–31]. Many of these sites provide essential refuge and resources for numerous species. Previous studies have shown that the VCA can maintain a high diversity of vertebrate organisms such as amphibians, reptiles, and birds [32,33]; however, they are surrounded by fragmented or degraded landscapes, so a thorough analysis is still required to fully understand their biological richness.

In this regard, CONANP has implemented community monitoring projects for vertebrate populations and communities in various regions of Oaxaca, both in PNA and VCA [34]. Community-based biodiversity monitoring (CBM) involves the participation of residents in data collection [35]. This local involvement increases the likelihood of conservation project success because it creates a sense of ownership among participants [35,36]. Additionally, it promotes local employment, increases human capital, and enhances tolerance to human–wildlife conflicts [37,38]. Therefore, CBM has become a tool that contributes to the generation of biological information, as observed in various studies [31,39]. It is important to mention that there are VCAs in the Physiographic Province of the Central Valleys near the city of Oaxaca (the state capital and the most populous city), which stand out for the participation of community monitors from the Zapotec and Mixtec ethnic groups. These monitors have been working in conservation for approximately ten years and have contributed to the generation of biological information [40].

One of the groups for which significant information has been generated through CBM is mammals. Medium and large mammals are key components of tropical biodiversity, playing crucial ecological roles such as seed dispersal, population control, and plant recruitment [41]. However, they face unprecedented threats due to hunting and habitat loss [42,43]. Two of the ecosystems that support diverse mammal species, including keystone species, are pine–oak forests and tropical deciduous forests [44,45]. The decline in wild mammal populations directly and indirectly impacts the ecosystem services they provide [46].

Given this, it is essential to evaluate the diversity of medium and large mammals present in PNA and VCA, as this information is key for developing any conservation strategy [47,48]. Previous studies have shown that VCA can maintain a high diversity of medium and large mammals, significantly contributing to the preservation of local biodiversity and the maintenance of ecosystem functions in areas under high anthropogenic load [31,39,49].

Given the limited knowledge available on the effectiveness of ADVs in Mexican territory, it is necessary to evaluate the effectiveness of the strategy in these areas. For this reason, we analyzed the information generated by community monitors with the interest of knowing what the diversity patterns of medium and large mammals are in these conservation areas; also, what would be the most appropriate strategy for the conservation of diversity, according to the observed results?

To evaluate the importance of PNA and VCA as conservation islands, (1) we estimated the diversity (in terms of richness and structure) of medium and large mammals in four areas with different vegetation types (one PNA and three VCAs) located in central Oaxaca, Mexico; (2) we categorized the sites according to their management strategy, comparing the federally decreed protected area (PNA) with Areas Destinadas Voluntariamente a la Conservación (VCA). Finally, (3) we determined the species turnover between the four sites and between the different conservation strategies. It is presumed that PA, being one of the most widely used conservation instruments globally (with management plans and funding), will show greater diversity of medium and large mammal species compared to VCA. Additionally, we expect the greatest similarity in mammal composition to be observed between the sites closest to each other, especially in the VCA located in the Physiographic Province of the Central Valleys.

2. Materials and Methods

2.1. Study Area

The study area is in the central portion of the state of Oaxaca, encompassing four physiographic provinces [50] (Figure 1).

The VCA "Danii Idoo" is in the Central Valleys province, in the municipality of Villa de Díaz Ordaz (DO). It is situated at the confluence of the Tlacolula Valley and the Sierra Juárez, covering an area of 3148 hectares. It has an altitudinal gradient ranging from 2050 to 2770 m above sea level. The types of climates present are semi-arid temperate climate (BS1kw), sub-humid temperate climates C(w0) and C(w1), and sub-humid temperate climate C(w2). The vegetation is induced grasslands (0.07 ha), oak forest (757.48 ha), oak–pine forest (2076.75 ha), pine–oak forest (243.48 ha), and tropical deciduous forest (37.48 ha) [51]. In this area, nine camera trap stations were installed (Table 1; Figures 1 and 2).

The VCA "La Capitana" is in the Central Valleys province in the municipality of San Andrés Ixtlahuaca (SAI). It covers 958 hectares and has an altitudinal gradient ranging from 1780 to 2425 m above sea level. Two types of climates predominate: sub-humid warm climate (A)C(w0), and sub-humid temperate climate C(w1). The vegetations present are grasslands (0.61 ha), croplands (22.62 ha), oak forests (222.96 ha), pine–oak forests (442,97 ha), and pine forest (269.49 ha) in the higher areas [52]. In SAI, data from three camera trap stations were analyzed (Table 1, Figures 1 and 2).

Table 1. Description of sites sampled in Protected Natural Areas in Oaxaca, México. VCA = Voluntary Conservation Area; PNA = Flora and Fauna Protection Area Boquerón de Tonalá.

Sampling Site (Total Surface Area)	Type of Protection	Description	Vegetation Cover	Number of Camera Traps per Camera Trapping Station	Mean Distance Between Camera Trap Stations (km)	Camera Trap Days	Number of Registered Species
DO (3148 has)	ADVC	It is located at the confluence of the Sierra Juárez, Sierra Mixe, and the Tlacolula Valley, with an altitudinal gradient ranging from 2050 to 2770 masl. It is near the town of Tlacolula.	1. Oak Forest (757 has), 24%.	3	1.353	2188	15
			2. Oak–Pine Forest (2076 has), 66%.	5		4421	18
			3. Pine–Oak Forest (243 ha), 7.82%.	1		375	14
SPE (2335 has)	ADVC	It is located at the confluence of the Etla Valley and the Sierra Juárez, with an altitudinal gradient ranging from 1900 to 3250 masl. It is near the city of Oaxaca.	1. Pine–Oak Forest (1556 has), 66%.	6	1.032	10,132	20
			2. Pine Forest (550 has), 24%.	3		3355	16
SAI (958 has)	ADVC	In the Central Valleys, it features an altitudinal gradient ranging from 1780 to 2425 masl. Its conservation area is surrounded by several small communities.	1. Oak Forest (223 has), 23%.	1	1.524	1976	10
			2. Pine–Oak Forest (442 has), 46%.	1		982	7
			3. Pine Forest (269 has), 28%.	1		1339	11
TON (3912.31 has)	PNA	Mountainous areas of the Lower Mixteca region, with an altitudinal gradient ranging from 1375 to 2130 masl. Located near the town of Santo Domingo Tonalá.	1. Tropical Deciduous Forest (2608 has), 67%.	7	1.593	3242	17
			2. Juniper Forest (563 has), 14%.	1		1114	15
			3. Oak Forest (712 has), 18%.	1		180	11

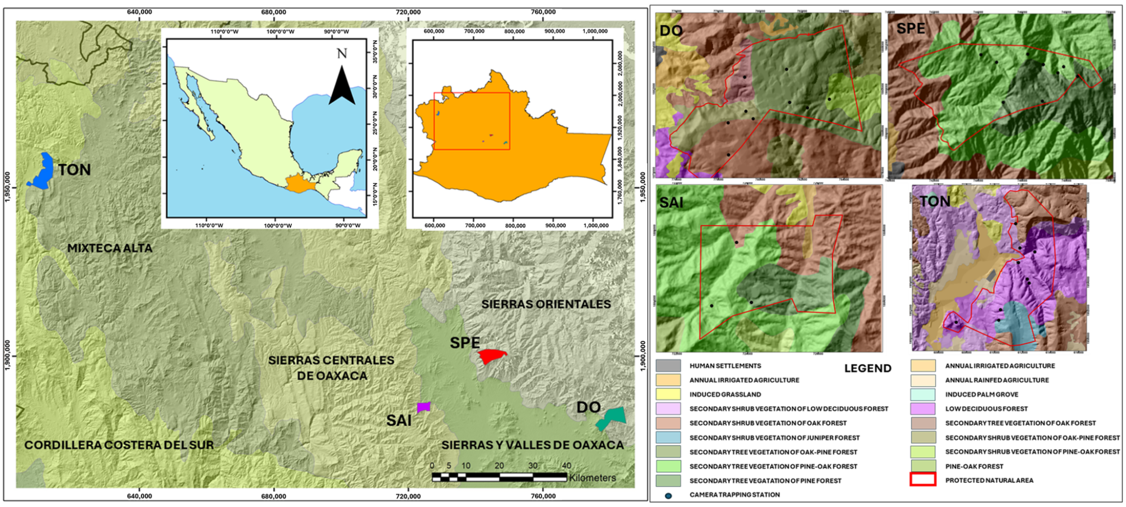

Figure 1. The geographical location of the study areas in the state of Oaxaca, Mexico. The locations of the trapping stations are marked with dots. DO: Diaz Ordaz; SPE: San Pablo Etla; SAI: San Andres Ixtahuaca; TON: ANP Flora and Fauna Protection Area Boquerón de Tonalá.

Figure 2. Images of the study areas. (**A**,**B**): DO (Diaz Ordaz); (**C**,**D**): SPE (San Pablo Etla); (**E**,**F**): SAI (San Andres Ixtahuaca); (**G**,**H**): TON (ANP Flora and Fauna Protection Area Boquerón de Tonalá).

The VCA "La Cruz-Corral de Piedra" is in the Sierra Madre de Oaxaca province, in the municipality of San Pablo Etla (SPE). It covers an area of 2335 hectares and has an altitudinal gradient ranging from 1900 to 3250 m above sea level. In this area, three types of climates are identified: sub-humid C(w0), sub-humid temperate C(w1), and sub-humid cold Cb'(w2). The vegetations present are oak forests (221.71 ha), pine–oak forests (1555.91 ha), and pine forest (550.13 ha). Additionally, gallery forests develop along streams [53]. In this region, nine camera trap stations were installed (Table 1, Figures 1 and 2).

The PNA "Flora and Fauna Protection Area Boquerón de Tonalá" (TON) differs from the previous three as it has a federal decree. It is in the Western Mountains and Valleys province, in the municipality of Santo Domingo Tonalá, and covers an area of 3912.31 hectares. It has an altitudinal gradient ranging from 1375 to 2130 m above sea level. Two types of climate present are semi-warm (BS1hw) and sub-humid temperate C(w0). The vegetations present are croplands (28.33 ha), juniper forest (563.31 ha), oak forest (712.13 ha), and tropical deciduous forest (2608.55 ha). The precipitation is scarce (less than 40 mm in the driest month), so the vegetation remains leafless for much of the year [54]. In TON, data from nine camera trap stations were analyzed (Table 1, Figures 1 and 2).

2.2. Community Monitoring

Through CONANP and with financial support from five institutional programs, monitoring and surveillance committees were formed in each of the VCAs. The committees, composed of local community members, were trained by the first author and CONANP technical staff, mainly in the placement of camera traps, data collection from the cameras, and handling of the GPS.

In DO, SPE, and TON, nine camera trap stations were installed, while in SAI, three stations were deployed. In DO, three stations were in oak forest, five in oak–pine forest, and one in pine forest. In SPE, five stations were placed in oak–pine forest and four in pine forest. In SAI, one station was installed in oak forest, one in pine–oak forest, and one in pine forest, distributed evenly due to its smaller area, covering only 958 hectares and comprising three distinct vegetation types. In TON, seven stations were set in tropical deciduous forest, one in juniper forest, and one in oak forest. The distribution of the cameras covered diverse vegetation types and mountainous conditions, avoiding areas with frequent human traffic to minimize the risk of damage or theft.

The cameras used in the study included two Cuddeback 1279 20MP X-Change Color Day & Night units, nineteen Bushnell Trophy Cam HD 12MP cameras, eight Bushnell Trophy Cam E3 Essential 16MP cameras, and one Bushnell Core Low-Glow camera, totaling thirty sampling stations. All cameras had a sensitivity range of 10 to 20 m and operated continuously over a seven-year period, from 2013 to 2019. However, some cameras experienced operational issues due to battery depletion or errors during reinstallation, particularly during transitions between monitoring committees, which typically rotate every three years, coinciding with changes in communal land management boards. These initial transitions often resulted in placement errors. The specific operational schedule for each station varied over time (Table 2).

Table 2. The number of independent events recorded at camera trap stations across four sites in central Oaxaca, Mexico: San Pablo Etla (SPE), Villa de Díaz Ordaz (DO), San Andrés Ixtlahuaca (SAI), and Boquerón de Tonalá (TON). The table includes the vegetation types associated with each camera trap station within the Protected Natural Areas studied in Oaxaca, Mexico, including Tropical Deciduous Forest (TDF), Oak Forest (OF), Juniperus Forest (JF), Oak–Pine Forest (OPF), Pine–Oak Forest (POF), and Pine Forest (PF).

Area	Stations	Altitude (m.a.s.l.)	Vegetation Type	2013	2014	2015	2016	2017	2018	2019	TOTAL
DO	Bluch	2541	OPF	27	221	36	39	136	274	127	
DO	Chivaguela	2609	OPF	204	128	252		52	217	60	
DO	Lat bezz	2441	OF	253	234	51		33	228	22	
DO	Llano copal	2677	OPF	201	209	121		51	365	122	
DO	Ojo de agua	2594	OPF		199	287		132	231	107	
DO	Rio Concha	2425	OF		130	255		101	42	187	
DO	Rio del Jaguar	2566	OPF			203		80	258	82	
DO	Rio Vaquero	2242	OF			36		111	302	203	
DO	Tobalto	2556	POF					31	210	134	
DO	TOTAL			685	1121	1241	39	727	2127	1044	6984
SPE	La 2000	2942	POF	43	365	38	365	233	324	365	
SPE	El Paredón	2860	POF	209	89	364	262	189	24	364	
SPE	Cañada de Gregorio	2595	POF	138	89	366	366	292	190	184	
SPE	Mano de León 2	2765	POF	249	72	365	252	292	266	365	
SPE	Hermenegildo	3259	PF	178	325	365	174	292	235	185	
SPE	La Calera	2881	POF	166	355	310	332	292	319	365	
SPE	El Mogote del Pozo	2747	PF		268	365	212	292	136		
SPE	Al pie de la Peña	2735	PF				105	258	226		
SPE	La Acahualera	3034	PF				366	292	354		
SPE	TOTAL			983	1563	2173	2434	2432	2074	1828	13,487
SAI	Río Verde	1892	OF	39	335	342	334	308	322	296	
SAI	Loma Larga	2132	POF	39	335	342	153			113	
SAI	La Concha	2040	PF	39	189	342	232	172	260	105	
SAI	TOTAL			117	859	1026	719	480	582	514	4297
TON	Cuesta del Obispo	1529	TDF	365	24	140					
TON	Santa Catarina	1608	TDF	226	30	132	209				
TON	Pozo del Jabalí	1839	JF	164	84	215	62	346		243	
TON	Yucununi	1533	TDF	86	12		209				
TON	La Cañada	1873	TDF	226	88	200	3			79	
TON	Los Limoncitos	1554	TDF		15	104	201	59			
TON	La Pedrera	1433	TDF		44	36	117		157		
TON	El Mango	1379	TDF		20	159	117		121	63	
TON	Yuvijasa	1391	OF		46	34			46	54	
	TOTAL			1067	363	1020	918	405	324	439	4536

The camera traps were installed at heights between 30 cm and 1 m on tree trunks, in sites with signs of wildlife such as tracks, droppings, and trails. No baits or attractants were used. The distance between the camera and trap ranged from 0.5 to 3 km, with an overall average of 1341 km in the four areas studied. The average density of installed cameras ranged from 0.0023 cameras/ha (equivalent to 2.3 cameras per 1000 ha) to 0.0038 cameras/ha (3.8 cameras per 1000 ha). Each station was georeferenced with a Garmin eTrex 20x® GPS. The cameras operated 24 h a day and were programmed to capture three photos per motion detection. Every 30 to 40 days, a review was conducted to replace the batteries and memory cards.

2.3. Data Analysis

The photographed species were identified using the specialized literature [55,56]. The classification and nomenclature were based on Ramírez-Pulido et al. [57]. Medium-sized mammals were defined as those with a body weight greater than 100 g but less than 10 kg, while large mammals were considered those with a weight greater than 10 kg [55].

Independent events were considered as consecutive photographs of clearly distinguishable individuals, as well as those of individuals of the same species separated by an interval of more than 24 h [58]. In the case of species with gregarious habits, the number of independent records corresponded to the number of individuals observed in each event [58]. We evaluated richness and diversity through two comparisons: first, among the four study sites; and second, between the two conservation strategies: the PNA (TON) versus the VCA (DO, SAI, and SPE).

We estimated inventory completeness to determine if the sampling effort was sufficient to adequately represent the species likely to be captured by camera trapping. To perform this, we calculated the sample coverage (Cm), which evaluates sample completeness considering the total number of individuals captured and the number of rare species. The calculation of sample coverage was performed in the iNEXT package version 2.0.20, and is expressed as

$$C_n = 1 - (f_1 N)\left(1 - \frac{f_1}{N}\right)$$

where

C_n: Sample coverage.
f_1: Number of species observed only once.
N: Total number of individuals in sample.

We used rarefaction and extrapolation methods based on sample size and coverage, specifically incidence matrices with a 95% confidence interval [59,60]. All analyses were conducted using the iNEXT package version 2.0.20. The iNEXT program uses rarefaction to estimate diversity at standardized sample sizes and extrapolation to predict diversity at larger sample sizes. It is based on the cumulative function of the expected diversity:

$$\hat{R}(n) = \sum_{i=1}^{S}\left[\binom{N-n_i}{n} \Big/ \binom{N}{n}\right]$$

where

$R(n)$: Expected number of species in sample of size n.
N: Total sample size.
n_i: Number of individuals of species i.
n: Size of subsample to be evaluated.

Species Diversity: We analyzed the diversity indices using Hill numbers to estimate species richness, based on incidence data [61]. Hill numbers represent a comprehensive family of diversity indices that encompass species richness, Shannon's diversity index, and Simpson's diversity index. These indices are calculated using the following formula:

$$^{q}D = \left(\sum_{i=1}^{S} P_q^i\right)^{\frac{1}{1-q}}$$

^{q}D: Diversity of order q.
S: Total number of species.
p^i: Relative proportion of individuals of species i in sample.
q: Parameter that determines sensitivity of index to species abundance.
q = 0: Diversity of order 0 (species richness, all species are weighted equally).
q = 1: Diversity of order 1 (Shannon diversity, sensitive to proportional abundance).
q = 2: Diversity of order 2 (Simpson diversity, more sensitive to dominant species).

This index is sensitive to the relative abundances of species. When q = 0, species richness is obtained; near q = 1, Shannon entropy or a simple transformation of it is calculated, being sensitive to species evenness. On the other hand, when q = 2, the formulas provide the Simpson index or a simple transformation of it, being sensitive to species dominance. The analysis was conducted using the iNEXT package version 2.0.20.

Species Abundance: To obtain the relative abundance index (RAI) of each species, we used the following equation: IAR = (C/EM) * 100 trap-nights, where C is the number of events; EM is the sampling effort (number of camera traps used by monitoring days) per 100 trap-nights (standard correction factor) [58].

Rank–Abundance Curves: Rank–abundance (diversity–dominance) curves were constructed for each zone and each conservation strategy [62]. The curve was plotted based on the logarithm of the proportion of each species, LN(Pi+1). This graph allows comparing species richness (represented by the points on the graph), evenness (indicated by the slope), the number of rare species (represented by the tail of the curve), and the relative abundance of each species (determined by the order of the species on the graph). The analyses were performed with the BiodiversityR package, v.2.13-1, and vegan v.2.6-4 in R version 4.0.2 [63]. In this study, we define rare species as those characterized by a combination of low abundance, restricted geographic distribution, and/or dependence on highly specific habitats. These species are often more vulnerable to environmental threats such as habitat fragmentation, climate change, and overexploitation [64].

To evaluate similarities in the composition and structure of mammal communities, two non-metric multidimensional scaling (NMDS) analyses were performed in three dimensions using Bray–Curtis distance as a similarity metric. In the first analysis, the four study areas were considered to identify similarities and differences in species composition among the different conservation areas. The results were visualized in a three-dimensional graph representing the relationships among the camera trap stations. In the second analysis, the monitoring stations were grouped into two main categories: PA and VCA. This analysis allowed evaluating the general differences and similarities in mammal communities between the two management categories. The software PAST v. 4.09 was used. Additionally, convergence polygons were generated for each group, facilitating the visualization and interpretation of beta diversity patterns between voluntary and decreed areas.

To test statistical differences in community composition (species richness and their relative abundance), we used a permutational multivariate analysis of variance (perMANOVA—Anderson 2001) v. 2.6-4 in R software [63]. This analysis tested the differentiation in community structure among the four sites and between the two conservation strategies.

3. Results

We obtained 60,725 photographic records, corresponding to 11,114 independent events, with a sampling effort of 29,304 camera-nights (Table 2). For DO, the total sampling effort was 6984 camera-nights (39–2127, $\overline{X}$ = 997); for SAI, the total effort was 4297 camera-nights (117–1026, $\overline{X}$ = 613); for SPE, the sampling effort was 13,487 camera-nights (983–2434, $\overline{X}$ = 1926); and finally, for TON, it was 4536 camera-nights (324–1067, $\overline{X}$ = 6448).

In total, we recorded 23 species of medium and large mammals, belonging to 12 families and six orders (Table 3, Figures 3 and 4). The order Carnivora was best represented, with five families and 15 species (Figure 4).

It is worth noting that in the four sites, the largest numbers of species were recorded in different types of vegetation: in DO, there were 18 species within the oak–pine forest; in SPE, 20 species were recorded in the pine–oak forest; in SAI, 11 species were within the pine forest; and finally in TON, 17 species were recorded in tropical deciduous forest (Table 1).

The species with the highest number of independent events was the white-tailed deer (*Odocoileus virginianus*) with 3738 records, followed by the collared peccary (*Dicotyles angulatus*) with 2543. Four species are included in the NOM-059-SEMARNAT-2010: the jaguar (*Panthera onca*), margay (*Leopardus wiedii*), tayra (*Eira barbara*), and jaguarundi (*Herpailurus yagouaroundi*) (Table 3).

The rarefaction and extrapolation analysis indicated that the sample coverage was representative, reaching a value of 99% and showing an asymptotic trend in the graphs

(Figure 5). We found significant differences in species richness based on coverage among the four analyzed sites, with SAI showing the lowest richness compared to the other three sites (Figure 5A). Similarly, we observed significant differences between the two conservation strategies (PNA and VCA) (Figure 5B).

According to Hill numbers, considering only species richness (q = 0), SPE had the highest species richness, with a total of 22 species. The second site with the highest richness was DO, with 19 species. In the TON area, 18 species were recorded, while SAI had the lowest richness, with 13 species. When considering species abundance among the zones (q = 1), diversity in TON was higher (9.83 effective species), while SPE recorded the lowest (5.65 effective species) (Figure 6).

Table 3. Relative abundance of medium and large mammals recorded in the Protected Natural Areas studied in Oaxaca, Mexico. San Pablo Etla (SPE), Villa de Díaz Ordaz (DO), San Andrés Ixtlahuaca (SAI), and Boquerón de Tonalá (TON); Voluntary Conservation Area (VCA). End = Endemic to Mexico; A = Threatened; P = Endangered (SEMARNAT, 2010).

Order/Family/Species	Independent Events (Relative Abundance Index)					Conservation
	DO	SAI	SPE	TON (ANP)	VCA	NOM-059
Didelphimorphia						
Didelphidae						
Didelphis virginianus	13 (0.75)	263 (14.14)	8 (0.191)	332 (9.925)	284 (3.655)	
Cingulata						
Dasypodidae						
Dasypus novemcinctus	1 (0.058)	16 (0.860)	0	47 (1.405)	17 (0.219)	
Lagomorpha						
Leporidae						
Sylvilagus cunicularius	9 (0.525)	0	11 (0.262)	3 (0.090)	20 (0.257)	End
Sylvilagus floridanus	186 (10.845)	0	379 (9.030)	276 (8.251)	565 (7.271)	
Rodentia						
Sciuridae						
Sciurus aureogaster	122 (7.114)	420 (22.592)	177 (4.217)	122 (3.647)	719 (9.252)	
Cuniculidae						
Cuniculus paca	1 (0.058)	0	22 (0.524)	0	23 (0.296)	
Carnivora						
Felidae						
Herpailurus yagouaroundi	0	0	9 (0.214)	37 (1.106)	9 (0.116)	A
Leopardus wiedii	19 (1.108)	1 (0.053)	30 (0.515)	121 (3.617)	50 (0.643)	P
Lynx rufus	3 (0.175)	0	68 (1.620)	9 (0.269)	71 (0.914)	
Puma concolor	29 (1.691)	0	124 (2.954)	110 (3.288)	153 (1.969)	
Panthera onca	8 (0.466)	0	0	0	8 (1.103)	P
Canidae						
Canis latrans	19 (1.108)	6 (0.322)	62 (1.477)	3 (0.090)	87 (1.120)	
Urocyon cinereoargenteus	183 (10.671)	73 (3.926)	77 (1.835)	200 (4.913)	333 (4.285)	
Mephitidae						
Conepatus leuconotus	14 (0.816)	3 (0.161)	18 (0.429)	99 (2.960)	35 (0.450)	
Mephitis macroura	53 (3.090)	16 (0.860)	8 (0.191)	16 (0.478)	77 (0.991)	
Spilogale angustifrons	3 (0.175)	14 (0.753)	6 (0.143)	15 (0.448)	23 (0.296)	
Mustelidae						
Eira barbara	0	0	1 (0.024)	0	1 (0.013)	P
Mustela frenata	0	0	4 (0.095)	0	4 (0.051)	
Procyonidae						
Bassariscus astutus	37 (2.157)	75 (4.034)	8 (0.191)	120 (3.587)	120 (1.544)	
Nasua narica	121 (7.055)	62 (3.335)	27 (0.643)	400 (11.958)	210 (2.702)	
Procyon lotor	0	1 (0.053)	26 (0.619)	88 (2.631)	27 (0.347)	
Artiodactyla						
Tayassuidae						
Dicotyles angulatus	6 (0.350)	0	2537 (60.448)	0	2543 (32.724)	
Cervidae						
Odocoileus virginianus	888 (51.778)	909 (48.897)	594 (14.153)	1347 (40.269)	2391 (30.768)	

Figure 3. Most abundant species: (**a**) white-tailed deer (DO); (**b**) collared peccary (SPE); (**c**) mountain rabbit (TON); (**d**) squirrel (SAI).

Figure 4. Felines present in the study areas: (**a**) jaguar (DO); (**b**) tigrillo (TON); (**c**) pumas (SPE); (**d**) lynx (SPE); (**e**) yaguarundi (SPE); (**f**) puma (TON).

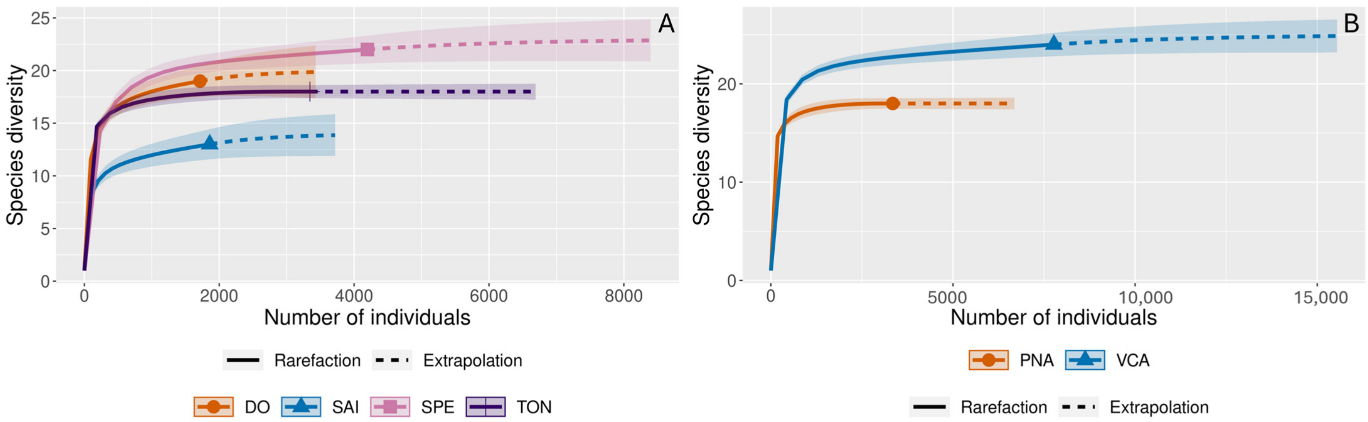

Figure 5. Species richness estimation. Rarefaction and extrapolation curves based on sampling in the four study areas (**A**) and two conservation strategies (**B**). Shaded areas represent a 95% confidence interval. The solid line indicates interpolation, and the dashed lines indicate extrapolation. DO: Diaz Ordaz; SAI: San Andres Ixtlahuaca; SPE: San Pablo Etla; TON: Flora and Fauna Protection Area Boquerón de Tonalá.

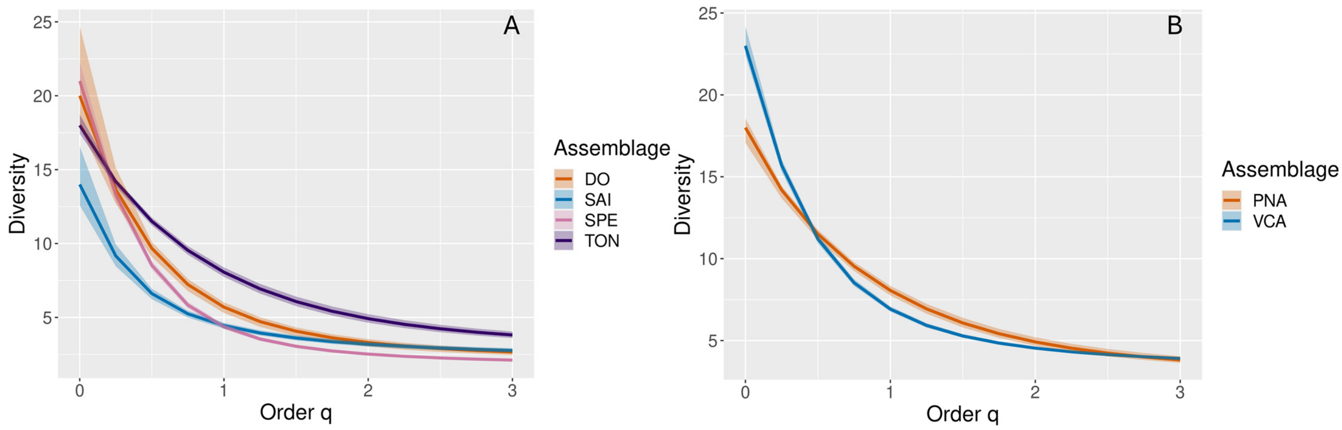

Figure 6. Diversity estimation according to Hill numbers in the four study areas (**A**) and the two conservation strategies (**B**). Shaded areas represent a 95% confidence interval. A—DO: Diaz Ordaz; SAI: San Andres Ixtlahuaca; SPE: San Pablo Etla; TON: Flora and Fauna Protection Area Boquerón de Tonalá.

Finally, when considering the dominant species (q = 2), the highest diversity was recorded in TON (6.37 effective species) and the lowest in SPE (3.11 effective species) (Figure 6A). For the comparison between conservation strategies, we recorded a higher number of species in the VCA (n = 27). When considering species abundance (q = 1), we recorded very similar values (PNA = 9.83 effective species, VCA = 9.48 effective species). Similarly, when considering dominant species (q = 2), we recorded similar values (PNA = 6.37 effective species, VCA = 6.22 effective species) (Figure 6B).

The rank–abundance curves for the four areas showed notable differences in the structures of mammal communities. The most dominant species belong to the order Artiodactyla in all areas. In three of them (DO, SAI, and TON), it was the white-tailed deer (*O. virginianus*), while in SPE, it was the collared peccary (*D. angulatus*). Many rare species were recorded in all four areas; in three of these (SPE, DO, and SAI), at least 50% of the species that make up the medium and large mammal community were rare. In TON, although abundances were low, six of them were rare (29%). Species such as the jaguar (*Panthera onca*) in DO were very scarce, with only one and eight independent records, respectively. Similarly, species like the tayra (*E. barbara*) and the long-tailed weasel (*Mustela frenata*) in the SPE area had one and four independent records, respectively (Figure 7).

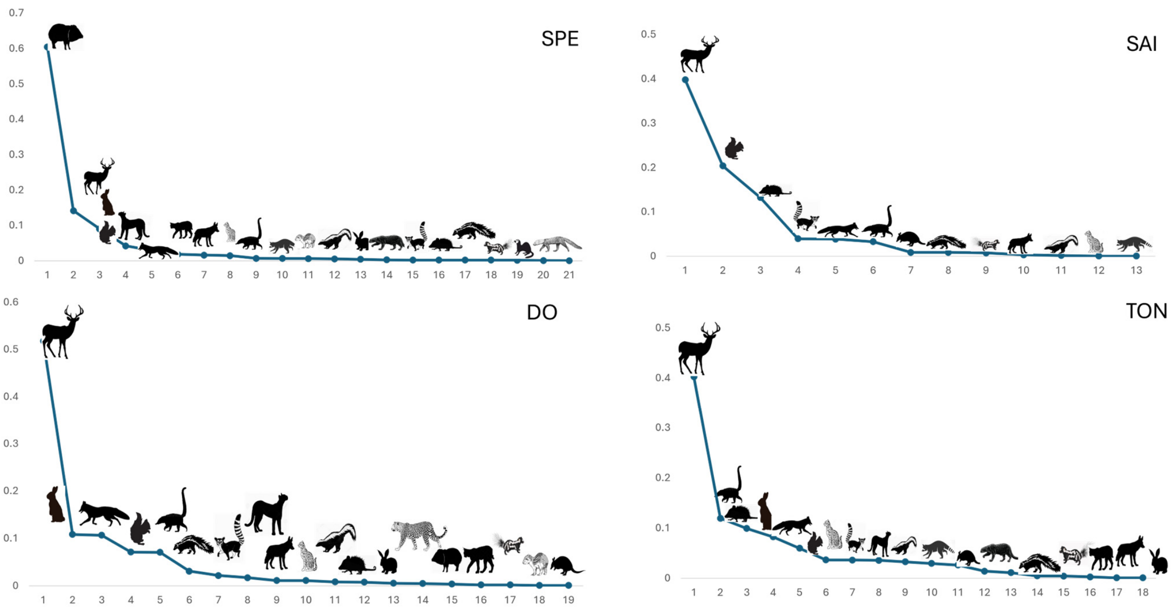

Figure 7. Rank–abundance curves of medium and large mammal assemblages in four areas of study, Oaxaca, México. SPE = San Pablo Etla; DO = Diaz Ordaz; SAI = San Andrés Ixtlahuaca; TON = Boquerón de Tonalá.

When comparing the two conservation strategies, we recorded the white-tailed deer (*O. virginianus*) as the most dominant species in the PNA, while the collared peccary (*D. angulatus*) was the most dominant in the VCA. The jaguar (*P. onca*) was only recorded in the VCA, although its records were scarce (Figure 8).

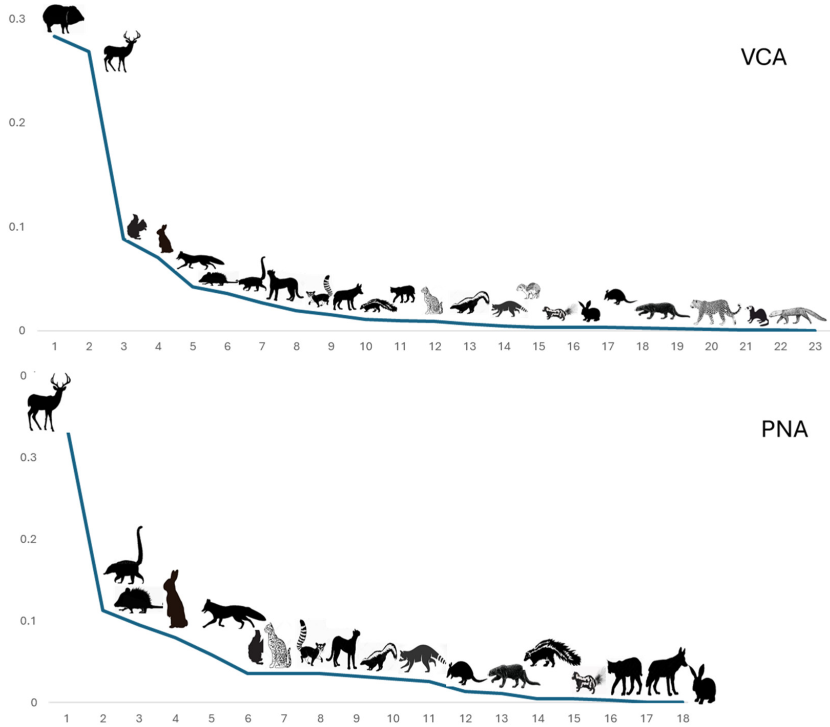

Figure 8. Rank-abundance curves of medium and large mammal assemblages under two conservation strategies, highlighting a greater species richness in Voluntary Conservation Areas (VCA) compared to Protected Natural Areas (PNA).

Regarding beta diversity, 12 species were recorded as shared in all four areas. Notable species include the white-tailed deer (*O. virginianus*), the Virginia opossum (*Didelphis virginiana*), the Mexican gray squirrel (*Sciurus aureogaster*), the coyote (*Canis latrans*), the gray fox (*Urocyon cinereoargenteus*), and three skunks (*Conepatus leuconotus*, *Mephitis macroura*, and *Spilogale angustifrons*), among others. Three species of medium and large mammals were exclusive to a single area: the tayra (*E. barbara*) and long-tailed weasel (*M. frenata*) in the SPE area and the jaguar (*P. onca*) was only recorded in the DO area (Table 3).

The analysis revealed differences in the composition and distribution of medium and large mammals in the different study areas. The Permanova analysis showed significant differences (F = 4.033; $p = 0.0001$), indicating that the composition of the medium and large mammal community differs among the four areas, although the obtained stress level had a moderate representation (stress = 0.136, Figure 9).

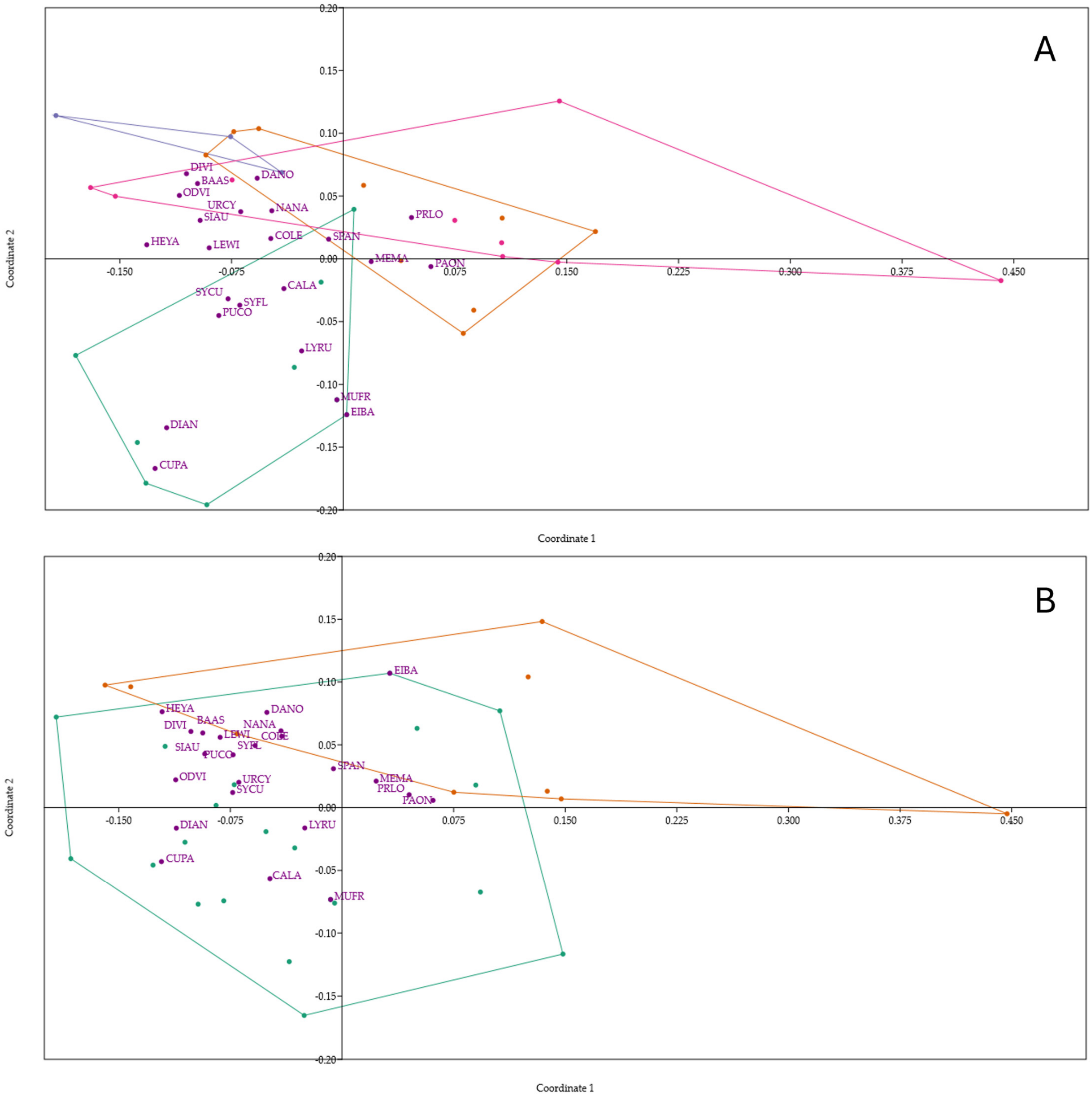

Figure 9. Non-metric multidimensional scaling (NMDS) of medium and large mammals from the four studied protected natural areas (3D solution) (**A**) (pink line: TON; purple: SAI; orange: DO; green: SPEI), and the two conservation strategies (**B**) (orange line: PNA; and green: VCA), based on Bray–Curtis distance, using convergence polygon representation with a relative abundance index (RAI).

Regarding the analysis between VCA and PNA, 19 species are shared between both conservation strategies. Six wild species were exclusively recorded in the VCA: the paca (*Cuniculus paca*), jaguar (*P. onca*), tayra (*E. barbara*), long-tailed weasel (*M. frenata*), and collared peccary (*D. angulatus*). The Permanova analysis was statistically significant ($F = 3.108$; $p = 0.0033$), indicating that the composition of the medium and large mammal community differs between the two conservation strategies, with the obtained stress level also showing a moderate representation (stress = 0.1362, Figure 9).

4. Discussion

We recorded a total of 48% of the medium and large mammals of the state of Oaxaca [65]. This is significant given that the area of the three VCAs and the PNA is small, covering only 0.088% (8251 hectares) of the state's surface, and, in addition, the four sites are located very close to human settlements. It was also notable that the analyzed VCAs protect a high diversity of mammals [39]. The richness of mammals in the analyzed areas was considerably high compared to other similar studies on medium and large mammals. For example, Ruíz-Gutiérrez et al. recorded 22 species of medium and large mammals in Guerrero, Mexico [66]; Cortés-Marcial and Briones-Salas reported the same number of species in the Sierra de Tolistoque, Oaxaca, Mexico [67]. Lavariega et al. reported 18 species in the Sierra de Juárez, Oaxaca, Mexico [68]. Cervantes-Reza and Riveros-Lara recorded 14 species in the municipality of Cosoltepec, in the Mixteca of Oaxaca [69]. Our results demonstrate that VCA functions as conservation sites or islands that, along with PNA, support conservation actions, especially when conducted over a long period, as was the case in our study.

Species richness among the four sites was different. Diversity profiles show that SPE had the highest species richness, mainly in the pine–oak forest ($n = 20$), but it was the least diverse site for ($q = 2$), reflecting a greater dominance of a few species like the collared peccary (*D. angulatus*) or less heterogeneity in species abundance. TON and DO have higher diversity for ($q = 1$) and ($q = 2$), indicating high diversity in terms of species evenness and suggesting that species are more evenly distributed in terms of abundance, behaving as a more balanced community. This also suggests a greater presence of less abundant species in the community. These differences may reflect ecological variations between the areas, such as resource availability, or human impacts, as observed in other studies [70]. They also reflect the type of vegetation found in TON and DO. In TON, the largest area of vegetation corresponds to tropical deciduous forest, where most of the cameras were placed, seven, while in pine forest, one was placed, as well as in juniperus forest. In this region, six species were not recorded: *Sylvilagus cunicularius*, *Panthera onca*, *Mustela frenata*, *Eira Barbara*, *Dicotyles angulatus*, and *Cuniculus paca*. However, in the other VCAs, they were recorded; this is possibly because most of the species do not inhabit this type of ecosystem, and they prefer tropical forests [55].

For the two conservation strategies, although we initially expected to find more species in the PNA, we clearly observed greater species richness in the VCA. This may be because the combined area of the three sites is larger and also has different types of vegetation that have a direct effect on mammal richness [71]. However, when considering species abundances ($q = 1$) and common and rare species ($q = 2$), we observed very similar values, so no significant differences were recorded between the communities of the two conservation strategies.

There are different indicators of the conservation status of a given site, one of which is the presence of predators and their respective prey [72,73]. We recorded four felines in three areas (SPE, DO, and the PNA), while in SAI, only the margay (*Leopardus wiedii*) was recorded, with the lowest abundance indices in the entire study. This may be due to the numerous records of mesopredators, which are often related to the decline in top predator populations caused by factors such as hunting and habitat fragmentation [74,75]. In the case of SAI, these results may be related to its history of anthropization, as it is near the city of Oaxaca and surrounded by small towns that have used natural resources for centuries [76,77]. Additionally, we detected a high abundance of opossums (*Didelphis virginiana*), which are favored by human impact [78]. We consider that a study is needed in SAI to determine the causes of these results because the absence of predators can trigger cascading effects within the ecosystem, affecting biodiversity and species interactions [79].

On the other hand, the jaguar (*P. onca*) was only recorded in DO, highlighting its importance for the conservation of this species. These records are important because the jaguar plays a crucial ecological role in ecosystems and its conservation is closely linked to the quality of the habitat [80]. Another species recorded, which is uncommon in the area, was the spotted paca (*Cuniculus paca*). The records of the jaguar and the spotted paca may be related to the proximity to the Sierra Madre de Oaxaca, which contains a large area of well-preserved forest [31], suggesting that DO may function as a corridor for these species.

In SPE, the highest abundance indices of the puma (*Puma concolor*) and bobcat (*Lynx rufus*) were recorded, possibly due to the abundance of some of their prey, such as the collared peccary (*D. angulatus*) and rabbits (*Sylvilagus* spp.) [81,82]. Additionally, spotted pacas (*C. paca*) and tayras (*E. barbara*) were recorded; these species are uncommon in pine–oak forests, suggesting a possible connection to nearby source areas like the Sierra Madre de Oaxaca, like DO [31].

In TON, the high relative abundance indices of pumas (*P. concolor*) could be related to prey availability, as their preferred prey, the deer (*O. virginianus*), was abundant [82,83]. Pumas might also feed on coatis (*Nasua narica*), opossums (*Didelphis virginiana*), and rabbits (*Sylvilagus* spp.), which had high abundance indices and are part of their diet [82–85]. Other predators recorded with high abundance indices compared to the other three sites were the margay (*L. wiedii*) and the jaguarundi (*Herpailurus yagouaroundi*). The presence of three felines in TON is explained by niche partitioning and resource availability [86]. Each species occupies a distinct ecological niche, which minimizes competition: pumas seek larger terrestrial prey, margay specializes in arboreal hunting of small prey, and jaguarundi feed primarily on small terrestrial animals [82,83,87]. These records demonstrate that TON is an area with a wealth of mammals capable of supporting these four felines.

The beta diversity analysis among the four sites showed differences in the mammal community composition; however, more generalist species with greater adaptation to disturbance were recorded in all four sites. This includes the opossum (*D. virginiana*), the Mexican gray squirrel (*S. aureogaster*), and the coyote (*Canis latrans*) [55]. It is worth mentioning that the VCAs are relatively close to towns (<5 km), which may attract the species in search of food.

VCAs in Mexico, particularly in Oaxaca, have served as refuges for wildlife, as demonstrated in other studies [39]. Geographically close sites can act as biological corridors, facilitating the dispersal and reproduction of many species. According to the island biogeography theory [88], there is a decrease in species richness on islands as their area decreases and their isolation from the nearest island increases. Some studies have shown species richness patterns consistent with this expected relationship [89,90]. In our study, we observed greater similarity in the species composition of mammal communities that were geographically closer to each other, as was the case with the three VCAs, undoubtedly contributing to mammal movement in this region.

VCAs are established and managed directly by indigenous or mestizo communities, promoting a sense of ownership and responsibility over the territory. As part of the results obtained, the inhabitants, through community assemblies, decided to prohibit hunting and livestock management within these areas, as the results recorded the presence of poachers and domestic animals. These actions will undoubtedly help maintain healthier and more balanced communities [91].

This study highlights the importance of evaluating species richness in PNA and VCA. Habitat fragmentation and productive activities in surrounding areas can significantly influence the abundance of medium and large mammals, affecting their distribution and behavior, studies that should be performed in the future. Therefore, in addition to strengthening local conservation, these areas could also play a key role in creating biological corridors that facilitate species movement and dispersal, helping to ensure ecosystem integrity and quality [92]. These aspects are essential for improving the effectiveness of conservation strategies and ensuring the long-term viability of wildlife populations in the region. To achieve this, it is crucial to establish agreements between communities and keep residents informed about the biodiversity recorded in their region, not just their locality. This would allow for the establishment of regional conservation goals in collaboration with different communities.

As more complete and accurate information on species distribution and population trends becomes available, it will be possible to conduct more detailed evaluations of the effectiveness of protected areas, facilitating the implementation of better-planned strategies and increasingly accurate solutions [93].

5. Conclusions

We conclude that both conservation strategies are effective in maintaining mammal richness. VCA had greater species diversity than PNA, highlighting the importance of these areas as refuges for wildlife. We observed greater species exchange between geographically close areas, confirming that VCA can serve as connector sites and dispersal points for mammal species. This will allow, in the future, the proposal of zones that connect these areas, serving as potential biological corridors. Additionally, the sampling effort by community monitors has provided a more accurate estimate of mammal richness and diversity in these areas, forming a solid basis for future studies and conservation programs.

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