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Delimitation of regional management units for desert bighorn sheep in Baja California. An application of the potential species distribution model

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Models of the potential geographic distribution of species are decision-making tools for wildlife population management, especially for species with broad ranges, such as bighorn sheep. In the present study, a potential geographic distribution model was generated for managing bighorn sheep in Baja California, Mexico. The model was produced with the maximum-entropy algorithm to estimate the geographic range of the species. The variables used as predictors were climate, relief, and vegetation. Meanwhile, known sites where bighorn sheep were recorded were obtained from aerial counts in Sierra Juarez in 2012 and at the regional level in 2021 by Romero-Figueroa *et al.* (2024). Additional records of terrestrial observations used were reported by Ruiz-Mondragón *et al.* (2023) for Sierra Juarez in 2016, Sierra La Asamblea and Calamajué in 2021, and Sierra Santa Isabel and Sierra Juarez in 2022, as well as records from the Global Biodiversity Information Facility (GBIF 2021). The geographic distribution model revealed that bighorn sheep in the state of Baja California are distributed along the mountain range of the Gulf of California, covering an approximate area of 317 160 ha. The variables that contributed the most to the construction of the model were roughness, type of vegetation, and precipitation of the coldest quarter. The geographic distribution model was used to define 12 regional management units for the species. Each unit is shared between two or more agrarian communities. In Baja California, bighorn sheep should be managed through community monitoring, habitat protection, and sustainable use programs with the participation of all rural communities that own land within the distribution range of this species.

Los modelos de distribución geográfica potencial de especies son herramientas para tomar decisiones sobre el manejo de las poblaciones de vida silvestre, especialmente de especies que ocupan grandes extensiones de área, como el borrego cimarrón. En el presente estudio se generó un modelo de distribución geográfica potencial que puede ser utilizado para el manejo del borrego cimarrón en el estado de Baja California, México. El modelo se generó con el algoritmo de máxima entropía para estimar el área de distribución geográfica de la especie. Las variables utilizadas como predictoras fueron climáticas, de relieve y de vegetación. Mientras que, los sitios conocidos donde se registró al borrego cimarrón se obtuvieron de conteos aéreos realizados en Sierra Juárez en 2012, y a nivel regional en 2021, por Romero-Figueroa *et al.* (2024). Asimismo, se incluyeron registros de observaciones terrestres reportados por Ruiz-Mondragón *et al.* (2023) en Sierra Juárez en 2016; en la Sierra de la Asamblea y en Calamajué en 2021; y en Sierra Santa Isabel y Sierra Juárez en 2022. Así como, del Sistema Global de Información sobre Biodiversidad (GBIF 2021). El modelo de distribución geográfica reveló que la especie en el estado de Baja California se distribuye a lo largo del macizo montañoso del Golfo de California, en una superficie aproximada de 317,160 ha. Las variables que contribuyeron más en la construcción del modelo fueron la rugosidad, el tipo de vegetación y la precipitación del trimestre más frío. El modelo de distribución geográfica se utilizó para definir 12 unidades de manejo regional para la especie. Cada una se comparte entre dos o más comunidades agrarias. En Baja California el manejo del borrego cimarrón se debe realizar a partir de programas de monitoreo comunitario, protección del hábitat y aprovechamiento sostenible en los que, se considere la participación de todas las comunidades rurales que poseen terrenos dentro del área de distribución de esta especie.

Keywords: big game species; ecological niche model; maximum entropy; *Ovis canadensis*; wild sheep; wildlife management.

Introduction

Management units are geographic areas delimited for the conservation and sustainable management of wildlife species and their habitats (Swihart *et al.* 2020). However, their definition and delimitation consider only political boundaries without taking into account the biological aspects of the species (Bischof *et al.* 2016). An example of this issue is the management of bighorn sheep (*Ovis canadensis*) populations in Mexico. The distribution ranges of this species frequently surpass the boundaries of management units, which are delimited by property lines where there are no barriers restricting the movement of animals (Rubin *et al.* 2009; Ruiz-Mondragón *et al.* 2018). Therefore, to achieve sustainable bighorn sheep management in Mexico, it is necessary to design and delimit regional management units (RMUs) whose boundaries match the limits of the distribution area of the populations of the species (Gallina-Tessaro *et al.* 2009).

Potential geographic distribution models (PGDM) of species are useful tools for predicting the area of occurrence of species, identifying the environmental characteristics of the sites where they thrive, and projecting their presence over wider areas (Guisan and Thuiller 2005; Melo *et al.* 2020). These models are useful for designing efficient strategies for *in situ* management of populations, since they allow focusing monitoring and protection actions on the specific areas of the habitat used (Guisan and Thuiller 2005; Villero *et al.* 2017). One of the main applications of PGDMs in wildlife population management is RMU delimitation (Rodríguez-Soto *et al.* 2011; Maciel-Mata *et al.* 2015).

PGDMs are used primarily in the formulation of conservation and management plans and programs for at-risk species of hunting importance or with wide ranges (Guisan and Thuiller 2005; Refoyo *et al.* 2014; Eyre *et al.* 2022), such as wild ungulates (Ortíz-García *et al.* 2012; ENETWILD consortium *et al.* 2022). However, the reliability and functionality of the PGDM results depend on several factors: scale of the study area, accuracy and randomness of the geographic records of the species, and relevance, autocorrelation, and resolution of the environmental variables used as predictors (Austin 2007; Mateo *et al.* 2011).

Bighorn sheep are found in extensive mountain ranges with steep slopes, deep cliffs, and large canyons, where vegetation cover is scarce and temperatures are extreme, making it difficult to carry out regular and representative monitoring of population size and dispersal (Hansen 1980; Álvarez-Cárdenas *et al.* 2009; Ruiz-Mondragón *et al.* 2018). In the state of Baja California, Mexico, bighorn sheep populations inhabit 13 mountain ranges that cover an area of approximately 967 910 ha from La Rumorosa, on the border with the United States of America, to the Agua de Soda mountain range, located 50 km north of the border with Baja California Sur, Mexico (Romero-Figueroa *et al.* 2024). In this range, sheep populations are concentrated in areas where conditions are suitable for their persistence (Simmons and Hansen 1980), such as rugged terrain, open vegetation cover, presence of medium-sized shrubs (less than 1.5 m high), and water availability (Hansen 1980; Ruiz-Mondragón *et al.* 2018; Jones *et al.* 2022).

This study aimed to develop a PGDM for bighorn sheep, aiming to determine the RMUs for the species in Baja California. The following research questions were addressed: a) Where are the areas with the largest bighorn sheep populations? b) What is the extent of its potential range? c) What is the relative importance of the environmental variables that limit their distribution? d) How many bighorn sheep RMUs can be defined in the state?

Materials and methods

Description of the study area. The study was carried out in the Mexican state of Baja California, which covers an area of 71 446 km^2. This region extends from 32°43'07" to 28° N, and from 112°17'48" to -118°21'54" W (Figure 1). The main relief forms include mountain ranges, hills, plateaus, descents, plains, valleys, and dunes (INEGI 2001). The predominant climates in the region are temperate dry, very warm very dry, semi-warm very dry, temperate very dry, semi-cold sub-humid, and temperate sub-humid (García and CONABIO 1998). The dominant vegetation types are chaparral, microphyllous scrub, rosetophyllous scrub, and sarcocaulescent shrub (INEGI 2021).

Baja California has 13 mountain ranges where wild bighorn sheep populations thrive (Romero-Figueroa *et al.* *2024*; Figure 1). Land tenure at these sites is mainly ejido

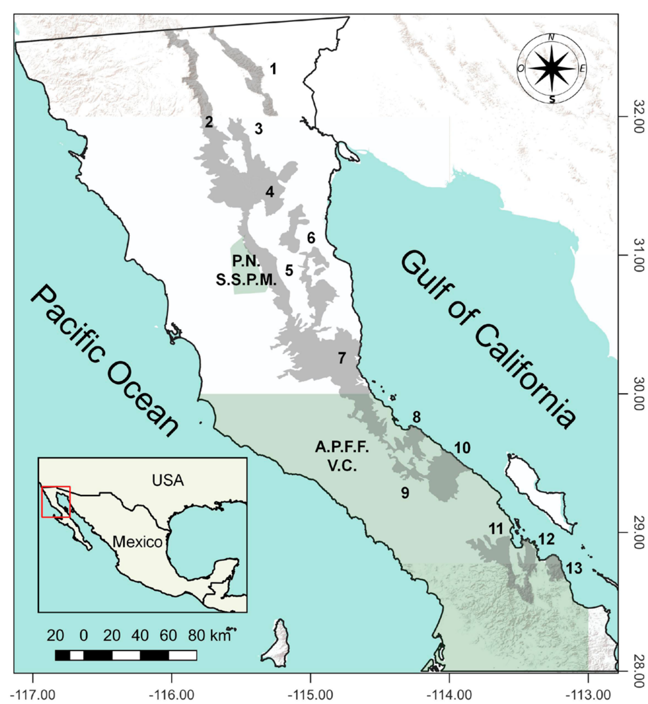

Figure 1. State of Baja California, Mexico, showing the mountain ranges (marked in grey) in which bighorn sheep occur: (1) Cucapá; (2) Sierra Juárez; (3) Las Tinajas; (4) Las Pintas; (5) San Pedro Mártir; (6) San Felipe; (7) Santa Isabel; (8) San Francisquito; (9) Calamajué; (10) La Asamblea; (11) La Libertad; (12) Las Ánimas; (13) Agua de Soda. Also shown (in green) are the NPAs that are within the distribution area of bighorn sheep. P.N. S.S.P.M.: Parque Nacional Sierra de San Pedro Mártir. A.P.F.F. V.C.: Área de Protección de Flora y Fauna Valle de los Cirios.

(RAN 2016). Similarly, the bighorn sheep distribution area is partially located within natural protected areas (NPAs): the Sierra de San Pedro Mártir National Park (PNSSPM, in Spanish) and the Valle de los Cirios Flora and Fauna Protection Area (APFFVC, in Spanish; CONANP 2024).

Generation of the database of bighorn sheep presence records. The bighorn sheep presence database was built from records of the species obtained from sampling campaigns carried out in different years. This study used data from aerial monitoring conducted by the San Diego Zoo in Sierra Juárez in 2012 (Ruiz-Mondragón *et al.* 2018) and from the surveillance flight by the Autonomous University of Baja California in 2021 that covered the 13 distribution areas recognized for bighorn sheep in Baja California (Romero-Figueroa *et al.* 2024). Additional records used regard direct sightings and indirect evidence of the presence of the species (fecal groups and footprints) obtained in terrestrial monitoring as part of a study of the distribution of bighorn sheep in the Sierra Juárez mountain range in 2016 (Ruiz-Mondragón *et al.* 2018); in terrestrial monitoring carried out within the framework of the Cimarrón Sanctuary project in the Sierra de La Asamblea and Calamajué in 2021; and in surveillance and camera-trap installation tours in Sierra Santa Isabel and Sierra Juárez in 2022 as part of a participatory community monitoring program (Ruiz-Mondragón *et al.* 2023).

The database was supplemented with records available in the Global Biodiversity Information System (GBIF; 2021), which were refined to exclude occurrence points in the sea or outside the distribution area reported in the literature. Records within 2 km of one other were excluded from our database to reduce spatial bias in the data (Merow 2013).

Predictors of environmental variables. Climate, relief, and vegetation were the environmental variables used to generate the PGDM for bighorn sheep (Rubin *et al.* 2009; Ruiz-Mondragón *et al.* 2018; Salas *et al.* 2018). Of these, 19 variables were bioclimatic, two were topographic (orientation and terrain roughness index), and two were vegetation variables (vegetation type and enhanced vegetation index). Geospatial information was handled in raster format and was processed in the QGIS 3.22.10 geographic information system (QGIS Development Team 2022).

The bioclimatic variables were generated by Cuervo-Robayo *et al.* (2013) for Mexico with a 90 m spatial resolution, available at the Idrisi Resource Center of the Autonomous University of the State of Mexico (UAEM 2021). These variables were rescaled to a 30 m spatial resolution to match the resolution of the relief and vegetation variables. Orientation and terrain roughness index (TRI) data were extracted from a digital elevation model with a 30 m resolution (INEGI 2013). The vegetation type was obtained from the Series VII of the Land Use and Vegetation Layer of Mexico (INEGI 2021) rasterized with a 30 m pixel resolution. The Enhanced Vegetation Index (EVI) was calculated from Landsat 8 OLI/TIRS satellite images captured between October and November 2022 (USGS 2022), which correspond to the months when the local vegetation greened after the passage of Hurricane Kay, thus favoring the discrimination power of the vegetation index. A mosaic was constructed with the EVI images that covered the entire study area. The generated geospatial information layers were adapted to match the extent of the study area.

The variance inflation factor ($FIV = 1*[1-r^2]^{-1}$) was used as a criterion to exclude redundant variation between variables (Akinwande *et al.* 2015). The index was obtained from multiple regressions used to estimate the correlation of the variables considered for the potential distribution model; the variables whose information was contained in any other variable were excluded ($FIV > 5$; Alvarado-Avilés *et al.* 2020). From this analysis, eight environmental variables were selected for use as predictors to estimate the distribution area of bighorn sheep in Baja California (Table 1).

Table 1. Environmental variables used as predictors to construct the potential geographic distribution model of bighorn sheep in Baja California.

Variable	Description	Units
Bio08	Mean temperature of the rainiest month	°C
Bio14	Precipitation of the dryest month	mm
Bio18	Precipitation of the warmest quarter	mm
Bio19	Precipitation of the coldest quarter	mm
Orientation	Direction of exposure of a slope	°
TRI	Degree of surface irregularity. It is calculated as changes in terrain elevation within a 3 × 3 pixel matrix and summarizes the point change in elevation in each pixel and in the 8 pixels surrounding it (Riley *et al.* 1999).	m
Vegetation type	According to the Land Use and Vegetation Layer of INEGI (2021)	
EVI	Contrast between absorption and radiation of vegetation (Liu and Huete 1995). The index is used as an indicator of vegetation cover; it takes values between 0 and 1. Values close to zero indicate areas devoid of vegetation, while values close to one (1) are typical of areas densely covered by plant species.	

Prediction of potential geographic distribution. The Maxent 3.4.4 program (Phillips *et al.* 2020) was used to predict the geographic distribution area of bighorn sheep in Baja California. The algorithm was implemented based on the criteria by Phillips *et al.* (2006) for basic niche modeling with a logistic output format, and the result indicates the probability of occurrence of the species of interest in a geographical space. The model was generated with a mean of 50 replicates with 1,000 iterations each. We used 80% of the localities of occurrence to construct the model and 20% to validate it. The predictive accuracy of the model was determined by calculating the area under the curve (AUC) of the receiving operating characteristic (ROC), and the fraction of sites classified erroneously as absences (omission errors) was determined by calculating the omission rate and the mean predicted area.

The number of replicates used for the model construction was determined based on the normality of the distribution of AUC values of the replicates (Plasencia-Vázquez *et al.*

2014) using the Shapiro-Wilk test; it was found that the 50 replicates fit a normal distribution (W = 0.96; p = 0.11). In the Maxent program interface, the *Do Jacknife to measure variable importance* and *Create response curves* options were activated. The Jacknife analysis was performed to evaluate the percentage of contribution of variables to the model generation. Response curves were created to determine the range of values for each variable within which the species is likely to occur (Phillips *et al.* 2006).

The continuous predictive model was transformed into a binary model (presence-absence). The cut-off threshold was determined from the mean of the minimum presence of training of the 50 replicates generated (Alvarado-Avilés *et al.* 2020). The binary model was projected over the Baja California mountain ranges (INEGI 2001), whose contours were used as the basis to define bighorn sheep RMUs, since these relief forms include the suitable habitat for the populations of this species (Hansen 1980; Álvarez-Cárdenas *et al.* 2009). The boundaries of RMUs were established at the points where the decrease in the concentration of binary-model pixels coincided with the boundaries of the mountain ranges, which was interpreted as an indication of the presence of barriers that limit the dispersal of organisms and, therefore, as the natural limit for a given bighorn sheep population (Epps *et al.* 2007). Similarly, the binary model was projected onto NPA polygons (CONANP 2024) to determine the fraction of the potential geographic distribution area found within an NPA in Baja California.

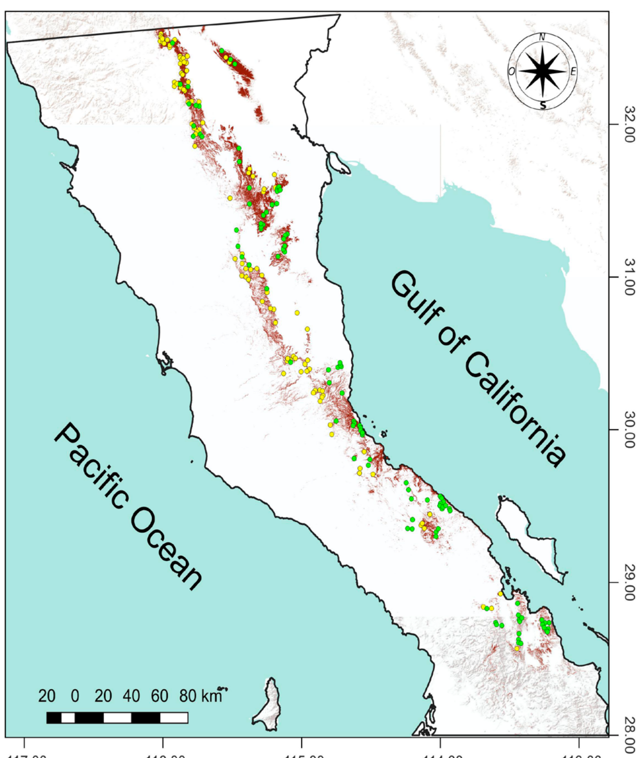

Figure 2. Potential distribution of bighorn sheep in Baja California (dark red). The image shows the presence records obtained from population monitoring (green) and the GBIF (yellow) used to generate the model.

Results

A total of 509 records of bighorn sheep were obtained for Baja California: 183 from population monitoring and 326 from the GBIF. After excluding records less than 2 km from each other, the database was reduced to 201 locations: 102 from population monitoring and 99 from the GBIF (Figure 2). The potential bighorn sheep distribution area in Baja California was calculated at 317 160 ha (4 % of the state area), stretching along the mountain massif of the Gulf of California coast from the US border to the Baja California Sur border. The AUC of the potential distribution model was 0.93, with a standard deviation of 0.02, and the omission rate was 0.40 (Figure 3).

The most important variables for the PGDM were roughness, vegetation type, and precipitation of the coldest quarter, which together contributed 78 % to the model construction. Each of the remaining variables contributed less than 10% (Table 2). According to the maximum-entropy algorithm, bighorn sheep in Baja California thrive in places where the roughness index varies between 35 m and 165 m covered by microphyllous scrub, sarcocaulescent scrub, riverbank vegetation or natural palm grove, and the precipitation of the coldest quarter ranges between 30 mm and 55 mm.

Table 2. Relative contribution (in percentage) of the environmental variables used to estimate the potential distribution area of bighorn sheep in Baja California and ranges of occurrence of the species.

Variable	Contribution (%)	Range of occurrence
TRI	38	35–165 m
Vegetation type *	23	MS, SCS, RV, NPG
Bio19	17	30–55 mm
Bio14	6	0.25–2.5 mm
Bio08	5	7–12 °C
Orientation	5	0°–100°
Bio18	4	0–65 mm
EVI	2	0–0.04

*MS = microphillous scrub; SCS = sarcocaulescent scrub; RV = riverbank vegetation; NPG = natural palm grove.

We defined 12 Regional Management Units (RMUs) for bighorn sheep in Baja California (Table 3; Figure 4). Within these RMUs, 85 % (271 044 ha) of the bighorn sheep distribution area is located on ejido land shared by 22 agrarian communities in the state. Furthermore, 23.6 % (71 520 ha) of the potential geographic distribution area of bighorn sheep is within a natural protected area: 22.3 % (70 626 ha) in Valle de los Cirios and 0.3 % (889 ha) in San Pedro Mártir.

Discussion

The most recent proposals regarding bighorn sheep distribution in Baja California were those of Lee *et al.* (2012) and Gutiérrez-Granados *et al.* (2020). Lee *et al.* (2012) indicate that bighorn sheep are distributed throughout the Gulf of California mountain range and interrupted in the

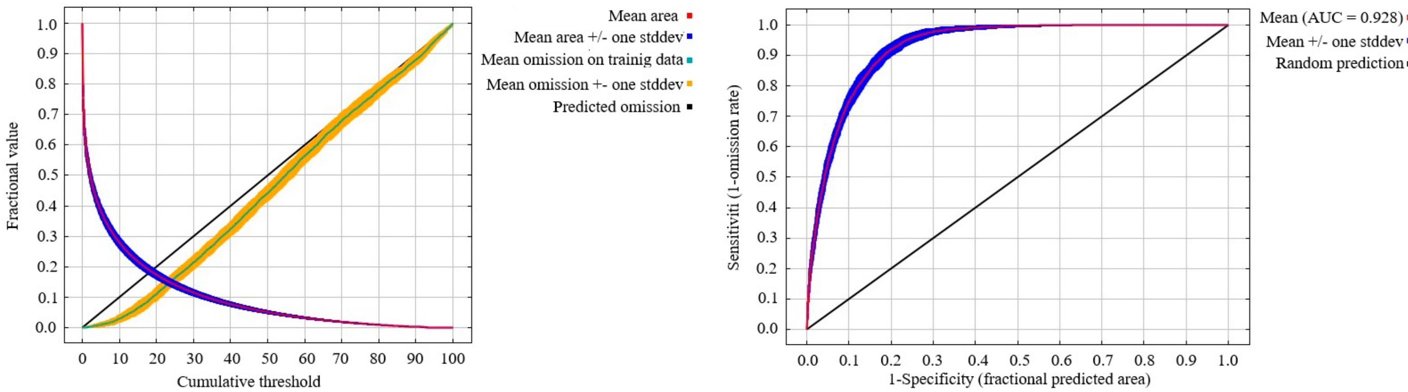

Figure 3. Area under the curve (AUC; left) and mean omission rate (right) of the 50 replicates used to estimate the potential distribution area of bighorn sheep in Baja California.

Agua de Soda mountain range, approximately 50 km north of the border with Baja California Sur (Figure 1). For their part, Gutiérrez-Granados *et al.* (2020) point out that the species is distributed continuously throughout the Gulf of California mountain range. Both proposals are inconsistent with the PGDM generated in this study, which indicates that in Baja California, bighorn sheep are distributed in patches throughout the Gulf of California mountain range (Figure 2).

Lee *et al.* (2012) defined the bighorn sheep distribution area in Baja California as the mountain ranges in which sightings were recorded in the aerial monitoring performed in the state. Therefore, the delimitation of the distribution area was conditioned by the geographical scope of the aerial surveillance. This explains why the authors point to the Agua de Soda mountain range as the distribution limit of bighorn sheep, since there were no flights south of this mountain range (Romero-Figueroa *et al.* 2024). However, despite its limitations, the distribution proposed by Lee *et al.* (2012) was hugely relevant because it represented the first effort to define the boundaries of the bighorn sheep range in Baja California, and is, therefore, one of the main references used to define the study area of the research on bighorn sheep in the state (Escobar-Flores *et al.* 2015; Ruiz-Mondragón *et al.* 2018; Ruiz-Mondragón *et al.* 2023; Romero-Figueroa *et al.* 2024).

On the other hand, Gutiérrez-Granados *et al.* (2020) constructed a PGDM to delimit the distribution area of bighorn sheep. Their work was also an important contribution to the matter because it defined the limits of the habitat available for the species in Baja California. However, it proposes a potential distribution area with an atypical pattern for any wild sheep species since they are not distributed evenly throughout the habitat but tend to concentrate around patches of habitat that provide the resources required by the species to survive, such as water, food, and escape ground (Bleich *et al.* 1990; Epps *et al.* 2007; Rubin *et al.* 2009; Salas *et al.* 2018). Another constraint of the PGDM generated by these authors is the size of the calculated distribution area, as it is too large to be used in decision-making on the management and monitoring of the species.

The lack of precision of the PGDM by Gutiérrez-Granados *et al.* (2020) is attributed to the inclusion of altitude and slope as predictor variables, the use of bioclimatic variables from WorldClim (Hijmans *et al.* 2005), and the use of a database of species occurrence made up entirely of GBIF records. In this type of analysis, altitude and slope are variables with marginal influence on the distribution of wild ungulates that inhabit mountainous areas (Keya *et al.* 2016; Khan *et al.* 2016; Ruiz-Mondragón *et al.* 2018; Salas *et al.* 2018). The low spatial resolution of WorldClim bioclimatic surfaces is a source of uncertainty for the model, as they do not reflect climate variations at the local level (Harris *et al.* 2014; Stewart *et al.* 2022). GBIF is a website with a particularly pronounced spatial bias due to uneven sampling effort, storage, and mobilization of data between the different areas in the range of a species, in addition to the lack of certainty about the quality of the data uploaded to the platform (Beck *et al.* 2014).

The PGDM presented in this study was developed from a database in which spatial bias was reduced by incorporating a similar number of records from field monitoring and the GBIF (Beck *et al.* 2014). Likewise, it was constructed using high-resolution bioclimatic variables developed especially for Mexico (Cuervo-Robayo *et al.* 2013), in addition to other predictor variables that are highly correlated with the distribution of bighorn sheep in the PGDM: terrain roughness, orientation, vegetation cover, and vegetation type (Rubin *et al.* 2009; Ruiz-Mondragón *et al.* 2018; Salas *et al.* 2018). This resulted in a PGDM showing a clustered distribution along a mountain range, consistent with the distribution pattern reported for the species (Bleich *et al.* 1990; Epps *et al.* 2007; Rubin *et al.* 2009; Ruiz-Mondragón *et al.* 2018). This suggests that this PGDM provides a more accurate representation of the distribution of bighorn sheep in Baja California than the one developed by Gutiérrez-Granados *et al.* (2020). In addition, it is a more useful tool for decision-making than the model of Gutiérrez-Granados *et al.* (2020), since it reduces by 75 % the distribution area proposed by these authors, facilitating the identification of areas of importance for the species.

The PGDM AUC assessment indicates good accuracy in discriminating between suitable and unsuitable sites for the species. However, the calculated distribution area is probably smaller than the actual range, as the omission rate of the training points did not fully match the predicted omission rate (Phillips *et al.* 2006; Figure 3).

The analysis of the contribution of the variables to the construction of the model indicated that roughness was the most relevant habitat component for bighorn sheep in Baja California (Table 3). This is an important variable for wild sheep species, as it is related to the availability of escape ground (Álvarez-Cárdenas *et al.* 2009; Salas *et al.* 2018). Furthermore, the presence of bighorn sheep was associated with sites with roughness values between 35 m and 165 m, typical of medium and high mountain ranges with canyons that provide protection to bighorn sheep in the Baja California peninsula (Álvarez-Cárdenas *et al.* 2009; Escobar-Flores *et al.* 2015; Ruiz-Mondragón *et al.* 2018).

Table 3. Fraction of the distribution area of bighorn sheep in each RMU and ejidos within its limits.

RMU	Area (ha)	Percentage	Ejidos*
Las Tinajas-Las Pintas	66 019	20.8	CM, MSC, Jam, JS, PNA
Santa Isabel	59 281	18.7	RAI, Mat, Rev
Sierra Juárez	58 736	18.5	EZ, Jac, AV, CM, MSC, Jam, DS, TK
San Pedro Mártir	30 040	9.5	Tep, PNA
Cucapá	29 474	9.3	EZ, HJ, LM
San Felipe	19 388	6.1	PNA, Del, Mat
La Asamblea	18 496	5.8	Juar, TL
La Libertad-Las Ánimas	13 567	4.3	TL, NR, CNC
Agua de Soda	12 362	3.9	TL
San Francisquito	6213	2	Mat
Calamajué	2781	0.9	Mat, Rev
La Sirena	805	0.3	Ind
Total	317 160	100	

*CM = Cordillera Molina; MSC = Misión de Santa Catarina; Jam = Jamau; JS = José Saldaña II; PNA = Plan Nacional Agrario; RAI = Reforma Agraria Integral; Mat = Matomí; Rev = Revolución; EZ = Emiliano Zapata; Jac = Jacumé; AV = Aubanel Vallejo; DS = Dieciséis de Septiembre; TK = Tribu Kiliwas; Tep = Tepi; HJ = Heriberto Jara; LM = López Mateos; Del = Delicias; Juar = Juárez; TL = Tierra y Libertad; NR = Nuevo Rosarito; CNC = Confederación Nacional Campesina; Ind = Independencia.

The vegetation type was another variable that contributed to the construction of the PGDM (Table 3) because it indicates the availability of forage and water for the species. In addition, it is related to the predator-avoidance strategy of bighorn sheep, which consists of using patches in which the vegetation foliage does not reduce visibility and, therefore, allows detection of predators from a distance (Wilson *et al.* 1980; Álvarez-Cárdenas *et al.* 2009; Escobar-Flores *et al.* 2015). As in other studies carried out in Baja California, it was determined that bighorn sheep are distributed in microphyllous scrub, sarcocaulescent scrub, riverbank vegetation, and natural palm groves (Escobar-Flores *et al.* 2015; Ruiz-Mondragón *et al.* 2018).

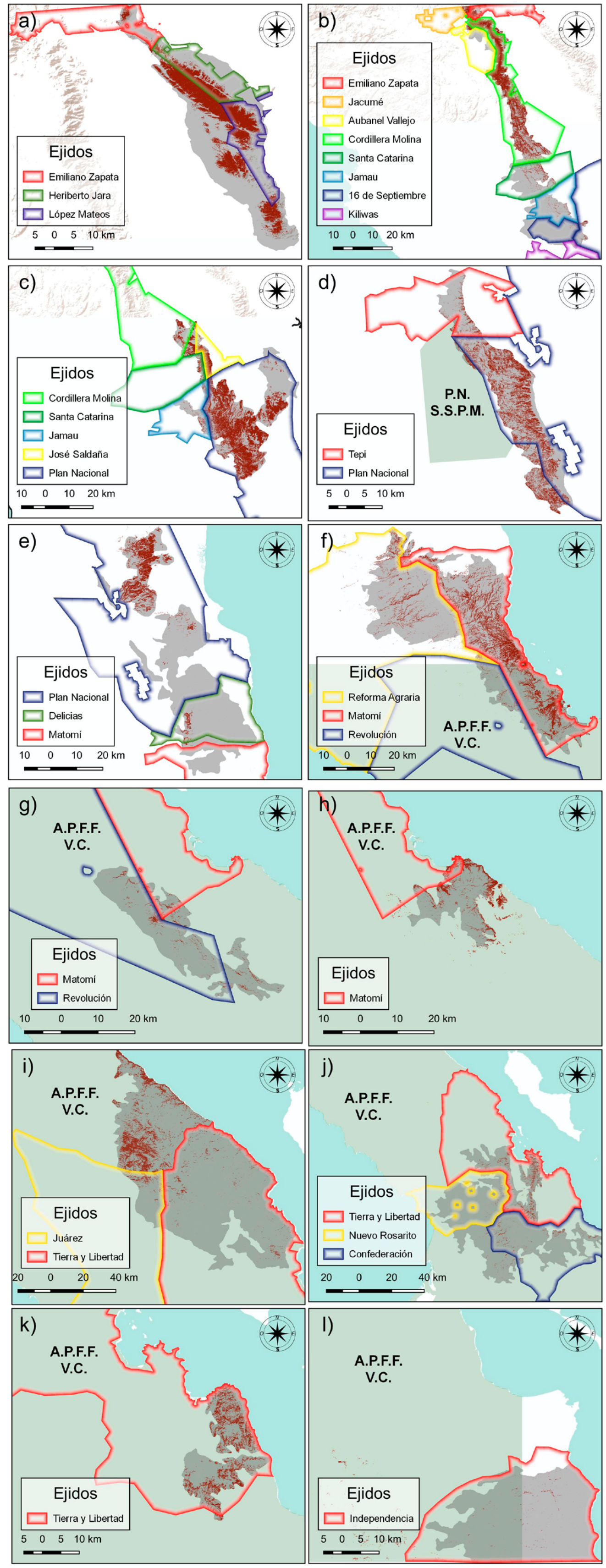

Figure 4. Regional Management Units (RMU) for bighorn sheep in Baja California (gray): a) Cucapá; b) Sierra Juárez; c) Las Tinajas - Las Pintas; d) San Pedro Mártir; e) San Felipe; f) Santa Isabel; g) Calamajué; h) San Francisquito; i) La Asamblea; j) La Libertad - Las Ánimas; k) Agua de Soda; l) La Sirena. The image shows the potential distribution of the species (dark red), NPAs (green), and ejidos that are within the limits of the RMU. P.N. S.S.P.M.: Parque Nacional Sierra de San Pedro Mártir. A.P.F.F. V.C.: Área de Protección de Flora y Fauna Valle de los Cirios.

Precipitation of the coldest quarter was the most important bioclimatic variable for bighorn sheep in Baja California (Table 3). This is attributed to the fact that the highest percentage of rainfall in the state occurs in winter (García and CONABIO 1998), and, therefore, this variable is related to water recharge in the habitat of the species. In addition, winter rains are related to the growth and flowering of quality forage for wild herbivores in Baja California (Delgadillo-Rodríguez and Macías-Rodríguez 2002).

In the state of Baja California, bighorn sheep management units are currently bounded by the boundaries of private land, ejidos, or the common use of ejidos, which have no relationship with the distribution patterns of bighorn sheep populations or their metapopulation dynamics (SEMARNAT 2022). This research outlines the first proposal for the definition of bighorn sheep management units in Baja California based on information on an ecological aspect of the species: its potential distribution. This proposal differs from the previous one by Lee *et al.* (2012), who proposed three RMUs: the northern RMU, which extends from Sierra Juárez to Sierra de San Felipe; the central RMU, from Santa Isabel to Sierra de La Asamblea; and the southern RMU, which includes the La Libertad, Las Ánimas, and Agua de Soda mountain ranges. This regional management proposal is based on the assumption that there are three metapopulations of bighorn sheep in Baja California; however, they do not provide evidence to support their existence. In this sense, there are also no studies showing that, in Baja California, a bighorn sheep metapopulation is distributed in two or more mountain ranges; on the contrary, genetic studies suggest that a mountain range can host more than one metapopulation (Buchalski *et al.* 2015).

The PGDM indicates that in Baja California the bighorn sheep shows a clustered distribution pattern, typical of wild sheep (Figure 2); that is, specimens of the species are concentrated in cores of suitable habitat connected by patches that function as biological corridors (Bleich *et al.* 1990; Epps *et al.* 2007; Rubin *et al.* 2009; Salas *et al.* 2018). The cores of suitable-habitat concentration are delimited by natural barriers that restrict the displacement of animals, which, according to the analysis of the contribution of variables, may be relatively flat areas with no escape terrain for the species (Berger 1991), a vegetation type unsuitable for the species because of a dense vegetation cover that reduces visibility (Bleich *et al.* 1997), or areas devoid of nutritious forage and water sources due to extremely aridity (Epps *et al.* 2004). This is why the boundaries of cores of suitable-habitat concentration were used to define the boundaries of RMUs for bighorn sheep, since the natural barriers between them contribute to confining the populations of the species, and, in this way, the abundance in each core of suitable-habitat concentration does not undergo significant fluctuations due to migratory processes (Epps *et al.* 2007; Creech *et al.* 2014).

The largest proportion of the bighorn sheep distribution area in Baja California is ejido land, and, in general, the land tenure of RMUs delimited in the present study corresponds to more than one ejido. This implies that each RMU should establish monitoring and protection programs for the bighorn sheep population with the participation of all landowners within the RMU (Dowsley 2009; Mandujano-Rodríguez and González-Zamora 2009). Furthermore, decision-making on the sustainable use of sheep should prioritize ejido management units and be based solely on the results of joint monitoring by all management units within an RMU (Adhikari *et al.* 2021).

The main benefit of regional management is the prevention of overexploitation of bighorn sheep populations. In Mexico, this problem is common to all game species at sites where the distribution area of local populations is shared between two or more individual management units (Gallina-Tessaro *et al.* 2009). This is due to the fact that a particular and independent exploitation quota is granted to each management unit based on the results of individual monitoring of a given local population (Mandujano-Rodríguez 2011). For this reason, to ensure the sustainable use of bighorn sheep, exploitation quotas must be established at the regional level rather than at the level of individual management units (SPA 2013; Ruiz-Mondragón 2014; 2017).

However, granting regional exploitation quotas for bighorn sheep poses a serious social challenge: the distribution of the benefits of hunting the species. The alternatives to resolve this issue could be the establishment of regional wildlife conservation management units (UMA, in Spanish) or the distribution of exploitation quotas that correspond to each RMU among the ejido management units involved, based on the fraction of the total habitat that belongs to each. The formation of regional UMAs is not considered the best option because there are considerable differences in the number of members in each ejido (Ruiz-Mondragón *et al.* 2023) and in the fraction of the bighorn sheep habitat owned by each (Figure 4). In this regard, it is worth noting that two regional UMAs were formed in Baja California whose viability could not be verified because they never started operations: the UMA named Ejidos Asociados de Baja California, comprising the ejidos Cordillera Molina, Hermenegildo Galeana, José Saldaña, and Plan Nacional Agrario; and the UMA Valle de los Cirios, made up of the ejidos Nuevo Rosarito, Revolución, and Tierra y Libertad. The distribution of hunting permits granted to each RMU among the ejido management units based on the fraction of the bighorn sheep habitat owned by each is considered the most viable alternative to solve the problem of the distribution of the economic benefits of sheep hunting, since the larger the area available, the greater the investment required for its management (Ortega-Argueta *et al.* 2016). This approach ensures that larger management units have sufficient financial resources to invest in the conservation of bighorn sheep populations and their habitat, while smaller units also participate in the economic benefits of bighorn sheep exploitation.

In Baja California, approximately 25 % of the bighorn sheep range is within an NPA, and this fraction of the habitat concentrates about 38 % of the total population of the species in the state (Romero-Figueroa *et al.* 2024). This situation has important implications for both bighorn sheep conservation and NPAs. On the one hand, Mexico's National Commission of Natural Protected Areas (CONANP, in Spanish) has the power to participate in the formulation and monitoring of the correct implementation of the work plans developed to manage one-quarter of the habitat available for the species and more than one-third of the bighorn sheep population in the state of Baja California (CONANP 2006; SEMARNAT 2013). On the other hand, bighorn sheep management units within NPAs can potentially become the main promoters of the conservation of these sites, since they can provide working groups for biodiversity surveillance and monitoring, invest in infrastructure and in the implementation of habitat improvement actions, and finance productive diversification projects around bighorn sheep (Brenner and De la Vega 2014; Sandoval *et al.* 2019).

Conclusions

The calculated distribution area for bighorn sheep in Baja California was 317 160 ha, extending throughout the state through the Gulf of California mountain range. The most influential environmental variables in the construction of the distribution model were roughness, vegetation type, and precipitation of the coldest quarter. The predictor variables were related to the presence of escape terrain, its suitability for the predator-avoidance strategy, and water and food availability. Based on the PGDM, 12 RMUs were delimited for bighorn sheep in Baja California, whose land tenure is ejido. It is recommended that the management of bighorn sheep populations within each RMU be carried out based on monitoring, protection, and sustainable use programs for bighorn sheep populations, involving the participation of all ejidos that own land within it.

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