frontiers | Frontiers in Climate

TYPE Original Research
PUBLISHED 25 June 2025
DOI 10.3389/fclim.2025.1386632

OPEN ACCESS

EDITED BY
Robert Lempert,
RAND Corporation, United States

REVIEWED BY
Marcus Blum,
Texas A&M Natural Resources Institute,
United States
Ernesto Vicente Vega,
Institute for Ecosystem and Sustainability
Research in Morelia, National Autonomous
University of Mexico, Mexico

*CORRESPONDENCE
Hilda C. Zamora-Maldonado
✉ hilda.zm@tec.mx;
✉ hilda.zamoram@gmail.com

RECEIVED 15 February 2024
ACCEPTED 28 May 2025
PUBLISHED 25 June 2025

CITATION
Zamora-Maldonado HC, Avila-Foucat VS and Sánchez-Sotomayor VG (2025) Modeling climate change impacts on the potential distribution of bighorn sheep in Mexico. *Front. Clim.* 7:1386632.
doi: 10.3389/fclim.2025.1386632

Modeling climate change impacts on the potential distribution of bighorn sheep in Mexico

Hilda C. Zamora-Maldonado[1,2]*, V. Sophie Avila-Foucat[1] and Víctor G. Sánchez-Sotomayor[3]

[1]Institute of Economic Research, National Autonomous University of Mexico, Mexico City, Mexico, [2]Tecnologico de Monterrey, Institute of Advanced Materials for Sustainable Manufacturing, Monterrey, Mexico, [3]Conservación en Acción A.C. (Civil Association), Guerrero Negro, Mexico

Climate change is expected to significantly reshape the geographic distribution of many species worldwide. The bighorn sheep (*Ovis canadensis*), a species of ecological, economic, and cultural importance in Mexico, is particularly vulnerable to these environmental shifts. This study applies ecological niche modeling to estimate the probability of species occurrence based on bioclimatic variables under future climate scenarios. Using four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0, 8.5) and six General Circulation Models, projections are made for the period 2041–2060. This analysis is based on 280 georeferenced records of bighorn sheep occurrences and evaluates changes in temperature and precipitation, which are assumed to influence their potential distribution. Projections suggest a significant reduction in geographic distribution, with drier periods and extreme temperatures exerting the most detrimental effects. These findings pose considerable challenges for long-term conservation and management of bighorn sheep populations, as current strategies may be insufficient. The ecological niche model suggests focusing conservation efforts on Northern Baja California (Californian ecoregion) to identify potential distribution. This research emphasizes the critical need to integrate climate projections into conservation strategies to better manage the uncertainties of climate change.

KEYWORDS
ecological niche modeling, climate change, wildlife management, bighorn sheep, conservation planning

1 Introduction

Conserving species in a changing climate presents a significant challenge for wildlife managers. As environmental conditions shift, the habitats that species rely on today may no longer be suitable, while new areas may emerge as potential habitats. One of the most profound effects of climate change on wildlife is the alteration of temperature and historical precipitation patterns, which directly impact species based on their physiological traits and tolerance to environmental changes (Bellard et al., 2012).

Beyond direct effects, climate change can also disrupt species' food availability and reproductive timing, indirectly influencing their fitness and survival (Mondal and Martinez-Garcia, 2024; Sattar et al., 2021; Douglas and Leslie, 1983). As a result, future climate patterns are expected to drive significant shifts in species' geographic distributions (Garcia et al., 2014).

Preserving ecosystems and species in their current locations is becoming increasingly difficult, as climate change poses one of the greatest conservation challenges of the future (García et al., 2016; Hoegh-Guldberg et al., 2018). Therefore, understanding and analyzing these impacts is essential for developing effective management strategies that enhance species resilience and support their survival in an increasingly unpredictable environment.

Climate change can affect ecosystems both directly and indirectly. Direct impacts include alterations in seasonal patterns of rainfall and temperature, while indirect impacts encompass climate-induced changes in vegetation, as well as other disturbances such as fires, floods, and droughts (Chidumayo, 2011). These changes not only disrupt ecosystems (Peterson et al., 2014) but also lead to substantial economic losses, creating significant financial burdens. These challenges are not uniform; their impacts vary significantly across regions and economic contexts, disproportionately affecting resource-dependent communities that rely on wildlife for their livelihoods (Adger, 2010; Robinson and Bennett, 2001). As a result, these financial and ecological disruptions directly hinder wildlife conservation efforts, hamper habitat restoration initiatives, and complicate the implementation of effective management strategies.

These widespread ecological and economic disruptions underscore the need for a deeper understanding of how species respond to changing environmental conditions. One way to assess the effects of climate change on biological species is by analyzing shifts in temperature and precipitation patterns in relation to species' distributional changes (Peterson and Anamza, 2015). In this regard, ecological niche modeling (ENM) and species distribution modeling (SDM) have become valuable tools for evaluating the potential impacts of climate change on species distributions.

ENM and SDM are a suite of methods that characterize the suitable environmental conditions that allow species to persist (i.e., its ecological niche). The model of a species' ecological niche can be projected onto geographic space to generate a map representing the distribution of suitable conditions. These projections can then be further refined and simulated using alternative climate change scenarios. This approach allows researchers to produce potential distribution maps under different environmental conditions, helping to assess species' future potential distribution. Biologists have applied this approach to predict potential distribution loss for polar bears (*Ursus maritimus*) due to melting sea ice (Durner et al., 2009). Similarly, potential distribution models for the endangered golden-cheeked warbler (*Setophaga chrysoparia*) have been used to assess the effects of changing climate patterns on its breeding areas in Texas (Mathewson et al., 2012). These projections provide valuable insights for wildlife managers, aiding in habitat protection and restoration efforts in response to climate change pressures.

Bighorn sheep are both a symbolic game species in North America and a key indicator of ecosystem health. Valued for their ecological, cultural, and economic significance, they are highly sensitive to environmental changes. Their metapopulation structure depends on habitat connectivity for genetic diversity, and a thriving herd signals a well-balanced, resilient ecosystem. This dual role underscores their importance in conservation and ecological monitoring efforts, while also contributing to local economies through ecotourism and regulated hunting. However, the species faces growing challenges due to climate change, including habitat loss, altered forage availability, and increased disease susceptibility. Rising temperatures and shifting precipitation patterns are expected to reduce water availability, alter vegetation dynamics, and increase the frequency of extreme weather events, further stressing populations. A recent study by Creech et al. (2020) highlights the critical need to integrate climate change considerations into current management strategies to ensure the long-term viability of bighorn sheep populations. Without proactive adaptation measures, habitat fragmentation and resource scarcity may accelerate population declines. As environmental conditions continue to change, implementing forward-looking conservation strategies becomes essential to mitigate these threats and support population resilience.

While some studies as early as 2014 have highlighted the importance of considering climate factors in bighorn sheep conservation, none have proposed concrete strategies to address these challenges (Johnson, 2014; Brewer et al., 2014; Staudinger et al., 2015). The primary reason for this gap is the inherent uncertainty of climate change (Lempert, 2002). This uncertainty complicates wildlife conservation planning, especially in terms of decision-making for selecting suitable geographic areas, further intensifying the challenges for conservation managers.

In Mexico, economically important wildlife species are managed by a federal program called Units for the Conservation, Management and Sustainable Use of Wildlife (UMAs), which are policy instruments for conserving and managing flora and fauna species. Beyond the UMA system, conservation efforts also extend to Natural Protected Areas (ANPs), which are legally designated regions focused on preserving biodiversity, ecosystems, and natural resources. However, this broader conservation and management approach encompasses a larger geographic extension than ANPs alone (Avila-Foucat and Pérez-Campuzano, 2015), integrating landscape-scale strategies that enhance environmental protection and sustainability. The policy seeks to generate income for community and private land managers through the conservation of species and their habitats. UMAs are classified as either *extensive* (where species are managed in the wild) or *intensive* (where species are managed in enclosures or greenhouses). In extensive UMAs, population numbers are estimated through field sampling. In Mexico, bighorn sheep populations are managed within this system and are monitored using both aerial and terrestrial surveys. Bighorn sheep have been authorized to be managed in Mexico in the states of Baja California Sur, Sonora, Coahuila, Nuevo Leon, and Chihuahua since 1996. The Official Mexican Regulation (NOM) 059-ECOL-1994 considers the subspecies (*O. c. weemsi*) as subject to special protection and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) includes this subspecies in the international treaty's appendix II that includes species not necessarily threatened with extinction, but in which trade must be controlled in order to avoid utilization incompatible with their survival.

Given the significance of this conservation and resource management framework, this study explores climate change impacts on wildlife potential distribution and exemplifies ways in which this information can be used to guide long-term management decisions. We focus on three subspecies (*O. c. mexicana*, *O. c. cremnobatres*, and *O. c. weemsi*) distributed in northern Mexico, which represent one of the most profitable game species in the country, generating annual revenues of US$2,657,000 in Baja California Sur (Lee, 2011). The economic value and ecological role of these subspecies underscore the urgency of our investigation. Investigating bighorn sheep is crucial due to their role as an indicator species and their economic

 10.3389/fclim.2025.1386632

significance in Mexico. Understanding climate change impacts on the geographic areas where they occur informs conservation strategies, ensuring population resilience and sustainable management in a rapidly changing environment.

2 Methods

Climate change uncertainty presents a challenge both for developing scenarios of climate change's ecological impacts and for designing sustainable management strategies of natural resources (Wang et al., 2012). Often, projections about climate change impacts are based on a single climate change scenario or small number of general circulation models (GCMs) and greenhouse gas (GHG) emission scenario combinations used to represent a wide array of equally plausible future climates (IPCC, 2007). These simulation strategies reduce computational effort and simplify interpretation for decision-makers; however, relying on only one or a few arbitrarily selected climate change scenarios increases the likelihood of introducing biases in decision-making, which inadvertently can increase decisions' vulnerabilities.

To incorporate climate uncertainty in this analysis, we first projected the future potential distribution of the bighorn sheep niche using each projection as an ensemble of climate change scenarios separately; then we combined the results of multiple projections into a single "consensus" map on which each pixel was identified as the environmental conditions most frequently projected across all climate change scenarios.

2.1 Study area

Bighorn sheep (*Ovis canadensis*) have a wide geographic range, spanning western Canada, the western United States, and northern Mexico (Figure 1) (Brewer et al., 2014). Given the diversity of landscapes and environmental pressures across this range, management strategies must be adapted to address region-specific conservation challenges.

2.1.1 Bighorn sheep in Mexico: distribution and conservation challenges

Historically, bighorn sheep in Mexico occupied the steep hills and rugged terrain of Baja California (1), Baja California Sur (2), Sonora (3), Chihuahua (4), Coahuila (5), and Nuevo León (6) (Medellin et al., 2005). However, populations in Chihuahua, Coahuila, and Nuevo León were extirpated during the 20th century, and remaining populations in other parts of Mexico have become highly fragmented (Ceballos and Oliva, 2005). Despite these losses, populations in Sonora, Baja California Sur, and Baja California are now considered stable (Lee, 2003). Aerial surveys conducted in 2021 estimated a population of 1,697 bighorn sheep in Baja California (Romero-Figueroa et al., 2024).

This study was conducted in northwestern Mexico, where bighorn sheep inhabit arid and semi-arid regions in Baja California and Sonora. Additionally, successful reintroduction efforts have restored populations in Chihuahua and Coahuila, reversing past extinctions (Sandoval et al., 2019). However, the species remains at risk, as the

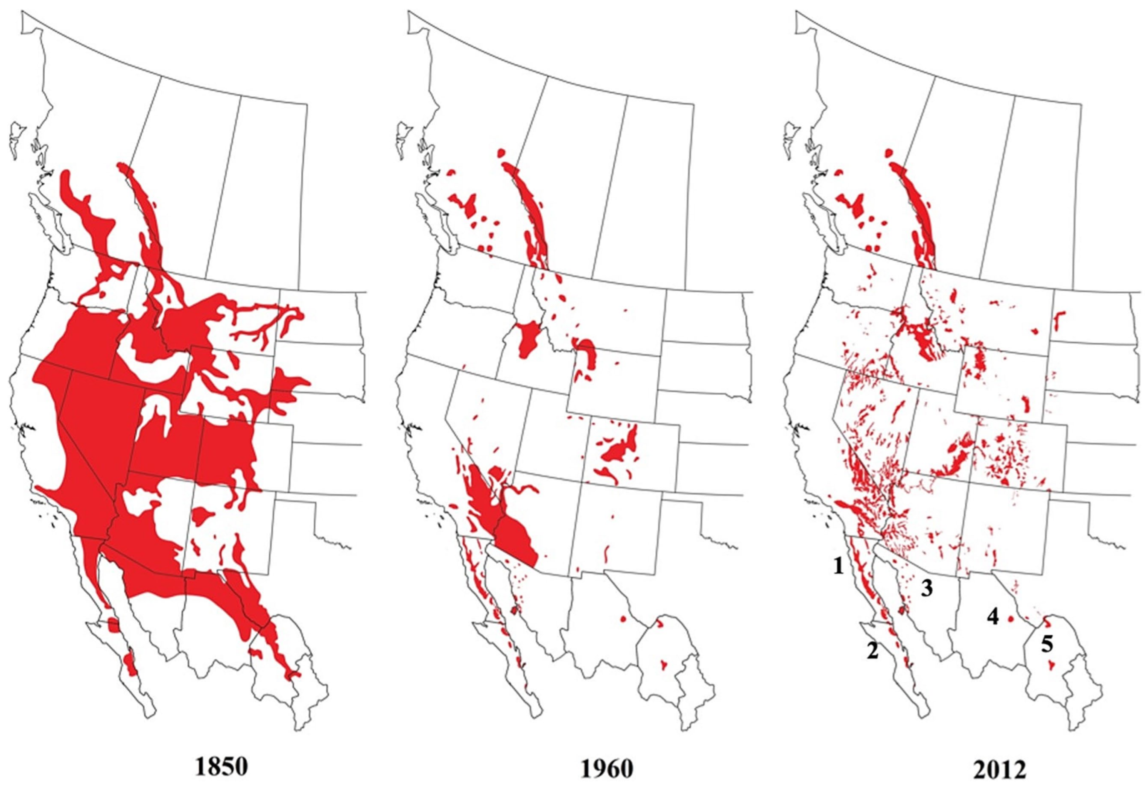

FIGURE 1
Historic distribution of bighorn sheep (1850, 1960) and more recent distribution (2012) (Wild Sheep Foundation and WAFWA Wild Sheep Working Group, 2012; Brewer et al., 2014).

Mexican federal government classifies bighorn sheep as threatened due to habitat loss and human-induced alterations (INE, 2000).

To ensure the long-term conservation of bighorn sheep, the State Strategy for the Conservation and Sustainable Management of Bighorn Sheep (*Ovis canadensis cremnobates*) in Baja California incorporates sport hunting as a management tool (Lee, 2008). By generating economic incentives, this approach seeks to fund habitat protection and conservation programs, aligning with broader efforts to maintain viable populations amid growing environmental challenges.

The importance of integrating conservation with sustainable use is reflected in Mexico's Bighorn Sheep Mexican Program, which was launched in 1996. This initiative was developed under the Biosphere Reserve scheme, in collaboration with Units for the Conservation, Management, and Sustainable Use of Wildlife (UMAs) and the Foundation for North American Wild Sheep (FNAWS). The program was first implemented in the "ejido" (i.e., land tenure) Alfredo Vladimir Bonfil, located within the El Vizcaíno Biosphere Reserve in Baja California Sur.

UMAs function under a management plan approved by the Secretariat of Environment and Natural Resources (SEMARNAT), which allows for the selective harvest of sheep while ensuring continuous monitoring of habitat and populations. Within this framework, ejidos serve as administrative units where managers make key conservation decisions regarding species management and sustainable use.

A management plan within ejidos is a strategic document that defines conservation objectives, outlines specific actions, and establishes timelines for implementation. These plans emphasize adaptive management, requiring continuous monitoring and adjustments to ensure long-term sustainability amid changing environmental conditions.

The primary goal of the 1996 conservation program was to establish a self-sustaining, long-term conservation model. The central premise of the program is that if local communities—rather than intermediaries—directly benefit from sustainable resource management, it will create strong economic incentives for habitat conservation.

Under optimal conditions, a single bighorn sheep hunting permit at ejido Alfredo Vladimir Bonfil can reach a market value of $65,000. However, hunting permits in Mexico typically range from $45,000 to over $100,000 (Lee, 2011; Ruiz, 2014). These high market values demonstrate how conservation can become a profitable and sustainable business model for communities, and potentially, for entire regions in the long term.

As part of its commitment to sustainability, the program reinvests revenue from regulated hunting into natural resource conservation and the well-being of local communities. By linking economic benefits with species conservation, this approach ensures that bighorn sheep populations remain stable while also fostering community involvement in long-term habitat management.

2.2 Input data

ENMs need two types of data to estimate potential distribution: a set of georeferenced locations where the species has been detected and a set of quantitative raster maps describing the environmental conditions under which the target species lives. One of the most-used algorithms for ENMs is MaxEnt (Maximum Entropy) (Phillips et al., 2006), which estimates the potential distribution index of a species by finding the most spread-out, or "maximum entropy," distribution given environmental constraints. MaxEnt is robust with small sample sizes and performs well when only presence data are available, making it a widely recognized tool for species distribution modeling. It is used for estimating the potential distribution index and potential range shifts under changing environmental conditions (Elith and Leathwick, 2009; Phillips et al., 2006; Merow et al., 2013). This study uses climatic variables that are among the most important factors driving species' distribution (Grinnell, 1917; Guisan et al., 2013), especially at large spatial extents, as they have a direct influence on organisms' behavior and physiology. They are particularly important for plants, which cannot evade adverse weather by sheltering or migrating.

Historical occurrence data for the bighorn sheep subspecies were obtained from an open-access repository, the Global Biodiversity Information Facility (GBIF.org) web database. GBIF collects biodiversity data by aggregating species occurrence records from global institutions, researchers, and citizen scientists, using standardized formats. Occurrence data were filtered from 1994 to 2020, and only the subspecies *O. c. mexicana*, *O. c. cremnobatres*, and *O. c. weemsi* were included. The 1,158 records underwent a spatial verification process, where data points carefully were reviewed to ensure their accuracy and consistency with the species' historical known range. This involved identifying and removing any erroneous or mislocated entries from the database. After this quality control, a final set of 280 georeferenced records remained, providing a reliable foundation for analysis. The calibration area, also referred to as the M region (Barve et al., 2011), defines the accessible area for species, crucial for accurate niche modeling by setting boundaries for potential distribution predictions and minimizing bias. For these subspecies in Mexico, the calibration area was based on the ecoregions in which they are distributed (Escobar-Flores et al., 2015), as these units represent geographic barriers for several species' dispersal. The selected ecoregions for *O. canadensis* in Mexico included the Californian, Baja Californian, Sonoran, Altiplano Norte (also known as the Chihuahuan Desert), Tamaulipas, and the Mexican transition zone Sierra Madre Occidental (Figure 2).

Nineteen bioclimatic layers representing annual, seasonal, and extreme climatic patterns were downloaded from the Chelsa database (https://chelsa-climate.org) (Brun et al., 2022), providing high-resolution climate data that offers a more accurate fit compared to simple monthly or yearly averages. The datasets in Karger et al. (2018) cover both the current period (1979-2013) and future projections (2014-2060). All layers were downloaded at a 30 arc-second resolution and clipped to the calibration area. Future GCMs were incorporated, based on scenarios of GHG emissions or representative concentration pathways (RCPs), to generate climate change projections. The layers were cropped to the M region, which defines the species' accessible area, enhancing the models' precision. Uncertainty in the climate projections was addressed by using four different RCPs (2.6, 4.5, 6.0, 8.5) alongside six GCMs (Supplementary Appendix 1). We developed a GCM consensus map (Figure 3) by averaging the outputs of multiple GCMs over 20-year horizon (2041–2060) to capture a robust range of climate projections. The RCPs represent a range of potential GHG emission trajectories, from the low-emissions pathway (RCP 2.6), which assumes emissions peak and decline shortly after 2020, to RCP 8.5, which assumes

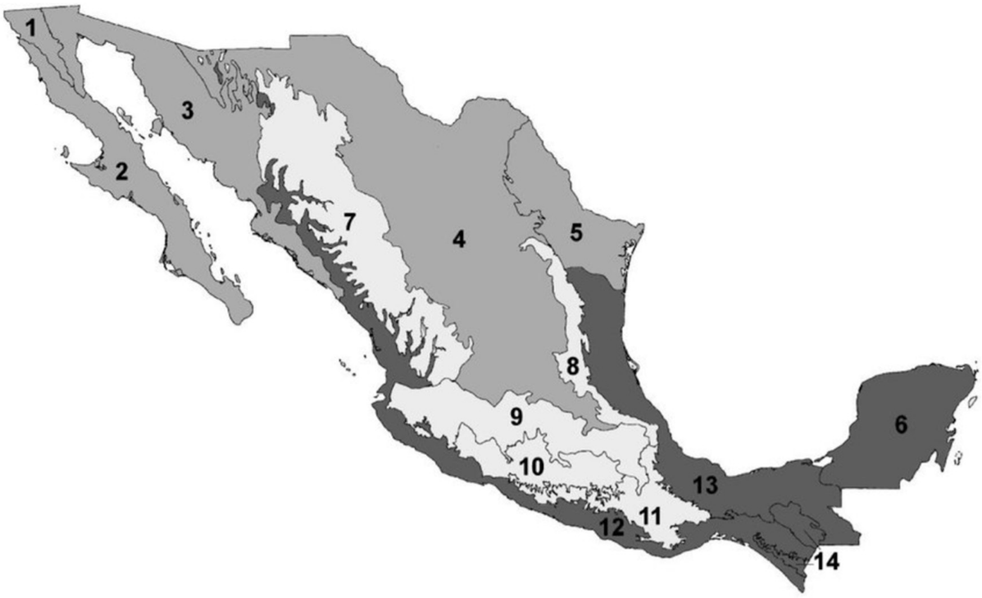

FIGURE 2
Ecoregions in Mexico. 1, Californian; 2, Baja Californian; 3, Sonoran; 4, Altiplano Norte (Chihuahuan Desert); 5, Tamaulipas; 6, Yucatan Peninsula; 7, Sierra Madre Occidental; 8, Sierra Madre Oriental; 9, Eje Volcanico Transmexicano; 10, Cuenca del Balsas; 11, Sierra Madre del Sur; 12, Costa Pacifica Mexicana; 13, Gulf of Mexico; 14, Chiapas. Modified from Morrone, 2005.

continued growth emissions through 2,100 (Weyant et al., 1996). Although RCP 8.5 has been widely used in ecological modeling to represent worst-case climate outcomes, recent literature suggests it no longer reflects a plausible "business-as-usual" scenario. Its underlying assumptions —such as high fossil fuel dependency and negligible mitigation— are increasingly inconsistent with global policy and energy trends (Peters and Hausfather, 2020). The IPCC Sixth Assessment Report (2023) similarly notes that recent mitigation efforts and the declining cost of low-emissions technologies are driving reductions in global energy and carbon intensity, making extreme high-emission pathways less likely. Nevertheless, we retain RCP 8.5 in this analysis to explore upper-bound climate risks and to apply the precautionary principle in conservation planning (Cooney, 2004; Rye et al., 2021), ensuring that even low-probability but high-impact outcomes are considered.

2.3 Data processing: preselecting the variables

After inputting the data, we followed a structured approach to process and refine the information. The first step involved preselecting the environmental variables to ensure model accuracy. To avoid redundancy, we assessed multicollinearity among environmental variables using the Pearson correlation coefficient in R (version 4.3.3, R Core Team, 2024). The correlation analysis was conducted within the R base environment, allowing us to identify and manage highly correlated variables.

When two variables had a Pearson correlation coefficient $|r| > 0.85$ (indicating strong correlation) (Pradhan, 2016; Schober and Schwarte, 2018), only one was retained for model development. Selection criteria were based on each variable's predictive strength and expert knowledge to ensure the most relevant covariates were used. This analysis determined that 10 environmental variables best explained bighorn sheep presence (Supplementary Appendix 2).

The predicted model was initially calibrated for the period 1979–2013 and then projected for 2041–2060, incorporating various Representative Concentration Pathways (RCPs) and General Circulation Models (GCMs) to account for different climate scenarios. The final dataset was analyzed using Tableau (version 2018.3), an interactive data visualization software, to better interpret spatial patterns and model outcomes.

Uncertainty in climate change projections was addressed by averaging outputs from six GCMs and four RCPs. This approach reduces model-specific biases and integrates a broad spectrum of greenhouse gas emission scenarios, from low to high. By combining multiple models and scenarios, the analysis captures both structural and scenario-related uncertainties, resulting in more reliable climate impact estimates.

This improved reliability strengthens conservation planning and habitat management by providing robust, data-driven insights. To apply these findings at a local scale, we incorporated a raster layer of ejido polygons in Mexico. Using ejidos in Baja California, Baja California Sur, and Sonora as a reference, we identified highly suitable areas for bighorn sheep. Identifying these areas is crucial for policy intervention, as ejidos play a key role in habitat management, conservation efforts, and species protection under changing environmental conditions.

2.4 Model settings

The MaxEnt model was run with five replicates, using 25% of the data for testing, and a maximum of 8,000 background points. The

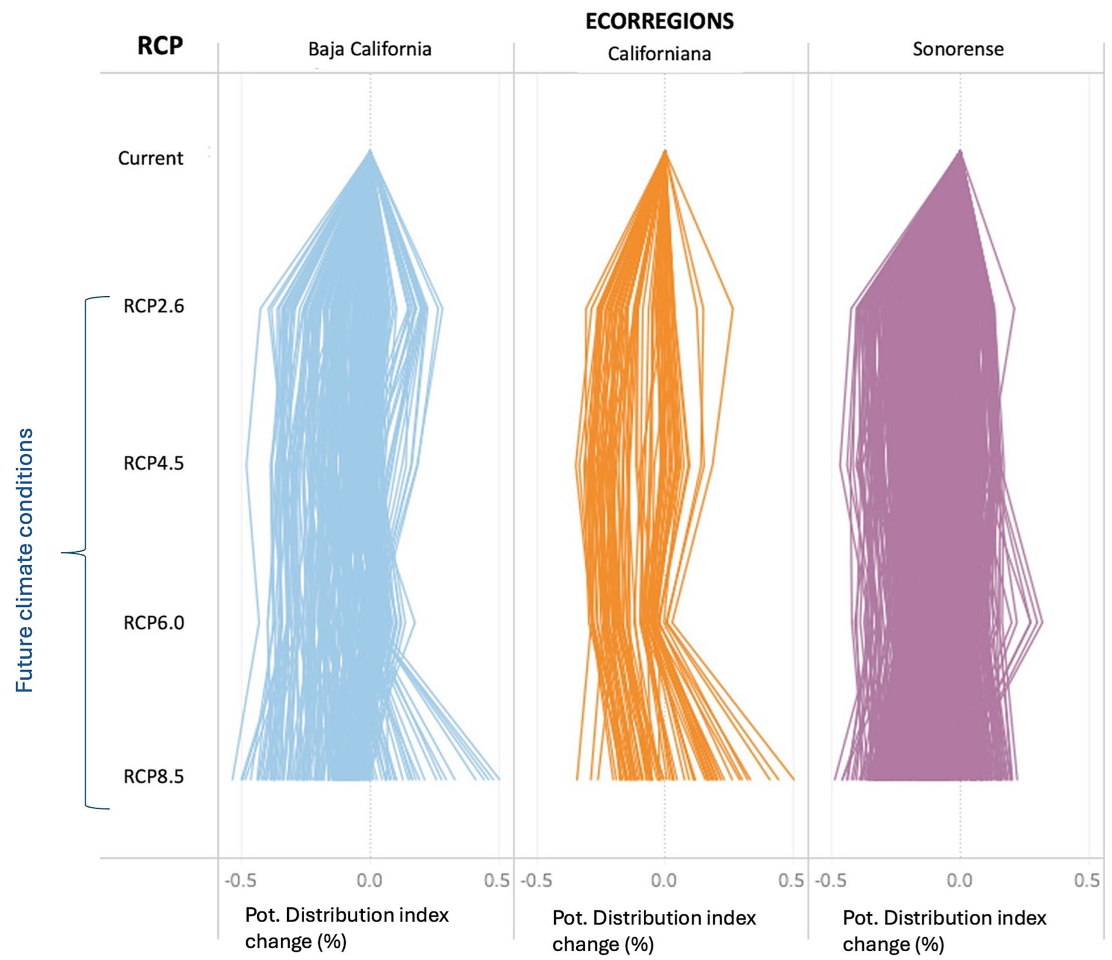

FIGURE 3
Bighorn sheep potential distribution index changes in ejido polygons (Baja California, Baja California Sur, and Sonora) under GCM average values and four RCPs (2.6, 4.5, 6.0, and 8.5).

model was set to run for up to 500 iterations with a regularization parameter of 0.5. To estimate potential distribution, we used a probability transformation method that accounts for species presence likelihood in a nonlinear way (log–log output format). The random test percentage was 25 percent, which means that 75 percent of the total database was used as the random sample to train the model, and the other 25 percent was used to test the model predictions. To avoid overfitting the test data, we set the regularization multiplier value to 0.5. The output format was a default cloglog transform, which has a stronger theoretical justification than the logistic transform (Phillips et al., 2017). This study used linear, quadratic, product, threshold, and hinge feature classes (auto features) based on sample sizes (Phillips and Dudík, 2008). Phillips and Dudík (2008) classified the features for sample sizes: an auto features setting for more than 80 records, quadratic and hinge setting for 15–79 records, linear and quadratic for 10–14 records, and linear setting for sample sizes fewer than 10 records.

The ENM established a relationship between the bighorn sheep occurrence and predictor variables and estimates the present and future climatic niche for Mexico's bighorn sheep. A potential distribution map for *Ovis canadensis* was produced by utilizing the area under the threshold-independent receiver operating characteristic curve (AUC) weight averages of the five log–log output format maps produced by five-fold cross-validation. The goodness-of-fit test of the MaxEnt model was evaluated by AUC in which the relative suitability ranged from 0 to 1, among which that of 0.5 suggests that the models show no predicting capability, while that of >0.7 represents that the models are acceptable. The model also was evaluated by the true skill statistic (TSS) that measures model performance, comparing predicted and actual species occurrences (Allouche et al., 2006) based on five-fold cross-validation. The TSS ranges between −1 and +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random (Zhang et al., 2020). The following ranges were used to interpret TSS statistics: values < 0.4 were poor, 0.4–0.8 useful, and > 0.8 were good to excellent (Zhang et al., 2015).

3 Results

3.1 Model performance and key climatic drivers of big horn sheep distribution

The average AUC value of niche models from five-fold cross-validation was 0.9887, indicating high discrimination accuracy between presence and background locations (Allouche et al., 2006). The True Skill Statistic (TSS) value was 0.4955, suggesting a useful and reliable model for predicting bighorn sheep distribution.

Precipitation and temperature are well-documented key climate variables influencing species distributions (Zhong et al., 2010). For bighorn sheep, three bioclimatic variables had the highest positive contributions to their probability of occurrence:

- Bio17 – Precipitation of the Driest Quarter,
- Bio12 – Annual Precipitation, and
- Bio9 – Mean Temperature of the Driest Quarter.

Extreme temperatures can constrain bighorn sheep distribution limits, affecting their ability to persist in certain regions and influencing distribution shifts over time.

3.2 Geographic distribution

Figure 4 illustrates that the current potential distribution of bighorn sheep in Mexico is primarily restricted to the northwest, including Baja California, Baja California Sur, and Sonora, as well as Tiburón Island. The map displays only areas with high potential distribution index (0.4 to 0.99) under current climate conditions. Baja California (Figure 4, number 1) has the highest number of ejidos with high potential distribution index ($n = 35$). Baja California Sur (Figure 4, number 2) has the highest number of ejidos (12) with high potential distribution index (0.6 and even close to 0.9). Sonora (Figure 4, number 3) is the third state with a high potential distribution index in five ejidos, including Tiburon Island.

We compared the potential distribution in all polygons. Figure 5 shows high potential distribution (30–99 percent) areas in the ejido polygons. The potential distribution estimated in each GCM differed. In general, the bighorn sheep potential distribution decreases in the future, especially in the extreme RCP 8.5. Notably, climatic suitability declines in key conservation areas, including Baja California, ejido Bonfil, and Tiburón Island, not only under the high-emission scenario (RCP 8.5) but also under RCP 6.0 and RCP 4.5 across nearly all General Circulation Models (GCMs). The only exception is the Earth System Model (ESM) from the College of Global Change and Earth System Science, Beijing Normal University, which projects more stable climatic conditions in these regions (Figure 5).

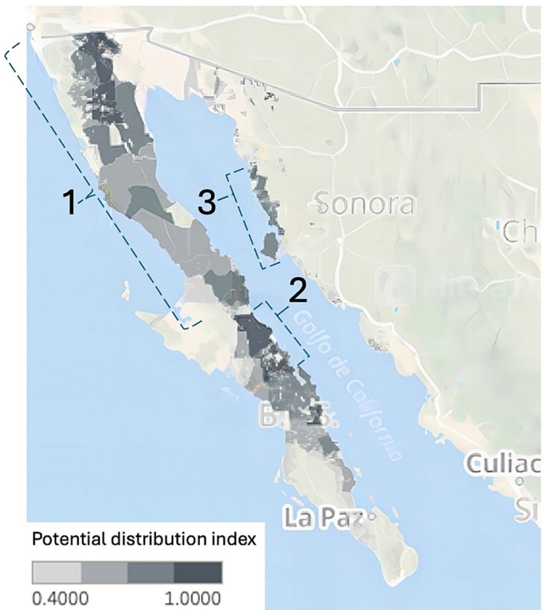

FIGURE 4
Bighorn sheep potential distribution in Mexico under current bioclimatic conditions (Chelsa time series 1979–2013).

Figure 3, column 1, shows that ejido polygons in Baja California (BC), Baja California Sur (BCS), and Sonora have an average potential distribution index of 0.85 under current conditions. However, when considering future climate scenarios, the potential distribution index changes, with a reduction in areas offering favorable precipitation and temperature conditions, especially under RCP 8.5.

Figure 3, column (BC, BCS, Sonora) shows that under RCP 8.5, the potential distribution for bighorn sheep populations decreases, with favorable areas predominantly shifting to the northern part of Baja California. The study shows significant changes in the potential distribution for bighorn sheep across future climate projections. Figure 3, column 2 (Baja California Sur), reveals a decline in potential distribution in the southern polygons of Baja California Sur (with an average potential distribution of 0.57, so a 32 percent decrease) and Sonora (with an average potential distribution index of 0.37, so a 56 percent decrease). However, under the more extreme RCP 8.5 scenario, some polygons in Baja California show an increase in potential distribution. It also is observed that the potential distribution index within the polygon boundaries of ejido Bonfil decreases by 38 percent under climate change scenarios from 0.87 to 0.55 (Figure 3, column Ejido Bonfil potential distribution).

MaxEnt outcomes give estimates of relative contributions of the environmental variables to the model (Table 1). Accordingly, Bios17—Precipitation of Driest Quarter and Bios12—Annual Precipitation are the variables contributing the most to potential distribution predictions of *Ovis canadensis* in Mexico.

Figure 6 suggests that negative changes to climatic suitability are more drastic at the Sonoran and Baja Californian ecoregion, where more than half of the ejidos present a negative percentage change with respect to the current potential distribution index, while ejidos in the Californian ecoregion seem to have a negative percentage change in at least half of its ejidos. Thus, the Californian ecoregion is where ejidos have a lower decrease in the bighorn sheep potential distribution index.

4 Discussion

4.1 Impacts of climate change on bighorn sheep potential distribution

Climate change poses a significant threat to bighorn sheep habitat in Mexico, with projections indicating a reduction in suitable areas under future climate scenarios. Under the high-emission RCP 8.5 scenario, the species' potential distribution is expected to decline, highlighting the substantial impact that climate change may have on habitat suitability.

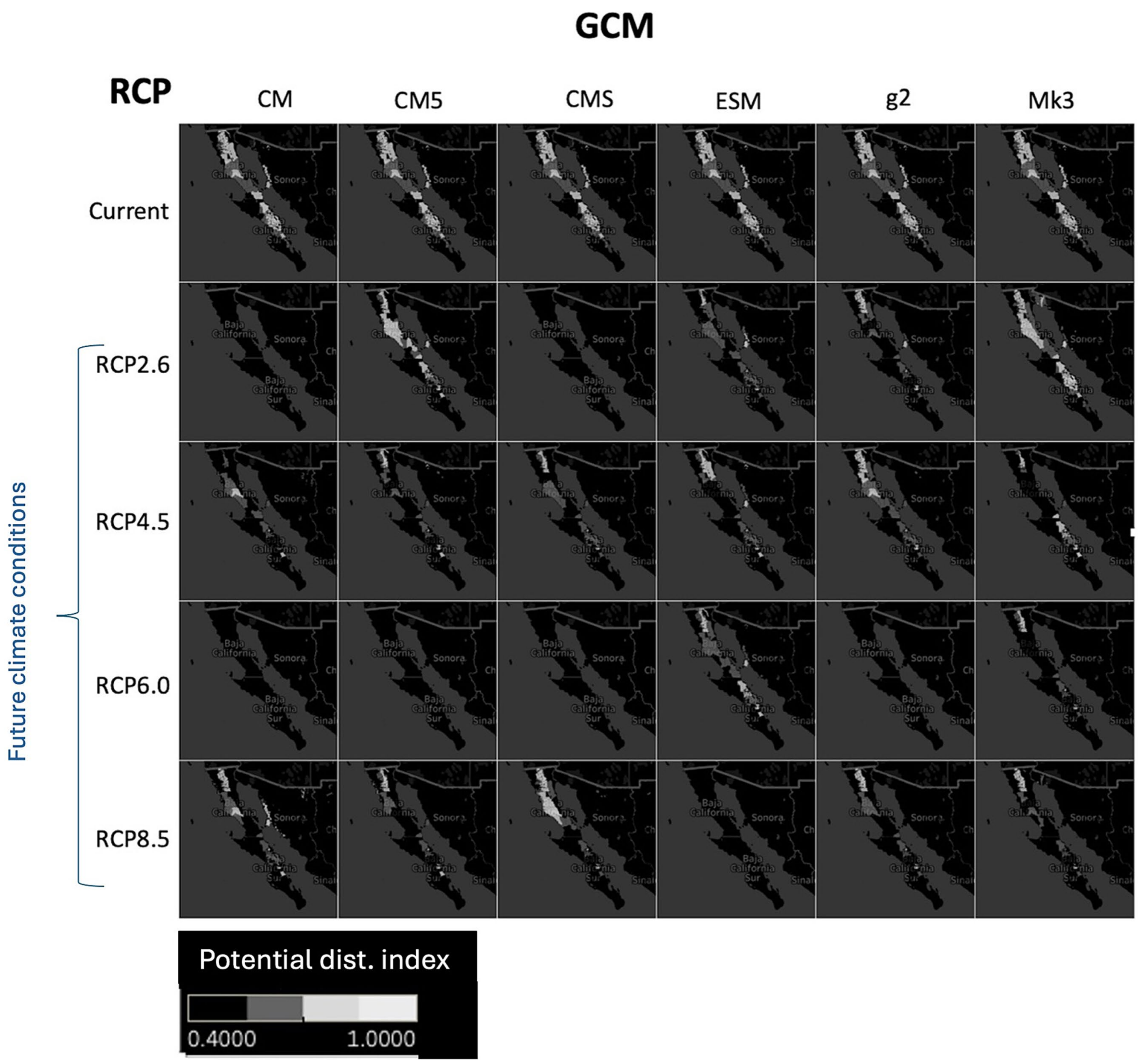

FIGURE 5
Bighorn sheep potential distribution in Mexico under current (Chelsa time series 1979–2013) and future (Chelsa time series 2041–2060) bioclimatic conditions.

TABLE 1 Contribution of bioclimatic variables in the potential distribution of bighorn sheep in Mexico by ejido.

Variable name	Percent contribution
Bio17—precipitation of driest quarter	64.3
Bio12—annual precipitation	18.6
Bio09—mean temperature of driest quarter	4.6
Bio11—mean temperature of coldest quarter	4.3
Bio13—precipitation of wettest month	3.7
Bio08—mean temperature of wettest quarter	2.5
Bio15—precipitation seasonality	2
Bio19—precipitation of coldest quarter	0.1

However, model results also reveal a geographic shift in favorable conditions, with some polygons in northern Baja California showing increased potential distribution under this more extreme scenario.

This seemingly paradoxical outcome may be explained by a northward shift in climatic conditions that more closely align with the species' bioclimatic niche—particularly in areas experiencing a relative decrease in seasonal water stress—. These localized increases in potential distribution highlight the complex, non-linear, and spatially heterogeneous nature of climate impacts. They also reinforce the need for geographically targeted and adaptive conservation strategies. One of the most concerning projections is the 38% decline in potential distribution within ejido Bonfil, where the potential distribution index drops from 0.87 to 0.55 under future climate change scenarios. Given that this area has been a key conservation stronghold for bighorn sheep, the projected reduction suggests that current management efforts may be insufficient to ensure the species' long-term viability in this location. This underscores the urgency of integrating climate adaptation measures into conservation planning, particularly in areas projected to undergo the most severe declines in the species' occurrence.

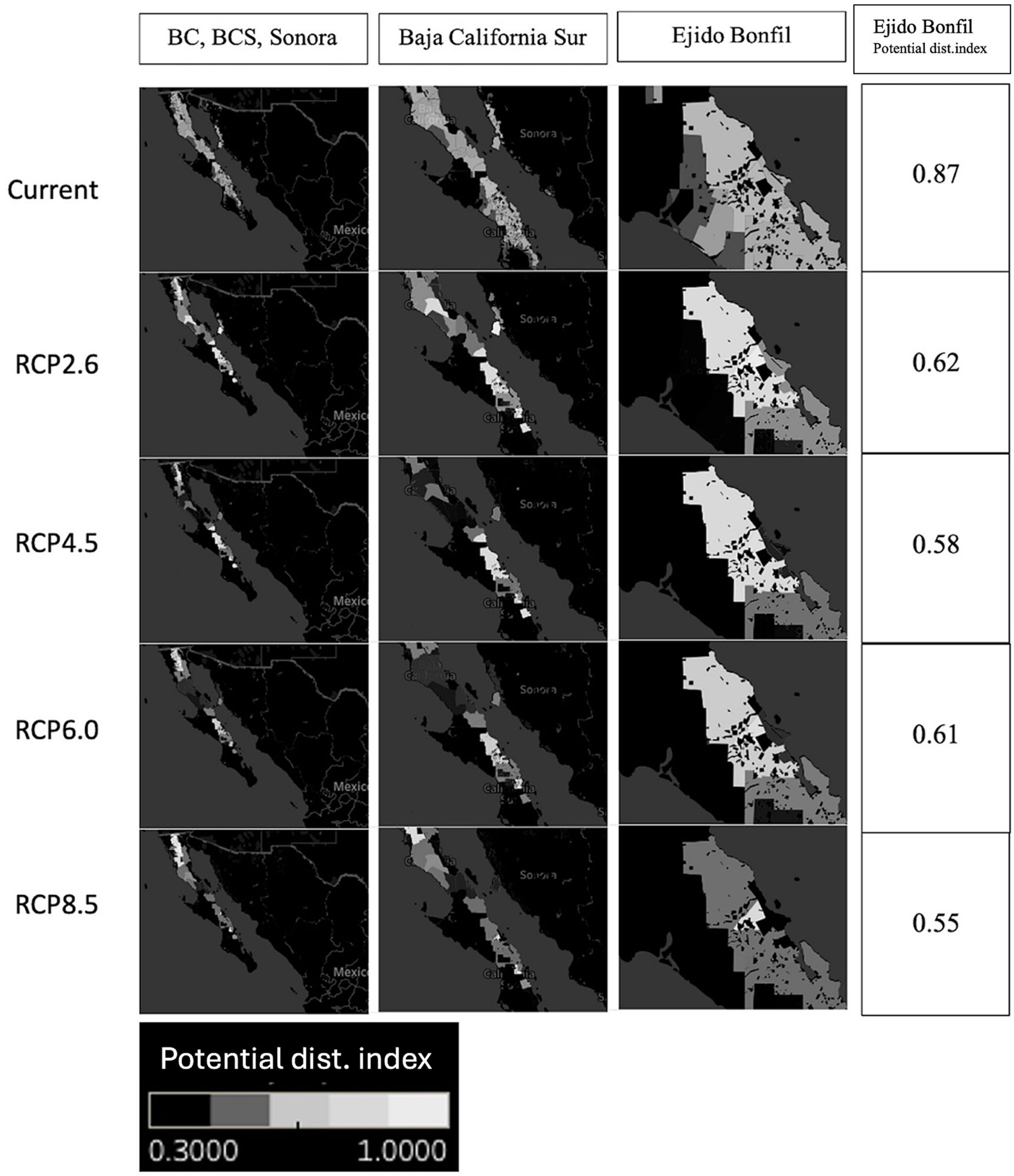

FIGURE 6
Bighorn sheep percentage change in potential distribution by ecoregion.

In this context, mapping potential future distributions becomes critical for guiding species management. Identifying and prioritizing high-potential distribution areas enables conservation managers to focus resources on the landscapes most likely to support bighorn sheep in the future. Moreover, the use of multiple GCMs highlights uncertainty in climate projections, yet consensus maps, such as the one developed in this study, serve as essential tools for policy-oriented wildlife management decisions.

4.2 Key climatic drivers and uncertainty considerations

Results from the MaxEnt model indicate that Bio17 (Precipitation of the Driest Quarter) and Bio12 (Annual Precipitation) are the most influential environmental variables (Supplementary Appendix 3). These findings reinforce the critical role of precipitation. In arid and semi-arid ecosystems, such stress is a key limiting factor, and for bighorn sheep, the driest part of the year imposes critical physiological and ecological challenges (Turner and Weaver, 1980). These variables capture the minimum precipitation during this period, influencing forage availability, hydration, and movement patterns. Incorporating these variables into the model allows the model to assess potential distribution under conditions of seasonal drought, which is projected to intensify in much of the species' range.

Given the variability in potential distribution across different GCMs, it is essential to integrate multiple computational approaches to address uncertainties in wildlife management planning. RCP 8.5 shows significant negative changes in temperature and precipitation, which could adversely affect species distributions. However, some northern Baja California polygons remain highly suitable, suggesting that shifts in conservation priorities may be necessary. While RCP 8.5 is increasingly considered less likely under current emissions trajectories (IPCC, 2023; Peters and Hausfather, 2020), its inclusion helps identify areas at high risk and stress-test management strategies under extreme climate futures. However, some northern Baja California polygons remain highly suitable, suggesting that shifts in conservation priorities may be necessary. Decision-makers must evaluate all possible futures by considering multiple GCMs and RCPs (Lempert et al., 2006), ensuring that management strategies remain flexible and responsive to new climate data.

4.3 Management strategies and policy implications

A key conservation strategy involves focusing on areas with a high potential distribution index, particularly in northern Baja California under RCP 8.5. Prioritizing these regions for habitat protection, restoration, and monitoring is essential to maintaining suitable environments for bighorn sheep as climate change impacts their current range. Understanding which populations are under the most climate-related stress is crucial for anticipating future conservation and management actions (Zamora-Maldonado et al., 2021).

The Bonfil ejido, with 28 years of experience (1996–2024) in bighorn sheep conservation and sustainable hunting programs, has developed extensive expertise in species management. This accumulated knowledge could serve as a foundation for establishing a training and collaboration program to assist other ejidos in adapting to future habitat shifts. As conservation efforts may need to shift toward northern Baja California, ejido-based management strategies should be expanded and restructured to align with these geographic changes. Importantly, ejido owners are already engaged in ongoing dialog to promote collaborative and sustainable decision-making regarding bighorn sheep management.

4.3.1 The role of niche modeling in adaptive management

Future potential species distribution is a multifactorial outcome, influenced by climatic, ecological, and anthropogenic factors. The present study demonstrates that GCMs and RCPs contribute to model uncertainty, highlighting the importance of exploring all potential climate futures when designing policy-oriented wildlife management plans. Our results confirm that the potential distribution index varies across GCMs, reinforcing the need to integrate all reliable and available data (species occurrences, climate projections, and species distribution models) to build a more robust, policy-relevant niche model.

4.3.2 Translocation and conservation planning

In anticipating potential distribution shifts, managers should explore potential reintroduction sites and corridors for dispersal in future high-potential distribution regions. Land acquisition strategies that secure conservation lands with greater potential to harbor refugia should be prioritized (Dreiss et al., 2022; Graziano et al., 2022; Hilty et al., 2020; Tingstad et al., 2017). The Californiana ecoregion in northern Baja California emerges as a priority conservation area, where potential distribution may remain stable despite climate shifts.

Given the successful translocation of bighorn sheep populations to Tiburón Island and Carmen Island in Mexico (Wilder et al., 2014), further efforts to translocate individuals into newly identified high-suitability areas may be a viable conservation strategy (Langridge et al., 2020; Ramos et al., 2018). These efforts demonstrate the potential for bighorn sheep conservation through assisted relocation, offering a science-based approach to species management.

4.4 Balancing conservation and economic considerations

Effective wildlife management must balance conservation priorities with economic incentives. Large herbivores such as bighorn sheep play a key role in ecosystem dynamics, influencing primary production, nutrient cycling, and habitat structure (Danell, 2006). However, they also provide economic benefits through regulated hunting programs, which generate revenue for local communities and conservation initiatives.

Assessing the impacts of climate change on economically valuable species is critical for biodiversity stewardship and local livelihoods (Saba et al., 2012). While much research has focused on fisheries and climate change (Islam et al., 2014; Sumaila et al., 2011), there is a need to further quantify how climate change will affect terrestrial wildlife species with economic significance, such as bighorn sheep (Advani, 2014).

4.5 Study limitations and considerations

While this study provides valuable insights into the potential effects of climate change on bighorn sheep potential distribution, we recognize its limitations. Landscape features such as slope, terrain ruggedness, and distance to water are undeniably critical for bighorn sheep at finer spatial scales. However, this study is not intended to replace localized assessments but rather to serve as a complementary tool for understanding broad-scale climate-driven habitat shifts.

Our decision to focus exclusively on bioclimatic variables is based on the study's primary objective: to assess how climate change influences potential bighorn sheep distributions. Bioclimatic factors are particularly suited for this purpose because they:

Directly and indirectly shape species distributions – Climate affects physiological tolerances (Epps et al., 2004) and influences vegetation patterns and water availability (Cruz et al., 2024), both of which are crucial for bighorn sheep survival.

Enable long-term projections – Unlike terrain variables, which remain largely unchanged over time, bioclimatic variables allow us to model habitat shifts under future climate scenarios (e.g., RCPs 2.6, 4.5, 6.0, 8.5) using multiple General Circulation Models (GCMs).

We acknowledge that integrating additional ecological and landscape variables could further estimate habitat suitability. However, the results of this study offer a valuable foundation for broad-scale conservation planning, helping to identify priority areas for further, more localized research. Future studies can build upon this analysis by incorporating landscape features and species movement patterns, ensuring a more comprehensive approach to bighorn sheep conservation under changing climate conditions.

5 Conclusions and recommendations

Estimating how climate change will impact bighorn sheep distribution is essential for effective conservation and management, not only in Mexico but across the species' entire range in Canada and the United States. Ecological niche modeling (ENM) combined with climate projections is a valuable tool for anticipating habitat shifts globally (Cheung et al., 2016; Pereira et al., 2010). However, regional-scale models, such as the one developed in this study, provide critical insights into the specific management challenges and opportunities for bighorn sheep conservation.

Our results highlight a significant contraction of potential distribution for bighorn sheep under extreme climate scenarios, particularly RCP 8.5, by the end of the century. These reductions may lead to serious ecological and socioeconomic consequences, particularly for communities that rely on sustainable wildlife management. Although RCP 8.5 is used to explore worst-case outcomes, we acknowledge recent critiques regarding its plausibility. Nevertheless, its inclusion allows conservation planners to identify areas of greatest vulnerability and evaluate the resilience of current management strategies. The potential distribution shifts northward, with some polygons in Baja California showing an increase in potential distribution, emphasizing the need for adaptive conservation strategies.

Mapping future potential distribution is critical for targeting conservation efforts efficiently, particularly for resource-limited managers. This study provides actionable insights that can inform policy adaptation, habitat restoration, and translocation initiatives, ensuring that conservation efforts remain effective in a changing climate. However, climate impact analyses often rely on a limited set of emission scenarios and general circulation models (GCMs), restricting the full range of potential futures. A more comprehensive approach—incorporating multiple climate models and uncertainty analyses—is needed to enhance conservation planning and decision-making (Groves and Lempert, 2007).

Existing conservation efforts, whether through Natural Protected Areas (ANPs), UMAs, or private conservation initiatives, may prove insufficient if they fail to anticipate climate-driven habitat shifts. Integrating climate projections into ecological niche models allows managers to identify areas likely to remain suitable for bighorn sheep under future conditions (Ashcroft, 2010; Ramirez-Villegas et al., 2014). This approach improves prioritization efforts, ensuring that long-term conservation goals align with changing environmental conditions.

5.1 Key conservation recommendations

This study underscores the importance of using ENM as a strategic tool for conservation planning. Future research should aim to deepen our understanding of how species interactions, land-use changes, and socioeconomic factors influence potential distribution. In this regard, we propose a series of proactive strategies to improve bighorn sheep conservation and management under future climate conditions:

5.1.1 Adopt adaptive management approaches

Conservation strategies should remain flexible and adaptable, adjusting to new climate data and model projections. Managers must continuously update distribution models and integrate new environmental data to ensure that conservation strategies remain relevant over time.

5.1.2 Prioritize high-potential geographic distribution as conservation areas

Our study identifies northern Baja California as a key conservation area, especially under extreme climate scenarios such as RCP 8.5. Prioritizing these regions for habitat restoration, monitoring, and translocation efforts can support bighorn sheep survival as environmental conditions change.

5.1.3 Strengthen collaboration and training programs

The Bonfil ejido's extensive experience (1996–2024) in sustainable bighorn sheep management provides an opportunity for establishing training and collaboration programs with other ejidos and local communities in northern Baja California. Sharing best practices and fostering regional cooperation will enhance conservation efforts.

5.1.4 Integrate socioeconomic considerations in wildlife management

Given the economic importance of sport hunting for local communities, conservation planning must incorporate economic insights to ensure that species protection efforts align with community livelihoods. Developing strategies that balance ecological and economic objectives will enhance long-term conservation success.

5.1.5 Expand climate scenario analyses

Broadening climate scenario assessments to include more RCPs and GCMs will capture a wider range of possible futures. This reduces biases and enhances the credibility of policy decisions, enabling more robust adaptation strategies.

5.1.6 Consider translocation as a conservation tool

Though controversial, bighorn sheep translocations have been successfully implemented on Tiburon Island and Carmen Island. Future management could explore relocating individuals to newly identified suitable areas, helping to sustain populations as climate-induced potential distribution shifts occur.

Overall, this study emphasizes the critical intersection of climatic, and socioeconomic factors in bighorn sheep conservation. Understanding how these elements interact will allow managers to anticipate challenges, evaluate alternative strategies, and develop adaptive conservation approaches. This is essential for ensuring the long-term sustainability of bighorn sheep populations while also supporting the communities that depend on them.

Overall, this study highlights the value of analyzing the intersection of socioeconomic and wildlife population dynamics in the context of climate change. By examining these factors, managers can better anticipate constraints on current and future strategies, respond to evolving conditions, evaluate alternative policy outcomes, and adopt adaptive management approaches. This method is essential for ensuring the long-term sustainability of bighorn sheep populations and supporting the communities that rely on them.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://chelsa-climate.org/downloads/; https://www.gbif.org/.

Author contributions

HZ-M: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. VA-F: Supervision, Validation, Writing – review & editing. VS-S: Resources, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

We want to thank the Mexican Council of Science and Technology (CONACYT) for the PhD scholarship at UNAM under which the present investigation was developed. We also thank the Protection Area of Flora and Fauna (APFF) "Valle de los Cirios" for the technical support granted during the interviews in the UMA Bonfil. Special thanks are given to everyone in the UMA Bonfil who granted our request and took the time for interviews.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2025.1386632/full#supplementary-material

References

Adger, W. N. (2010). "Social capital, collective action, and adaptation to climate change," in *Der Klimawandel. VS Verlag für Sozialwissenschaften, Wiesbaden*. ed. M. Voss. p. 327–345. doi: 10.1007/978-3-531-92258-4_19

Advani, N. (2014). Climate change vulnerability assessment for species. Technical report. *World Wildlife Fund*. doi: 10.13140/RG.2.1.3613.5522

Allouche, O., Tsoar, A., and Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *J. Appl. Ecol.* 43, 1223–1232. doi: 10.1111/j.1365-2664.2006.01214.x

Ashcroft, M. B. (2010). Identifying refugia from climate change. *Biogeography* 37, 1407–1413. doi: 10.1111/j.1365-2699.2010.02300.x

Avila-Foucat, V. S., and Pérez-Campuzano, E. (2015). Municipality socioeconomic characteristics and the probability of occurrence of wildlife management units in Mexico. *Environ. Sci. Pol.* 45, 146–153. doi: 10.1016/j.envsci.2014.08.005

Barve, N., Barve, V., Jiménez-Valverde, A., Lira-Noriega, A., Maher, S. P., Townsend Peterson, A., et al. (2011). The crucial role of the accessible area in ecological niche modeling and species distribution modeling. *Ecol. Model.* 222, 1810–1819. doi: 10.1016/j.ecolmodel.2011.02.011

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., and Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecol. Lett.* 15, 365–377. doi: 10.1111/j.1461-0248.2011.01736.x

Brewer, C. E., Bleich, V. C., Foster, J. A., Hosch-Hebdon, T., McWhirter, D. E., Rominger, E. M., et al. (2014). *Bighorn sheep: Conservation challenges and management strategies for the 21st century*. Cheyenne, Wyoming, USA: Wild Sheep Working Group, Western Association of Fish and Wildlife Agencies.

Brun, P., Zimmermann, N. E., Hari, C., Pellissier, L., and Karger, D. (2022). Data from: CHELSA-BIOCLIM+ a novel set of global climate-related predictors at kilometre-resolution. *EnviDat*. doi: 10.16904/envidat.332

Ceballos, G., and Oliva, G. (2005). *Los mamíferos silvestres de México*. Mexico City, Mexico: Fondo de Cultura Económica.

Cheung, W., Jones, M., and Lam, V. (2016). Transform high seas management to build climate resilience in marine seafood supply. *Fish Fish.* 18, 254–263. doi: 10.1111/faf.12177

Chidumayo, E. (2011). *Climate change and African forest and wildlife resources*. Nairobi, Kenya: African Forest Forum.

Cooney, R. (2004). *The precautionary principle in biodiversity conservation and natural resource management: An issues paper for policymakers, researchers and practitioners*. Gland, Switzerland and Cambridge, UK: IUCN – The World Conservation Union.

Creech, T. G., Epps, C. W., Wehausen, J. D., Crowhurst, R. S., Jaeger, J. R., Longshore, K., et al. (2020). Genetic and environmental indicators of climate change vulnerability for desert bighorn sheep. *Front. Ecol. Evol.* 8:279. doi: 10.3389/fevo.2020.00279

Cruz, T. M. P., Buchmann, S. L., and Prudic, K. L. (2024). Buzzing towards resilience: investigating the spatial alignment of the desert pallid bee, Centris pallida, and its host plants in response to climate change. *Insects* 15:793. doi: 10.3390/insects15100793

Danell, K. (2006). *Large herbivore ecology, ecosystem dynamics and conservation*. Cambridge, UK: Cambridge University Press.

Douglas, C. L., and Leslie, D. M. (1983). Influence of weather and density on lamb survival of desert mountain sheep. *J. Wildl. Manag.* 50, 153–156.

Dreiss, L. M., Lacey, L. M., Weber, T. C., Delach, A., Niederman, T. E., and Malcom, J. W. (2022). Targeting current species ranges and carbon stocks fails to conserve biodiversity in a changing climate: opportunities to support climate adaptation under 30 × 30. *Environ. Res. Lett.* 17, 1–13. doi: 10.1088/1748-9326/ac4f8c

Durner, G. M., Douglas, D. C., Nielson, R. M., Amstrup, S. C., McDonald, T. L., Stirling, I., et al. (2009). Predicting the 21st-century polar bear habitat distribution from global climate models. *Ecol. Monogr.* 79, 25–58. doi: 10.1890/07-2089.1

Elith, J., and Leathwick, J. R. (2009). Species distribution models: ecological explanation and prediction across space and time. *Annu. Rev. Ecol. Evol. Syst.* 40, 677–697. doi: 10.1146/annurev.ecolsys.110308.120159

Epps, C. W., Mccullough, D. R., Wehausen, J. D., Bleich, V. C., and Rechel, J. L. (2004). Effects of climate change on population persistence of desert-dwelling mountain sheep in California. *Conserv. Biol.* 18:102. doi: 10.1111/j.1523-1739.2004.00023.x

Escobar-Flores, J. G., Alvarez-Cardenas, S., Valdez, R., Torres-Rodriguez, J., Díaz-Castro, S., Castellanos-Vera, A., et al. (2015). Detección de las preferencias de hábitat del borrego cimarrón (*Ovis canadensis cremnobates*) en Baja California, mediante Técnicas de Teledetección Satelital. *Therya* 6, 519–534. doi: 10.12933/therya-15-284

García, J. T., Jiménez, J., Mateo, R., and Arroyo, B. (eds). (2016). *Current trends in wildlife research (Vol. 1)*. Springer, p. 283–293. doi: 10.1007/978-3-319-27912-1

Garcia, R. A., Cabeza, M., Rahbek, C., and Araújo, M. B. (2014). Multiple dimensions of climate change and their implications for biodiversity. *Science* 344, 486–497. doi: 10.1126/science.1247579

Graziano, M. P., Deguire, A. K., and Surasinghe, T. D. (2022). Riparian buffers as a critical landscape feature: insights for riverscape conservation and policy renovations. *Diversity* 14, 172–192. doi: 10.3390/d14030172

Grinnell, J. (1917). The niche-relationships of the California thrasher. *Auk* 34, 427–433. doi: 10.2307/4072271

Groves, D. G., and Lempert, R. J. (2007). A new analytic method for finding policy-relevant scenarios. *Glob. Environ. Change* 17, 73–85. doi: 10.1016/j.gloenvcha.2006.11.006

Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. T., et al. (2013). Predicting species distributions for conservation decisions. *Ecol. Lett.* 16, 1424–1435. doi: 10.1111/ele.12189

Hilty, J., Worboys, G. L., Keeley, A., Woodley, S., Lausche, B., Locke, H., et al. (2020). "Guidelines for conserving connectivity through ecological networks and corridors," in *IUCN best practice protected area guidelines series No. 30*. Gland, Switzerland.

Hoegh-Guldberg, O., Kenned, E., Beyer, H., McClennen, C., and Possingham, H. (2018). Securing a long-term future for coral reefs. *Trends Ecol. Evol.* 33, 936–944. doi: 10.1016/j.tree.2018.09.006

INE (2000). Proyecto para la conservación, manejo y aprovechamiento sustentable del borrego cimarrón (*Ovis canadensis*) en México. Report. Mexico City, Mexico: Secretaria del Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP), Instituto Nacional de Ecologia (INE), p. 92.

IPCC (2023). "Climate change 2023: synthesis report" in *Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change*. eds. H. Lee and J. Romero (Geneva, Switzerland: IPCC).

IPCC (2007). "directores de la publicación" in *Cambio climático 2007: Informe de síntesis. Contribución de los Grupos de trabajo I, II y III al Cuarto Informe de evaluación del Grupo Intergubernamental de Expertos sobre el Cambio Climático*. eds. R. K. Pachauri and A. Reisinger (Ginebra, Suiza: IPCC), 104.

Islam, M. M., Sallu, S., Hubacek, K., and Paavola, J. (2014). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: insights from coastal Bangladesh. *Reg. Environ. Chang.* 14, 281–294. doi: 10.1007/s10113-013-0487-6

Johnson, K. A. (2014). *Climate change vulnerability assessment for natural resource management: Toolbox of methods with case studies, version 2.0*. Arlington, VA: U.S. Fish and Wildlife Service.

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., et al. (2018). Data from: Climatologies at high resolution for the earth's land surface areas [Dataset: https://chelsa-climate.org/downloads/] Dryad. doi: 10.5061/dryad.kd1d4

Langridge, J., Sordello, R., and Reyjol, Y. (2020). Outcomes of wildlife translocations in protected areas: what is the type and extent of existing evidence? A systematic map protocol. *Environ. Evid.* 9:16. doi: 10.1186/s13750-020-00199-4

Lee, R. (2003). A review of recent wild sheep surveys in Baja California Sur, Mexico. *Desert Bighorn Counc. Trans.* 43, 43–46.

Lee, R. (2008). "Hunting as a tool for wildlife conservation: the case of sheep hunting in Mexico," in *Best practices in sustainable hunting: A guide to best practices from around the world*. eds. R. D. Baldus, G. R. Damm, and K. Wollscheid (International Council for Game & Wildlife Conservation, Hungary), p. 5–11.

Lee, R. (2011). Economic aspects of and the market for desert bighorn sheep. *Desert Bighorn Counc. Trans.* 51, 46–49.

Lempert, R. J. (2002). A new decision science for complex systems. *Proc. Natl. Acad. Sci. USA* 99, 7309–7313. doi: 10.1073/pnas.082081699

Lempert, R. J., Groves, D. G., Popper, S. W., and Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Manag. Sci.* 52, 514–528. doi: 10.1287/mnsc.1050.0472

Mathewson, H. A., Groce, J. E., McFarland, T. M., Morrison, M. L., Newnam, R. T., Snelgrove, R. T., et al. (2012). Modeling effects of climate change on the population dynamics of the golden-cheeked warbler. *J. Wildl. Manag.* 76, 933–947. doi: 10.1002/jwmg.352

Medellin, R., Manterola, C., Valdéz, M., Hewitt, D. G., Doan-Crider, D., and Y Fulbright, T. E. (2005). "Biodiversity, ecosystems, and conservation in northern Mexico" in *History, ecology, and conservation of the pronghorn antelope, bighorn sheep, and black bear in Mexico*. eds. J. L. E. En Cartron, G. Ceballos and R. S. Felger (Oxford, United Kingdom: Oxford University Press), 387404.

Merow, C., Smith, M. J., and Silander, J. A. (2013). A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. *Ecography* 36, 1058–1069. doi: 10.1111/j.1600-0587.2013.07872.x

Mondal, S., and Martinez-Garcia, R. (2024). Editorial: Climate change and developmental physiology. *Front. Physiol.* 15:1408809. doi: 10.3389/fphys.2024.1408809

Pereira, H., Leadleyvania, P., and Proença, V. (2010). Scenarios for global biodiversity in the 21st century. *Science* 330, 1496–1501. doi: 10.1126/science.1196624

Peters, G. P., and Hausfather, Z. (2020). Emissions – the "business as usual" story is misleading. *Nature* 577, 618–620. doi: 10.1038/d41586-020-00177-3

Peterson, D. W., Kerns, B. K., and Dodson, E. K. (2014). Climate change effects on vegetation in the Pacific Northwest: a review and synthesis of the scientific literature and simulation model projections. *Gen. Tech. Rep. PNWGTR-900*. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. p. 183. doi: 10.2737/PNW-GTR-900

Peterson, T., and Anamza, T. (2015). Ecological niches and present and historical geographic distributions of species: a 15-year review of frameworks, results, pitfalls, and promises. *Folia Zool.* 64, 207–217. doi: 10.25225/fozo.v64.i3.a3.2015

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., and Blair, M. E. (2017). Opening the black box: an open-source release of MaxEnt. *Ecography* 40, 887–893. doi: 10.1111/ecog.03049

Phillips, S. J., Anderson, R. P., and Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecol. Model.* 190, 231–259. doi: 10.1016/j.ecolmodel.2005.03.026

Phillips, S. J., and Dudík, M. (2008). Modeling of species distributions with MaxEnt: new extensions and a comprehensive evaluation. *Ecography* 31, 161–175. doi: 10.1111/j.0906-7590.2008.5203.x

Pradhan, P. (2016). Strengthening MaxEnt modelling through screening of redundant explanatory bioclimatic variables with variance inflation factor analysis. *Researcher* 8, 29–34. doi: 10.7537/marsrsj08051605

Ramirez-Villegas, J., Devenish, F., and Cuesta, F. (2014). Using species distributions models for designing conservation strategies of tropical Andean biodiversity under climate change. *Nat. Conserv.* 22, 391–404. doi: 10.1016/j.jnc.2014.03.007

Ramos, P., Colima, G., and Arana, R. (2018). Translocation as a conservation tool for endangered tortoises in Mexico. *Rev. Bio Cienc.* 5:e332. doi: 10.15741/revbio.05.01.01

R Core Team (2024). R: A language and environment for statistical computing R Foundation for Statistical Computing. Available online at: https://www.R-project.org/

Robinson, J. G., and Bennett, E. (2001) in *Hunting for sustainability in tropical forests*. eds. J. G. Robinson and E. Bennett, vol. *39* (New York: Columbia University Press).

Romero-Figueroa, G., Ruiz-Mondragón, E., Shahriary, E., Yee-Romero, C., Guevara-Carrizales, A., Paredes-Montesinos, R., et al. (2024). Population and conservation status of bighorn sheep in the state of Baja California, Mexico. *Animals* 14, 504–516. doi: 10.3390/ani14030504

Ruiz, E. (2014). Estado actual de la población del borrego cimarrón (*Ovis canadensis weemsi*) en la UMA Ejido La Purísima, Baja California Sur, México. Bachelor's thesis, Universidad Nacional Autónoma de México, Mexico City, Mexico. p. 57. Available online at: https://repositorio.unam.mx/contenidos/434638

Rye, C. J., Boyd, J. A., and Mitchell, A. (2021). Normative approach to risk management for insurers. *Nat. Clim. Chang.* 11, 460–463. doi: 10.1038/s41558-021-01031-8

Saba, V. S., Stock, C. A., Spotila, J. R., Paladino, F. v., and Tomillo, P. S. (2012). Projected response of an endangered marine turtle population to climate change. *Nat. Clim. Chang.* 2, 814–820. doi: 10.1038/nclimate1582

Sandoval, A., Valdez, R., and Espinosa-T, A. (2019) in *Desert bighorn sheep in Mexico. In wildlife ecology and Management in Mexico*. eds. R. Valdez and A. Ortega (TX, USA: Texas A&M University Press: College Station), 350–365.

Sattar, Q., Maqbool, M. E., Ehsan, R., and Akhtar, S. (2021). Review on climate change and its effect on wildlife and ecosystem. *Open J. Environ. Biol.* 6, 008–014. doi: 10.17352/ojeb.000021

Schober, P., and Schwarte, L. A. (2018). Correlation coefficients: appropriate use and interpretation. *Anesth. Analg.* 126, 1763–1768. doi: 10.1213/ANE.0000000000002864

Staudinger, M. D., Morelli, T. L., and Bryan, A. M. (2015). *Integrating climate change into northeast and Midwest state wildlife action plans*. Amherst, Massachusetts: DOI Northeast Climate Science Center Report.

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., and Herrick, S. (2011). Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Chang.* 1, 449–456. doi: 10.1038/nclimate1301

Tingstad, A. H., Lempert, R. J., Moskwik, M., Warren, D. L., Parmesan, C., Mcginnis, S., et al. (2017). Demonstrating the applicability of a robust decision making (RDM) to conservation decision-making under uncertain future climate: pilot study using the northern pygmy salamander (*Desmognathus organi*). *Journal of Conservation Planning* 13, 11–24.

Turner, J. C., and Weaver, A. (1980). "Water" in *The desert Bighorn: Its life history, ecology and management*. eds. G. Monson and L. Sumner (University Arizona Press), 370, 105–112. doi: 10.1002/jwmg.352

Wang, T., Campbell, E. M., O'Neill, G. A., and Aitken, S. N. (2012). Projecting future distributions of ecosystem climate niches: uncertainties and management applications. *For. Ecol. Manag.* 279, 128–140. doi: 10.1016/j.foreco.2012.05.034

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E. A., et al. (1996). "Integrated assessment of climate change: an overview and comparison of approaches and results" in *Economic and social dimensions of climate change*. eds. J. P. Bruce, H. L. Haites and E. F. Haites (Cambridge University Press: IPCC), 371–393.

Wilder, B. T., Betancourt, J. L., Epps, C. W., Crowhurst, R. S., Mead, J. I., and Ezcurra, E. (2014). Local extinction and unintentional rewilding of bighorn sheep (*Ovis canadensis*) on a desert island. *PLoS One* 9:e91358. doi: 10.1371/journal.pone.0091358

Wild Sheep Foundation, and WAFWA Wild Sheep Working Group. (2012). *North American Bighorn Sheep Distribution*. Available online at: https://www.wildsheepfoundation.org/cache/DOC270_2014-07BighornSheepConservationChallenges.pdf?20200226050005

Zamora-Maldonado, H. C., Avila-Foucat, V. S., Sánchez-Sotomayor, V. G., and Lee, R. (2021). Social-ecological resilience modeling: water stress effects in the Bighorn sheep management system in Baja California Sur, Mexico. *Ecol. Complex.* 45, 1–11. doi: 10.1016/j.ecocom.2020.100884

Zhang, K., Sun, L., and Tao, J. (2020). Impact of climate change on the distribution of *Euscaphis japonica* (staphyleaceae) trees. *Forests* 11:525. doi: 10.3390/f11050525

Zhang, L., Liu, S., Sun, P., Wang, T., Wang, G., and Zhang, X. (2015). Consensus forecasting of species distributions: the effects of niche model performance and niche properties. *PLoS One* 10:e0120056. doi: 10.1371/journal.pone.0120056

Zhong, L., Ma, Y., and Salama, M. S. (2010). Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan plateau. *Clim. Chang.* 103, 519–535. doi: 10.1007/s10584-009-9787-8