# Climate change threatens the most biodiverse regions of Mexico

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LJB: performance of the research; data interpretation; writing the manuscript

JL: performance of the research; data interpretation; writing the manuscript

JBB: design of the research; performance of the research; data interpretation; editing the manuscript

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JSC: performance of the research; expertise advice on methods; editing the manuscript

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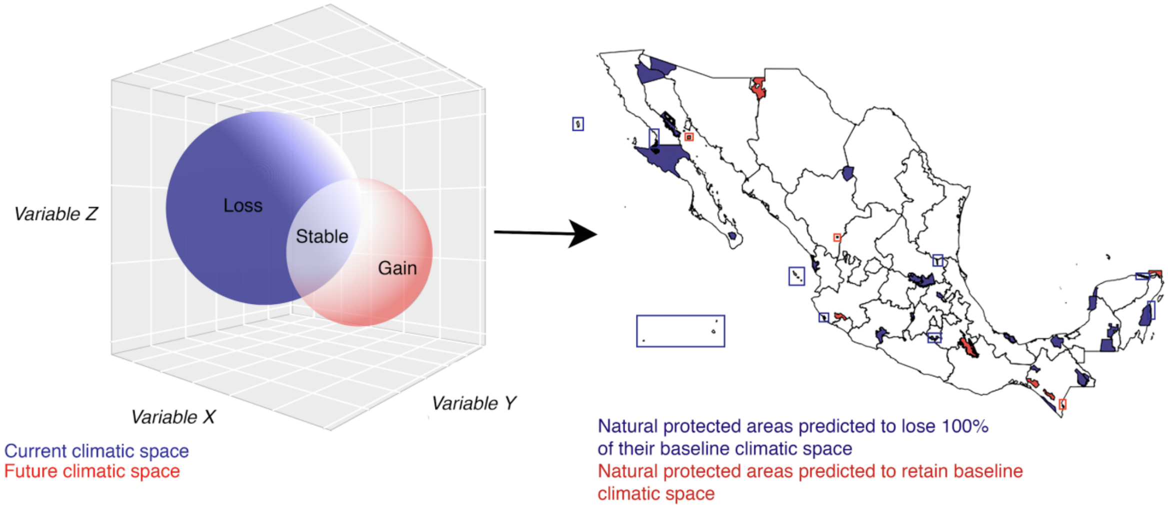
## GRAPHICAL ABSTRACT



## ABSTRACT

Climate change threatens Earth's biodiversity, although its impacts are variable and depend on the capacity of species and ecosystems to cope with the magnitude and speed of change. Natural protected areas (NPAs) constitute potential refugia for species' persistence and for sustaining the provisioning of ecosystem services. Biosphere reserves are NPAs that are less altered by human actions and provide habitat to endemic, threatened or endangered species. Here, we aim to evaluate the threat imposed by climate change on the network of biosphere reserves in Mexico. Focusing on five bioclimatic variables, we computed the climatic space – measured as an *n*-dimensional hypervolume – of 40 NPAs. Increases in temperature are predicted for all NPAs by 2050, whereas decreases in annual rainfall are predicted for 30 NPAs. By 2050, 31 NPAs that provide habitat to 22,866 recorded species are predicted to lose 100% of their baseline climatic space, shifting to completely novel climates. On average, the other nine NPAs are predicted to lose 55.7% (SD = 26.7%) of their baseline climatic space, while 54.5% (SD = 32.5%) of the future climatic space will be novel. Seventeen NPAs may lose climate variability (homogenization), decreasing species' niches. The extent to which non-analogue conditions will remain within the tolerance of species and ecosystems is currently unknown. Finally, we propose a vulnerability index to categorise NPAs based on their loss of existing climatic space, total geographic area, species richness, and uniqueness of species composition, finding los Tuxtlas and Tiburon Ballena as the most and least vulnerable NPAs, respectively.

**Key words**: Biosphere reserves; climatic space; climate niche; hypervolume; natural protected areas; vulnerability

## HIGHLIGHTS

- Across 40 protected areas, temperature is predicted to increase ~3°C by 2050
- 31 protected areas are predicted to lose 100% of their baseline climatic space
- 17 protected areas may lose climate variability (homogenization), decreasing species' niches
- The effect of non-analogue conditions on species and ecosystems is largely unknown
- We propose a vulnerability index to categorise natural protected areas

## INTRODUCTION

Rapid modern climate change is already altering species distributions and reorganising the composition of many ecosystems (Lenoir and Svenning 2015). These changes have important direct and indirect consequences on ecosystem functioning, human health, and climatic feedbacks (Bonebrake et al. 2018; Pecl et al. 2017; Scheffers et al. 2016). Thus, projected increases in temperature, shifts in precipitation patterns, and the increasing occurrence of extreme weather events jeopardize the persistence of ecosystems and the species they support (Field et al. 2014).

Effective conservation and management practices depend strongly on our ability to predict the impacts of climate change on natural and human-managed ecosystems (Mawdsley et al. 2009). However, predicting the impacts of climate change is particularly challenging, due to the complexities of climatic processes and uncertainty about the rate and magnitude of changes (Baumgartner et al. 2018; Beaumont et al. 2019; Fatichi et al. 2016; Grierson et al. 2011; Loarie et al. 2009; Ohlemüller 2011). As changes in climate intensify, assessments of the extent to which the available climatic space may change are particularly important in order to identify species most threatened by changing climate (Guisan et al. 2014).

During past abrupt climatic changes, populations persisted in areas with relatively stable climate, referred to as refugia (or microrefugia). These areas apparently retained local environmental conditions suitable for species persistence, amidst regionally unsuitable conditions (Correa-Metrio et al. 2014; Médail and Diadema 2009; Tzedakis et al. 2002). Thus, refugia are recognised as important areas fostering endemic biodiversity (Harrison and Noss 2017). Although the concept of refugia has been more commonly applied to historical periods during the Quaternary, the idea that some areas may act as potential refugia (or microrefugia) under contemporary and future anthropogenic climate change is now widely accepted by the scientific community (Hannah et al. 2014; Keppel et al. 2012; Keppel and Wardell-Johnson 2015). Hence, maintaining a functional network of protected areas that retain a sufficient proportion of their existing climatic space into the future will limit biodiversity losses associated with rapid climate change, promote the delivery of ecosystem services, provide livelihoods, and sustain local communities (Ervin 2003; IUCN 2005).

Mexico is a megadiverse country harbouring almost 10% of the world's biodiversity (Challenger 1998; Mittermeier et al. 1998; Sarukhán Kermez and Dirzo 1992). Currently, the Mexican natural protected areas (NPAs), administered by the National Commission of Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas; CONANP), cover more than 25.3 million hectares (Vargas Márquez et al. 2011). Such a large network has the potential to provide refugial capacity (sensu Keppel and Wardell-Johnson 2015) for ecosystems and adjacent areas, facilitating the maintenance of populations, water quality, nutrient cycling, and ecological flows (DeFries et al. 2010). These NPAs provide habitat for species considered endemic, threatened, or endangered (Batisse 1982; Ishwaran et al. 2008). Because of the significance of these NPAs, we highlight the importance of understanding the exposure of these ecosystems and the species they harbour to risks associated with future climate change. This understanding is essential for developing and designing effective management and conservation programs (Cash and Moser 2000). Such a task, in turn, requires the use of approaches and tools that can be applied to species, taxonomic groups, and regions to propose and design a climate-ready protected area network (Graham et al. 2019). One such approach is an assessment of the climatic space that is currently available and how this may be altered by modern rapid climate change.

Here, we evaluate the magnitude of climate change to which species and ecosystems in 40 of Mexico’s NPAs will be exposed by 2050. Specifically, we ask three questions: (1) How does climatic space differ across the 40 Mexican NPAs included in this study? (2) How much of the existing climatic space will be retained in the near future (2050)? and (3) Which protected areas are most vulnerable to climate change?

## METHODS

### *Natural protected areas (NPAs)*

Here, we provide a case study of the risks associated with climate change for 40 of Mexico’s 174 NPAs, administered by the federal government (CONANP). The 40 NPAs form part of the UNESCO's World Network of Biosphere Reserves and were designed to preserve goods and services provided by the ecosystems they harbour. Six of these NPAs have been named World Heritage Centres as natural assets: (1) Sian Ka'an (Quintana Roo); (2) El Vizcaíno (Baja California Sur); (3) Alto Golfo de California y Delta del río Colorado (Baja California-Sonora); (4) the Mariposa Monarca reserve (Mexico-Michoacan); (5) El Pinacate y Gran Desierto de Altar (Sonora); and (6) Archipelago of Revillagigedo (Colima) (CONANP 2006; UNESCO 2017; Villalobos 2000) (**Figure 1**). Combined, the 40 NPAs cover ~12.5

million ha (~50% of the total area of NPAs in Mexico), and are representative of ecosystems that need to be preserved and restored (CONANP 2006). We extracted the boundaries for the 40 NPAs from the 2010 CONABIO shapefile (Bezaury-Creel et al. 2009).

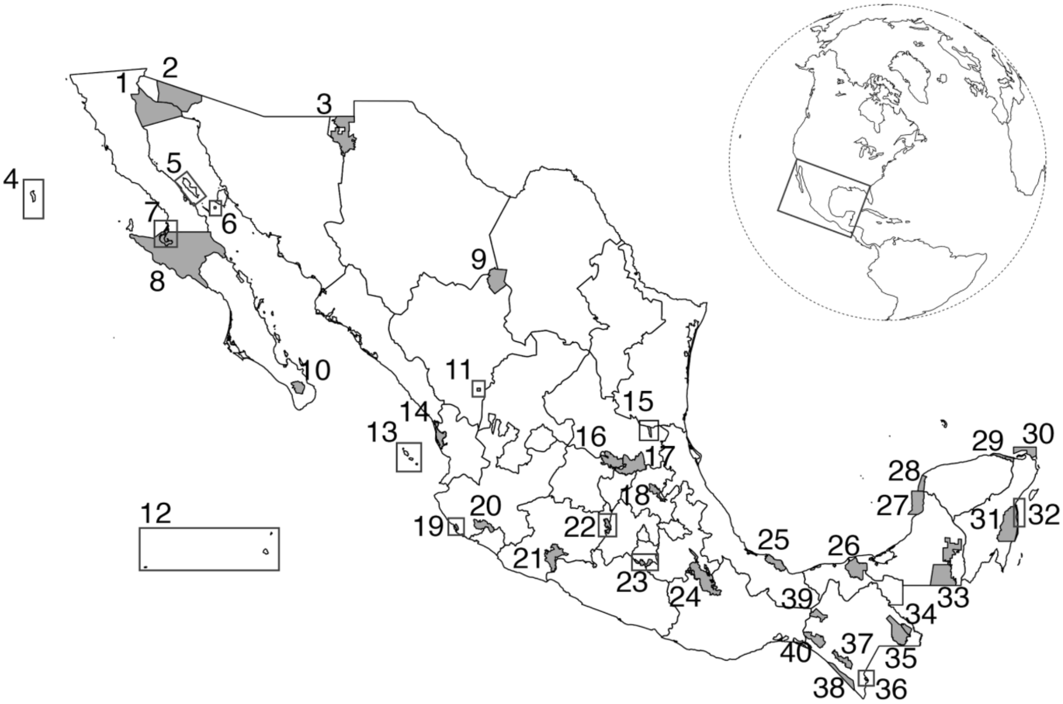


**Figure 1**. Location of the 40 protected areas of Mexico: 1) Alto Golfo de California y delta del río Colorado; 2) El Pinacate y Gran Desierto de Altar; 3) Janos; 4) Isla Guadalupe; 5) Bahia de los Angeles, canales de Ballenas y de Salsipuedes; 6) Isla San Pedro Mártir; 7) Complejo lagunar Ojo de Liebre; 8) El Vizcaíno; 9) Mapimí; 10) Sierra de la Laguna; 11) La Michilía; 12) Archipielago de Revillagigedo; 13) Islas Marias; 14) Marismas Nacionales; 15) Sierra del Abra-Tanchipa; 16) Sierra Gorda de Guanajuato; 17) Sierra Gorda; 18) Barranca de Metztitlán; 19) Chamela-Cuixmala; 20) Sierra de Manantlán; 21) Zicuirán Infiernillo; 22) Mariposa Monarca; 23) Sierra de Huautla; 24) Tehuacán-Cuicatlán; 25) Los Tuxtlas; 26) Pantanos de Centla; 27) Los Petenes; 28) Ría Celestún; 29) Ría

Lagartos; 30) Tiburón Ballena; 31) Sian Ka'an; 32) Arrecifes de Sian Ka'an; 33) Calakmul; 34) Lacan-Tún; 35) Montes Azules; 36) Volcán Tacaná; 37) El Triunfo; 38) La Encrucijada; 39) Selva el Ocote; and 40) La Sepultura.

*Climate data*

For both the baseline and future climate data across the 40 NPAs, we downloaded the set of 19 bioclimatic variables at a spatial resolution of 30 arc-seconds (~1 km at the equator) from WorldClim (Version 1.4) (http://www.worldclim.org/). Data were projected to the INEGI Lambert Conformal Conic equal area projection (EPSG:6362) with 1 × 1 km resolution. Baseline data represent climate conditions during the period 1960-1990. For future climate data, we downloaded projections of four Global Climate Models (GCMs) recommended for Mexico (Cavazos et al. 2013; Fernández Eguiarte et al. 2015): (1) MPI-ESM-LR (Germany); (2) GFDL-CM3 (USA); (3) HADGEM2-ED (United Kingdom); and (4) CNRM (France). For these four GCMs, we used the Representative Concentration Pathway (RCP) 8.5, which projects emissions to continue to rise throughout the 21st century (Meinshausen et al. 2011). Following the precautionary principle of risk assessment, we chose a high-emission scenario in order to investigate the maximum change that can be expected for climate and to maximize the impact of $CO_2$ concentration change and $CO_2$-related climate change on vegetation (Yu and Wang 2014). Additionally, this scenario is often used to assess risks and possible costs associated with climate change (Riahi et al. 2011). We selected data for 2050 (average for 2041-2060), aiming to explore a future scenario that matches the short-term timeframe of current management and conservation practices.

Extrapolating our results to a more distant future (e.g. 2070) would increase uncertainty.

We evaluated correlations among the 19 bioclimatic variables using Pearson's product-moment correlation (Legendre and Legendre 2012) (**Appendix 1**). Out of the highly correlated pairs (|r| > 0.7), we selected one of the covariates based on biological relevance. We retained a subset of nine uncorrelated bioclimatic variables. We then performed a principal component analysis (PCA) on baseline data and based on the magnitude and direction of the vectors (i.e. bioclimatic variables) in relation to main principal components (i.e. first two PC axes) and biological relevance, we selected a final set of five bioclimatic variables to perform our subsequent analyses: (1) Max Temperature of the Warmest Month (BIO5; *MTWM*); (2) Min Temperature of the Coldest Month (BIO6; *MTCM*); (3) Temperature Annual Range (BIO7; *TAN*); (4) Annual Precipitation (BIO12; *AP*); and (5) Precipitation Seasonality (BIO15; *PS*). This additional reduction in the number of variables was necessary to reduce computational demand associated with calculating hypervolumes (see details below).

Maximum and minimum temperature (*MTWM*, *MTCM*) are useful to examine how species distributions are affected by warm and cold temperature anomalies throughout the year. The temperature annual range (*TAN*) is useful when examining whether species' distributions are affected by ranges of extreme temperature conditions (O'Donnell and Ignizio 2012). Evidence suggests that increases in temperature might affect species' ranges, ecological interactions, and even survival of populations (Allen et al. 2010; Field et al. 2014; Thomas et al. 2004; Walther et al. 2002). Annual precipitation (*AP*) affects ecosystems differentially and plays a key role in determining species' distributions (Moles et al. 2014; O'Donnell and Ignizio 2012; Weltzin et al. 2003). The predicted changes in precipitation patterns and total rainfall represent a risk to both species and ecosystems (Anderegg et al. 2015; Field et al. 2014). Precipitation seasonality (*PS*) is a measure of the variation in precipitation throughout the year, with higher values indicating higher variability (O'Donnell and Ignizio 2012), and may be important for species dependent on seasonal patterns of rainfall. The values of these five variables were extracted for each NPA using a 1 × 1 km grid, yielding baseline and future scenarios comprising the average of future projections from the four GCMs. Baseline and future scenarios for each NPA were characterized in terms of the mean, standard deviation, and range of the five variables across all grid cells occurring within a given NPA. The magnitude of climate change in the NPAs was then assessed by estimating the absolute difference between baseline and future values (mean, standard deviation, and range) of each variable.

### *Climatic space*

We considered the climatic space as a 5-dimensional hypervolume (sensu Hutchinson 1957), constructed with the five aforementioned bioclimatic variables. These variables represent and quantify variation in climatic conditions across a given NPA. We extracted values of the five bioclimatic variables from the cells contained within each NPA. These data were standardized to have zero mean and unit variance before constructing baseline and future hypervolumes. The units of the hypervolumes are, therefore, given in standard deviations (SDs) (for a detailed derivation of data preparation, see Blonder et al. 2014).

To quantify the climatic space, we used the package *hypervolume* (version 2.0.11) (Blonder and Harris 2018) in R (version 3.4.4) (R Core Team 2018). Default settings were used to estimate hypervolumes with the Gaussian kernel density estimate method and the Silverman estimator for bandwidth selection. Specifically, we used the function <*hypervolume_overlap_statistics*> to compare baseline and future climatic space. This function provides a set of metrics: (1) unique fraction 1 (volume of the unique component of the baseline climatic space divided by the total volume of the baseline climatic space); and (2) unique fraction 2 (volume of the unique component of the future climatic space divided by the total volume of the future climatic space) (Blonder and Harris 2018).

Using the above metrics, for each NPA, we calculated: (1) the stable climatic space (i.e. 1 - unique fraction 1); (2) the loss of current climatic space (unique fraction 1); and (3) the gain of future climatic space (i.e. unique fraction 2) (**Figure 2**). Additionally, we identified cases where NPAs were predicted to undergo increases or decreases to the overall volume of climatic space available. An increase in hypervolume represents a gain in climate variability, while a decrease indicates a more homogenous future climate.

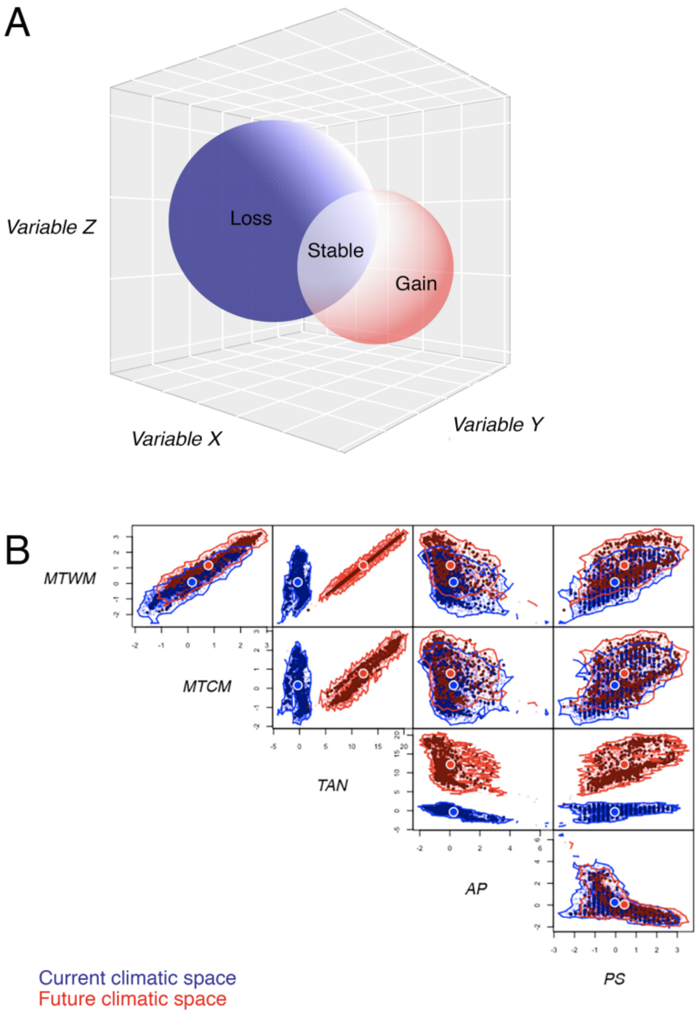


**Figure 2**. (A) Schematic figure to illustrate the concept of climatic space or hypervolume for baseline (blue; 1960-1990) and future (red; 2050, average for 2041-2060) conditions in a given protected area. We estimated: (1) the **stable** climatic space (i.e. intersection of baseline and future climatic spaces, as a proportion of the baseline hypervolume); (2) the **loss** of climatic space (i.e. proportion of baseline climatic space that is no longer represented in the future); and (3) the **gain** of novel climatic space (i.e. the proportion of future climatic space that was not represented under current climate). (B) Climatic space showing the interactions of five bioclimatic variables: (1) Max Temperature of Warmest Month (*MTWM*); (2) Min Temperature of Coldest Month (*MTCM*); (3) Temperature Annual Range (*TAN*); (4) Annual Precipitation (*AP*); and (5) Precipitation Seasonality (*PS*). Here,

we assessed the shift from baseline (blue) to future (red) climatic space for the protected area of Tehuacan-Cuicatlan, Puebla-Oaxaca. For this protected area, the predicted percentages of stable climate, climate loss and climate gain are ~44%, ~55.7% and ~56.6%, respectively. Axes are given in units of standard deviations (SDs) of baseline values.

*Vulnerability of natural protected areas to climate change*

To assess potential vulnerability to climate change, we developed a vulnerability index (modified from Esperón-Rodríguez and Barradas 2015a) that considers three components: (1) the loss of current climatic space, i.e. loss of current climatic space calculated from unique fraction 1 (climatic space loss; *CSL*); (2) total geographic area (*TA*); and (3) number of species (species richness, *SR*, see next section). We considered NPAs to be more vulnerable if they had a high loss of current climatic space and have relatively small total area, with a greater impact for a higher number of species (see below). This is a comparative vulnerability index (*V*) among NPAs, where the highest vulnerability corresponds to 1 and the lowest to 0, and is estimated for the *i*th NPA as:

$$V_i = (V_{\mathrm{CSL}} + V_{\mathrm{TA}} + V_{\mathrm{SR}}) / 3 \qquad (1)$$

The loss of baseline climate ($V_{\mathrm{CSL}}$) is obtained by dividing the analogue climatic loss for the *i*th NPA ($CSL_i$) by the highest analogue climatic loss among all NPAs ($CSL_{\mathrm{MAX}}$):

$$V_{\mathrm{CSL}} = (CSL_i \,/\, CSL_{\mathrm{MAX}}) \qquad (2)$$

The vulnerability component for total area ($V_{\mathrm{TA}}$) was obtained by dividing the total area of the $i$th NPA ($TA_i$) by the area of the largest NPA ($TA_{\mathrm{MAX}}$):

$$V_{\mathrm{TA}} = 1 - (TA_i \,/\, TA_{\mathrm{MAX}}) \qquad (3)$$

Similarly, the component for the number of species (species richness, $V_{\mathrm{SR}}$), was obtained by dividing the total number of species reported in the $i$th NPA ($SR_i$) by the greatest number of species within an NPA ($SR_{\mathrm{MAX}}$):

$$V_{\mathrm{SR}} = (SR_i \,/\, SR_{\mathrm{MAX}}) \qquad (4)$$

NPAs were then ranked from high ($V = 1$) to low ($V = 0$) overall vulnerability. Additionally, we identified the uniqueness of species composition across the 40 NPAs (see details below). This information can be used to prioritize management actions under future climate change.

*Species richness and composition of natural protected areas*

To assess species richness ($SR$) and composition at each NPA, we queried the Global Biodiversity Information Facility (January 2019; GBIF, http://www.gbif.org), identifying all species of vascular plants (Tracheophyte), fungi, and animals (amphibians, arthropods, birds, mammals, and reptiles) recorded in each NPA. Occurrence records were downloaded for all of Mexico and then subsetted to retain only records georeferenced within each NPA. We further restricted records to those with an observational basis reported as “human observation”, “observation”, “specimen”, “living specimen”, “literature occurrence”, or “material sample”.

Further, to assess species composition, we developed a species presence-absence matrix for the 40 NPAs. This matrix was then used in a non-metric multidimensional scaling (NMDS) analysis with *vegan* 2.5-4 (Oksanen et al. 2019) using the square root transformation and calculating the Bray-Curtis distances for our community-by-site matrix in R (version 3.4.4) (R Core Team 2018). NMDS projects multivariate data along latent axes based on distances between assemblages, preserving the underlying dissimilarity structure of the original dataset (McCune et al. 2002). The distance between NPAs in the ordination space reflects the dissimilarity in species composition. Thus, NPAs with similar scores along the axes of the ordinal space are similar in terms of species composition (Legendre and Legendre 2012).

## RESULTS

### *Climate change in the natural protected areas of Mexico*

Across all NPAs, average conditions for all temperature variables (*MTWM, MTCM, TAN*) are predicted to increase by 2050, with the exception of a decrease in *TAN* at Sierra de la Laguna. On average (± SD), *MTWM* is predicted to increase by 2.8 ± 0.5°C, with *MTCM* and *TAN* predicted to be 2.1 ± 0.2°C and 0.7 ± 0.4°C warmer relative to baseline climatic averages (1960-1990), respectively. In contrast, annual precipitation (*AP*) is predicted to decrease in 30 NPAs, by 34.4 ± 32 mm. Only ten

NPAs are predicted to have increases in *AP* (16.3 ± 17.3 mm). Precipitation seasonality is projected to increase by 2.3 ± 2.9% by 2050, although six NPAs are predicted to have declines in *PS*.

For baseline and future conditions, the highest values of *MTWM*, *MTCM*, *TAN*, *AP*, and *PS* were found in the Alto Golfo de California, La Encrucijada (Chiapas), Janos (Chihuahua), Montes Azules (Chiapas), and Sierra de la Laguna (Baja California Sur), respectively (**Appendix 2).** The greatest increases by 2050 were predicted in Janos (*MTWM* and *MTCM*), La Michilía (Durango, *TAN*), La Encrucijada (*AP*), and Ojo de Liebre (Baja California Sur; *PS*). The smallest increases in temperature were predicted for Sierra de la Laguna (*MTCM*), Tiburón Ballena (Quintana Roo; *MTCM*), and Sierra de la Laguna (*TAN*), while the greatest declines in *AP* and *PS* were predicted in Montes Azules (*AP*) and los Petenes (Campeche; *PS*) (**Appendix 2**).

*Climatic space*

Across all 40 NPAs, the volume of climatic space averaged 89.7 (± 107.7) and 120.3 (± 137.5) for the baseline and future time period, respectively, representing greater variability under future conditions relative to baseline. For both time periods, Volcan Tacana (Chiapas) had the broadest climatic space. The narrowest climatic space was found in Calakmul (Campeche) and Sian Ka'an for baseline and future time periods, respectively. Thirty-one NPAs (78%) were predicted to have no stable climate (i.e. no intersection between the baseline and future climatic space). Hence, these areas are projected to contain completely novel climates by 2050.

For the remaining nine NPAs, the proportion of the current climatic space remaining stable reached, on average, 48%, ranging from 1% in Janos to 86% in La Michilía. Across these NPAs, the average loss of baseline climatic space was 55.7% (± 26.7%), whereas 54.5% (± 32.5%) of future climatic space was novel. The greatest loss of current and gain of novel climatic space were found in Janos (98.8% and 99.01%, respectively), whereas the lowest loss and gain of climatic space were found in La Michilia (13.9%) and Tiburon Ballena (4.5%), respectively (**Figure 3**; **Appendix 3**).

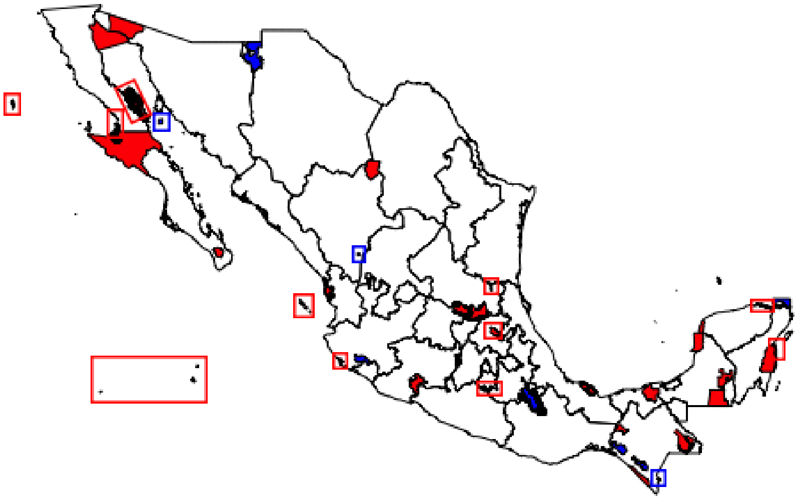


**Figure 3**. Protected areas in red are predicted to have no stable climate (i.e. no intersection between the baseline and future climatic space), hence the whole climatic space by 2050 will be novel. Protected areas in blue are predicted to retain some of their baseline climatic space as well as gain novel climatic space by 2050. See **Appendix 3** for details on changes in climatic space and **Figure 1** for names of protected areas.

Seventeen NPAs were predicted to experience decreases in the overall volume of climatic space available (i.e. more homogenous future climate) (-45.1% ± 20.8%, relative to the baseline), with the overall volume predicted to decline by at least 50% compared to the baseline (Arrecifes de Sian Ka'an [Quintana Roo], Tiburon Ballena, Sian Ka'an, Chamela-Cuixmala [Jalisco], Los Petenes, and La Encrucijada). In contrast, 23 NPAs were predicted to increase their overall volume of climatic space available by 2050 (+77.9% ± 55.8%, relative to the baseline), with eight of these NPAs predicted to experience an increase of >100% in the overall volume of their climatic space (**Figure 4**).

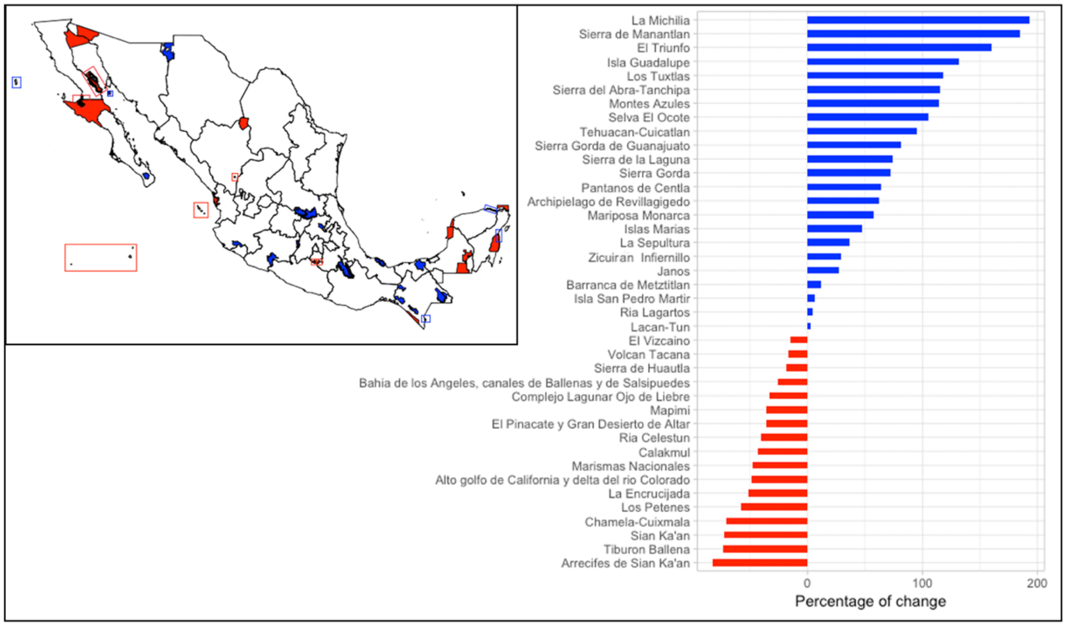


**Figure 4**. Percentage of decreases (red) and increases (blue) to the overall volume of climatic space between baseline (1960-1990) and future (2050, average for 2041-2060) conditions within 40 protected areas, and their location in Mexico (inset map). An increase in volume represents a gain in climate variability, while a decrease indicates a more homogenous future climate. For names of protected areas, see **Figure 1**.

*Vulnerability of natural protected areas to climate change*

The average size of the 40 NPAs spans 3127.11 km$^2$ (± 4260.7 km$^2$), with the largest being El Vizcaino (24,930.9 km$^2$) while the smallest is Volcan Tacana (63.8 km$^2$). The number of species for which there are GBIF records varied across NPAs, with an average of 2147 species (± 1740 species), a maximum of 7524 species recorded in Tehuacan-Cuicatlan (Oaxaca, Puebla) and a minimum of 98 species recorded in Isla San Pedro Martir (Sonora) (**Appendix 4**). The mean vulnerability (*V*) was 0.69 (± 0.11), with a maximum (high vulnerability) of 0.91 at Los Tuxtlas (Veracruz; 1551.22 km$^2$ and 5945 species), and a minimum (low vulnerability) of 0.38 at Tiburon Ballena (1459.9 km$^2$ and 334 species) (**Appendix 3**).

Species composition also varied across NPAs (**Figure 5**), with La Michilia (*V* = 0.40, ranked 39), Isla Guadalupe (Baja California; *V*= 0.62, ranked 32), Isla San Pedro el Martir (*V* = 0.48, ranked 37), and Sierra Abra Tanchipa (San Luis Potosí; *V*= 0.67, ranked 27) having a relatively different composition of species compared to the other NPAs. The set of NPAs identified to have higher vulnerability (in red and orange in **Figure 5**) clustered broadly in two geographical groups: (1) mountainous regions of central Mexico (except Sierra de la Laguna) with a more temperate climate and (2) south-east of Mexico in Chiapas and Veracruz (except for Chamela) where the climate is more tropical.

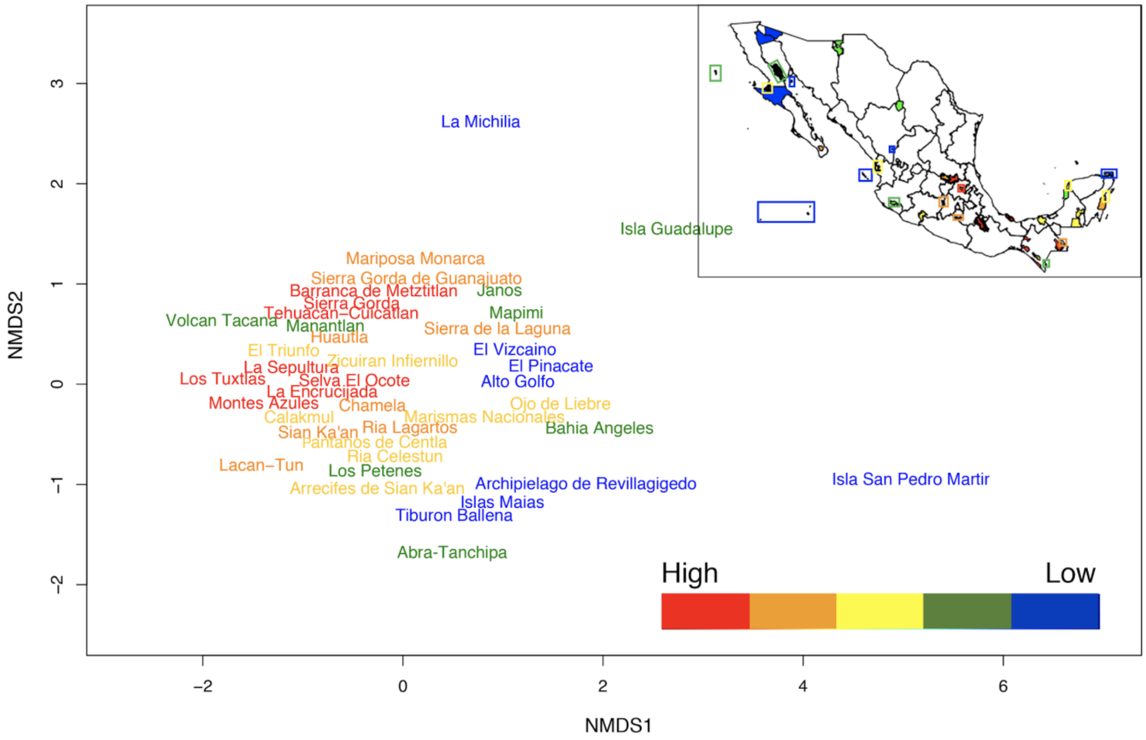


**Figure 5**. Non-metric multidimensional scaling (NMDS) plot for the ordination of the species composition of 40 protected areas and their location in Mexico (inset map). Colours are indicative of vulnerability ranked from high (red) to low (blue). For names of protected areas, see **Figure 1**.

## DISCUSSION

### *Climate change in natural protected areas of Mexico*

The predicted increases in temperature, and changes in both total precipitation and precipitation seasonality, will likely affect species' ranges, interactions, and even survival (Allen et al. 2010; Anderegg et al. 2015; Field et al. 2014; Thomas et al. 2004; Walther et al. 2002). Within Mexico, temperature is predicted to become warmer across all 40 NPAs by 2050, with larger increases (up to 3.75°C in *MTWM* and 2.5°C in *MTCM*) predicted to occur in arid regions that already experience high temperatures (e.g. Janos, Mapimí [Chihuahua, Coahuila, Durango], El Pinacate, and Tehuacán-Cuicatlán). Although the species within these NPAs are adapted to high temperatures, further increases in *MTWM* and *MTCM* might represent an additional stress, particularly to those species that are near their upper thermal limits (McCain and Colwell 2011).

Rising temperatures in NPAs located in mountainous regions and close to mountaintops are expected to exhibit severe impacts as geographic areas and therefore suitable habitats decrease at higher altitudes, impeding migration of species (Nogués-Bravo et al. 2007). We highlight such a risk at Sierra del Abra-Tanchipa (2477 m asl), Barranca de Metztitlán (Hidalgo, ranging from 1800 – 2600 m asl), Sierra Gorda (Queretaro; 1200 – 3000 m asl), Sierra Gorda de Guanajuato (Guanajuato; 900 – 2600 m asl), Sierra de Huautla (Morelos; 1700 m asl), Manantlan (Colima-Jalisco; 400 to 2860 m asl), Mariposa Monarca (2400 m asl), Tehuacán-Cuicatlán (2950 m asl), and Zicuirán Infiernillo (Michoacan; 1600 m asl). For instance, by 2050, the Mariposa Monarca NPA is predicted to experience an increase in *MTWM* by 3.5°C, and although future climatic space may be >50% broader than the baseline, this will consist of mostly novel conditions. These changes represent a potential risk to the temperate forest that provides habitat to the endangered monarch butterfly (*Danaus plexippus*), a global flagship species vulnerable to climate change (Lemoine 2015).

Decreases in precipitation are predicted in 30 NPAs, while for nine other NPAs, only minor increases in precipitation are likely to occur (i.e. <22 mm per year). The largest decreases in annual rainfall are predicted among NPAs where baseline precipitation is already high (>1000 mm per year). Additionally, 34 of the 40 NPAs studied here are predicted to experience changes in *PS*. An increase in *PS* indicates higher variability of precipitation (O'Donnell and Ignizio 2012), implying increased duration and severity of soil water stress (Knapp et al. 2008). This scenario poses a considerable risk for Sierra de la Laguna, which has the highest *PS* among the studied areas, and is predicted to experience the largest increases in the same variable by 2050. This NPA provides habitat to at least 1943 species. Of these, 86 are endemic plants, including *Arbutus peninsularis* (Ericaceae), *Opuntia lagunae* (Cactaceae), and the vulnerable *Pinus cembroides* ssp. *lagunae* (Arriaga et al. 2000; Farjon 2013). Importantly, some *Pinus* species are highly vulnerable to changes in precipitation and have low drought tolerance (Esperón-Rodríguez and Barradas 2015b).

### *Climatic space in Mexico's natural protected areas*

Here, we assessed the climatic space of 40 NPAs in terms of: (1) stable climatic space into the future; (2) loss of current climatic space; and (3) gain of novel climate by 2050. We found that 31 NPAs are predicted to retain none of their baseline climatic conditions. Species occurrence from GBIF indicate that these 31 NPAs harbour at least 22,866 species of animals, fungi, and vascular plants. The nine NPAs predicted to retain some parts of their baseline climate space by 2050, and hence may serve as climate refugia, harbour >14,526 species. Of these nine NPAs, Janos is predicted to suffer from the highest loss of stable climate (**Appendix 3**) and also is expected to have the highest increase in temperature conditions (*MTWM, MTCM*). The fauna of Janos is one of the most varied in North

America. It maintains the largest breeding population of burrowing owl (*Athene cunicularia*) and golden eagle (*Aquila chrysaetos*) in Mexico, as well as the only population of wild bison (*Bison bison*). This NPA also provides habitat to several endangered species, including the endemic prairie dog (*Cynomys mexicanus*) (Pacheco et al. 2000).

Along with the threat represented by rising sea levels for islands and coastal NPAs (Mimura 1999; Nicholls and Cazenave 2010), the loss of current climate space is a major concern for the ecosystems they harbor. Except for Isla San Pedro Mártir (stable climate of ~56.7%), the other NPAs on islands (Archipelago de Revillagigedo, Isla Guadalupe, and Islas Marias [Nayarit]) are predicted to lose all their baseline climatic space. Islands are highly vulnerable systems as they are geographically confined and, similar to mountaintops, their associated species have limited space to track changes in climate (Mimura et al. 2007). For Isla Guadalupe, for example, the loss of the current climatic space may affect at least 461 species, including 82 plants and nine bird species endemic to the island. This island is one of the main refugia of marine mammals, such as the northern elephant seal (*Mirounga angustirostris*) and the Guadalupe fur seal (*Arctocephalus townsendi*) (Arriaga et al. 2000; Gallo-Reynoso 1994).

Twenty-three NPAs are predicted to experience an increase in available climatic space by 2050, indicating that climatic conditions may be spatially more heterogeneous. However, for 16 of them, future climate will consist of entirely novel climatic conditions, relative to the baseline. Hence, these NPAs have little capacity to function as refugia for the ecosystems they currently shelter. Of higher concern are the 15 NPAs (including all NPAs in the Yucatan Peninsula, except for Tiburon

Ballena) predicted to lose all their baseline climatic space and also experience substantial decreases in the overall volume of climatic space (**Figure 3**). A decrease in the volume of climatic space within an NPA represents a loss of climatic variability (i.e. climatic conditions will become spatially more homogenous), and hence a decreasing array of niches that are available, potentially diminishing the refugial capacity of the area. Arrecifes de Sian Ka'an is predicted to suffer from the greatest decrease in climatic volume (~82%), in addition to vulnerability to sea level rise, invasive alien species, and growing pressure from tourism (Brenner 2010; CONABIO 1995).

*Vulnerability of natural protected areas to climate change*

A key finding is that the most vulnerable NPAs also share similar biodiversity composition (in red and orange in **Figure 5**). This result highlights the importance of monitoring and managing these locations and their species with vigilance (Smith et al 2019). Biodiversity loss in these NPAs may be significant if these species prove to be especially vulnerable to climate impacts and prone to local extirpation, and where protection alone will not be sufficient to stop the risk of extinction.

Although our index ranks NPAs in terms of their vulnerability, we note that this is a relative index that can only be used to prioritize management and conservation actions within the network of the 40 NPAs assessed here. A low vulnerability score does not mean that an NPA is not vulnerable to climate change per se. Furthermore, some NPAs, such as Isla San Pedro Martir and La Michilia, have relatively low vulnerability rankings ($V$ = 0.48, ranked 37 of 40 and $V$ = 0.40, ranked 39 of 40; respectively); however, these NPAs harbor a very unique composition of species (**Figure 5**) and are predicted to retain baseline climatic conditions in 2050. These characteristics make these NPAs important potential climate refugia and conservation actions are required to secure the persistence of species and ecosystems in those NPAs.

*What are the caveats and limitations of our study?*

A series of caveats are associated with our methodology. First, our assessment of the climatic space did not consider other environmental factors that can mitigate or exacerbate the effects of climate change, such as soil type and topography, or the presence/absence of water bodies; furthermore, our approach does not consider the potential feedback mechanisms between climate and biota (e.g. the role of vegetation in modulating temperature). Second, the climate data we used here are based on coarse-grained spatial interpolations from weather stations that are shielded from direct solar radiation and thus fail to account for the microclimate experienced by organisms living in their natural habitats (Lenoir et al. 2017). For instance, our analyses cannot explicitly consider locations where microclimatic conditions are more benign (e.g. protected slopes or areas with high canopy cover). Third, A key source of uncertainty arises from the use of alternative, yet plausible, climate scenarios. By selecting four different GCMs, we aimed to account for the variation among different models in terms of projected temperature and precipitation trends. The selected GCMs have been applied throughout the territory of Mexico and are recommended for impacts assessments (Cavazos et al. 2013; Fernández Eguiarte et al. 2015). Nevertheless, we acknowledge that different climate scenarios can produce different results, which might affect conservation and management actions (Beaumont et al. 2019; Baumgartner et al. 2018; Graham et al. 2019). Further, by selecting the scenario RCP8.5 with the highest radiative forcing and $CO_2$ emissions, our predictions might overestimate the losses of climatic space, in contrast to using a more conservative scenario, such as RCP6.0 (Raftery et al. 2017). Given that our aim is to assess risks, this approach is consistent with the precautionary principle.

Another limitation of our approach is that we did not consider the effects of elevated $CO_2$ on photosynthesis and transpiration. The combined effects of the $CO_2$ fertilization effect and climate change can increase plant biomass (Zhu et al. 2016) and affect the performance and functioning of plant species with cascading effects over the biota at each NPA. In NPAs where precipitation is predicted to decrease and temperature to increase, plant phenology may accelerate, reducing dry matter accumulation and altering ecosystem performance (Cao et al. 2010). However, under drought conditions, $CO_2$ fertilization may not counteract the effects of reduced water availability (Temme et al. 2019).

We recognize that our assessment of vulnerability only considers the exposure of protected areas to climate change. Species' sensitivity and adaptive capacity were not considered. Individual species respond idiosyncratically to climate change and differ in their capacity to endure its impacts. It is their environmental tolerance, migration ability, and genetic plasticity that facilitate species' resilience to climate change (Esperón-Rodríguez and Barradas 2015b; Lenoir et al. 2008; Pearson 2006; Pellegrini et al. 2017). However, the magnitude of shifts in the climatic space of NPAs might represent a useful general indicator of the potential for negative impacts on resident biota.

Importantly, our work does not consider additional threats to NPAs. Sea level rise and human impacts such as exploitation and pollution, land-use change and deforestation, may also erode the resilience of NPAs to climate change. In Mexico, deforestation and land-use change are issues of concern (Figueroa and Sánchez-Cordero 2008; SEMARNAT 2015). An example of deforestation is the case of Los Tuxtlas, the most vulnerable NPA ($V = 0.91$), which is predicted to retain only 8.7% of its natural vegetation in 2020 (Guevara et al. 2004; SEMARNAT 2015).

Lastly, we note that our index considers the number of species as a component, and although we collected species records for taxonomic groups with a good representation across NPAs, the sampling effort across NPAs is undoubtedly biased. Therefore, it is highly likely that we have underestimated the number of species occurring within each NPA. Additionally, our species composition analysis might be skewed due to the vastly different numbers of species recorded for these NPAs and represent only an approximation of this composition.

### *Future recommendations*

Our index can be used to categorise NPAs in terms of their bioregional vulnerability, their capacity to act as potential climatic refugia until 2050 (i.e. retain stable baseline climate), and the number of species that they harbour. This vital information can be used in prioritization frameworks which explicitly consider the benefits, costs, and feasibility of targeted conservation actions (Brown et al. 2015). While some vulnerable species within NPAs likely require immediate conservation interventions to mitigate direct impacts, such as the world's most endangered marine mammal, the vaquita (*Phocoena sinus*) in Alto Golfo de California y Delta del río Colorado (SEMARNAT 2017) whose primary threat is fishing, many other species can benefit from climate-mitigating actions taken in and around NPAs. Prioritizing what actions occur when and where to deliver the largest benefits to the existing NPA network will be a critical next step.

Actions that can be prioritized to help climate-proof Mexico's NPA system include the establishment of buffer zones. These zones improve the conservation efficiency of NPAs by promoting ecological flows within areas and increasing the ability of species to shift their distributions as climate changes (Beaumont and Duursma 2012; DeFries et al. 2010), and may help to mitigate losses in the climatic space of the current NPA network assessed here. An additional strategy to attenuate the impacts of climate change is the establishment of biological corridors (Hannah 2008). Habitat connectivity is fundamental to support resilient local populations (Brown and Kodric-Brown 1977). The effects of temperature and moisture on habitat availability and connectivity must remain the main consideration, particularly in fragmented systems such as the Mexican NPA network. Additional considerations include species' dispersal capacities, the accessibility of NPAs and the distance between them, and species' biology and behaviour (Henein and Merriam 1990).

In extreme cases where NPAs and additional area-based management (e.g. the establishment of buffer zones and corridors) fail to provide or retain suitable conditions, thereby jeopardizing species survival, species translocation or assisted migration may be necessary (Hoegh-Guldberg et al. 2008). While managed relocation of species remains a contentious issue, there are quantitative frameworks that could be explored for species with limited dispersal capacities which are found in the more vulnerable NPAs (McDonald-Madden et. al 2011) Yet, consideration must be given to minimise potential risks of invasion in the introduced area when translocating species. Further, the species and locations that will benefit most from translocation have yet to be explored for Mexico’s biodiversity.

Finally, we highlight that NPAs require continuous monitoring to assess other stressors that might increase their vulnerability. The characteristics of the non-protected areas surrounding NPAs will impact the condition and performance of each NPA. For instance, some of the 40 studied NPAs (e.g. Chamela-Cuixmala, Sierra Gorda de Guanajuato, Tehuacán-Cuicatlán, and Barranca de Metztitlán) are located near heavily populated areas and receive additional stressors including irregular human settlements, hydrometeorological hazards, and floods (CI 2002; SEDATU 2017). These stressors will undoubtedly affect habitat suitability and connectivity for species living in these NPAs, and combined with climate change, will exacerbate their vulnerability. The development of an accurate risk assessment with a more detailed analysis of each NPA is required. This assessment must aim at evaluating the magnitude of the impacts of future climate change of the most vulnerable NPAs and identify the species most at risk of extirpation.

## CONCLUSION

The capacity of Mexico's 40 UNESCO World Network of Biosphere Reserves to function as long-term refugia for biodiversity is likely to decline as the magnitude of climate change increases. By the mid-century, 31 NPAs, which together provide habitat to at least 22,866 species, are predicted to lose all their baseline climatic space, shifting to novel climates. The extent to which these conditions will be within the tolerance of species and ecosystems is currently unknown.

## SUPPLEMENTARY MATERIAL DESCRIPTION

**Appendix 1**. Pearson correlation of 19 bioclimatic variables.

**Appendix 2**. Changes in climate were assessed by comparing baseline (averages between 1960 and 1990) and future (2050 [average for 2041-2060]; average of four global circulation models) conditions based on five bioclimatic variables.

**Appendix 3**. Changes in climate spaces comparing baseline (averages between 1960 and 1990) and future (2050 [average for 2041-2060]; average of four global circulation models) conditions across the 40 NPAs.

**Appendix 4**. Number of species and records of each taxonomic group across the 40 NPAs.

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## DECLARATION OF INTERESTS

The authors declare that they have no conflict of interest to disclose.

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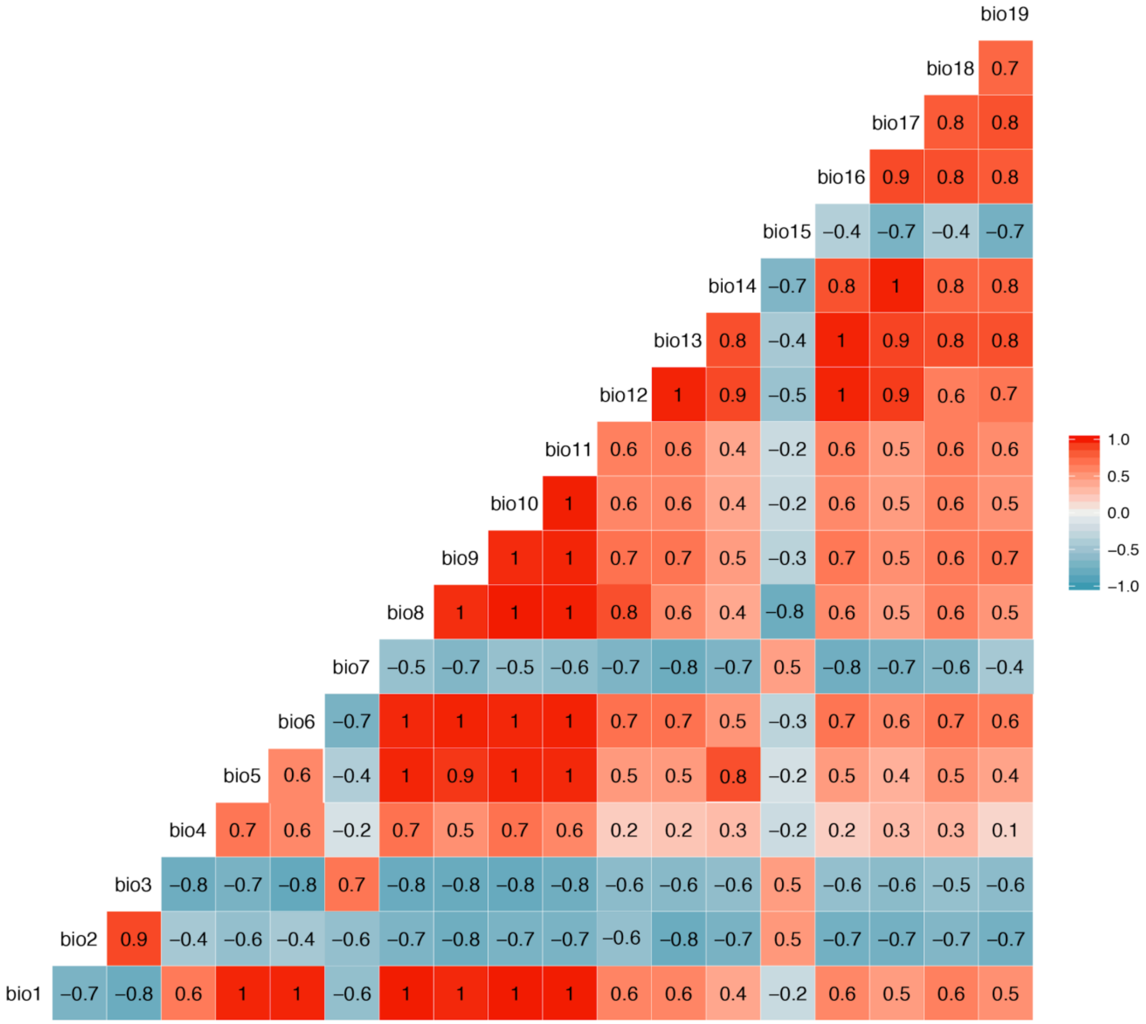
## SUPPLEMENTARY MATERIAL

# Changes in climatic space threaten the most biodiverse regions of Mexico

## Appendix 1

Pearson correlation of 19 bioclimatic variables



| | bio2 | bio3 | bio4 | bio5 | bio6 | bio7 | bio8 | bio9 | bio10 | bio11 | bio12 | bio13 | bio14 | bio15 | bio16 | bio17 | bio18 | bio19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| bio18 | | | | | | | | | | | | | | | | | | 0.7 |
| bio17 | | | | | | | | | | | | | | | | | 0.8 | 0.8 |
| bio16 | | | | | | | | | | | | | | | | 0.9 | 0.8 | 0.8 |
| bio15 | | | | | | | | | | | | | | | −0.4 | −0.7 | −0.4 | −0.7 |
| bio14 | | | | | | | | | | | | | | −0.7 | 0.8 | 1 | 0.8 | 0.8 |
| bio13 | | | | | | | | | | | | | 0.8 | −0.4 | 1 | 0.9 | 0.8 | 0.8 |
| bio12 | | | | | | | | | | | | 1 | 0.9 | −0.5 | 1 | 0.9 | 0.6 | 0.7 |
| bio11 | | | | | | | | | | | 0.6 | 0.6 | 0.4 | −0.2 | 0.6 | 0.5 | 0.6 | 0.6 |
| bio10 | | | | | | | | | | 1 | 0.6 | 0.6 | 0.4 | −0.2 | 0.6 | 0.5 | 0.6 | 0.5 |
| bio9 | | | | | | | | | 1 | 1 | 0.7 | 0.7 | 0.5 | −0.3 | 0.7 | 0.5 | 0.6 | 0.7 |
| bio8 | | | | | | | | 1 | 1 | 1 | 0.8 | 0.6 | 0.4 | −0.8 | 0.6 | 0.5 | 0.6 | 0.5 |
| bio7 | | | | | | | −0.5 | −0.7 | −0.5 | −0.6 | −0.7 | −0.8 | −0.7 | 0.5 | −0.8 | −0.7 | −0.6 | −0.4 |
| bio6 | | | | | | −0.7 | 1 | 1 | 1 | 1 | 0.7 | 0.7 | 0.5 | −0.3 | 0.7 | 0.6 | 0.7 | 0.6 |
| bio5 | | | | | 0.6 | −0.4 | 1 | 0.9 | 1 | 1 | 0.5 | 0.5 | 0.8 | −0.2 | 0.5 | 0.4 | 0.5 | 0.4 |
| bio4 | | | | 0.7 | 0.6 | −0.2 | 0.7 | 0.5 | 0.7 | 0.6 | 0.2 | 0.2 | 0.3 | −0.2 | 0.2 | 0.3 | 0.3 | 0.1 |
| bio3 | | | −0.8 | −0.7 | −0.8 | 0.7 | −0.8 | −0.8 | −0.8 | −0.8 | −0.6 | −0.6 | −0.6 | 0.5 | −0.6 | −0.6 | −0.5 | −0.6 |
| bio2 | | 0.9 | −0.4 | −0.6 | −0.4 | −0.6 | −0.7 | −0.8 | −0.7 | −0.7 | −0.6 | −0.8 | −0.7 | 0.5 | −0.7 | −0.7 | −0.7 | −0.7 |
| bio1 | −0.7 | −0.8 | 0.6 | 1 | 1 | −0.6 | 1 | 1 | 1 | 1 | 0.6 | 0.6 | 0.4 | −0.2 | 0.6 | 0.5 | 0.6 | 0.5 |

**Figure A1**. Pearson correlation of 19 bioclimatic variables (data from WorldClim (http://www.worldclim.org/). Bioclimatic variables are coded as follows:

BIO1 = Annual Mean Temperature

BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))

BIO3 = Isothermality (BIO2/BIO7) (* 100)

BIO4 = Temperature Seasonality (standard deviation *100)

BIO5 = Max Temperature of Warmest Month

BIO6 = Min Temperature of Coldest Month

BIO7 = Temperature Annual Range (BIO5-BIO6)

BIO8 = Mean Temperature of Wettest Quarter

BIO9 = Mean Temperature of Driest Quarter

BIO10 = Mean Temperature of Warmest Quarter

BIO11 = Mean Temperature of Coldest Quarter

BIO12 = Annual Precipitation

BIO13 = Precipitation of Wettest Month

BIO14 = Precipitation of Driest Month

BIO15 = Precipitation Seasonality (Coefficient of Variation)

BIO16 = Precipitation of Wettest Quarter

BIO17 = Precipitation of Driest Quarter

BIO18 = Precipitation of Warmest Quarter

BIO19 = Precipitation of Coldest Quarter

## Appendix 2

Changes in climate were assessed comparing baseline (averages between 1960 and 1990) and future (2050 [average for 2041-2060]; average of four global circulation models) conditions of five bioclimatic variables :1) Max Temperature of Warmest Month (*MTWM*); 2) Min Temperature of Coldest Month (*MTCM*); 3) Temperature Annual Range (*TAN*); 4) Annual Precipitation (*AP*); and 5) Precipitation Seasonality (*PS*) of 40 natural protected areas of Mexico.

**Table A2.1**. Mean, standard deviation [SD], minimum (Min) and maximum (Max) values across 40 protected areas of Mexico, for baseline (1960-1990) and future (2050 [average for 2041-2060]; average of four global circulation models) conditions. The bioclimatic variables are: (1) Max Temperature of Warmest Month (*MTWM*; °C); (2) Min Temperature of Coldest Month (*MTCM*; °C); (3) Temperature Annual Range (*TAN*; °C); (4) Annual Precipitation (*AP*; mm); and (5) Precipitation Seasonality (*PS*; %). Protected areas in brackets indicate where min and max values were found. Mean and SD were obtained from of all grid cells across protected areas.

| **Variable** | **Time period** | **Mean [SD]** | **Min** | **Max** |
|---|---|---|---|---|
| *MTWM* | Baseline | 33.7 [4.1] | 24 (Mariposa Monarca) | 40.6 (Alto Golfo de California) |
| | Future | 35.1 [3.8] | 27.2 (Isla Guadalupe) | 43.7 (Alto golfo de California) |

| | | | | |
|---|---|---|---|---|
| *MTCM* | Baseline | 12.4 [5.6] | -0.5<br>(Janos) | 19.1<br>(La Encrucijada) |
| | Future | 13.4 [5.6] | 2<br>(Janos) | 21.3<br>(La Encrucijada) |
| *TAN* | Baseline | 21.3 [5.9] | 13.2<br>(Isla Guadalupe) | 38.3<br>(Janos) |
| | Future | 21.6 [5.8] | 13.5<br>(Isla Guadalupe) | 39.6<br>(Janos) |
| *AP* | Baseline | 968 [748.4] | 77<br>(Alto Golfo de California) | 3720<br>(Montes Azules) |
| | Future | 948.8 [749.2] | 75.75<br>(Alto Golfo de California) | 3543<br>(Montes Azules) |
| *PS* | Baseline | 83 [19.7] | 47<br>(Tiburón Ballena) | 131<br>(Sierra de la Laguna) |
| | Future | 84.1 [19.9] | 53.8<br>(Tiburón Ballena) | 139.3<br>(Sierra de la Laguna) |

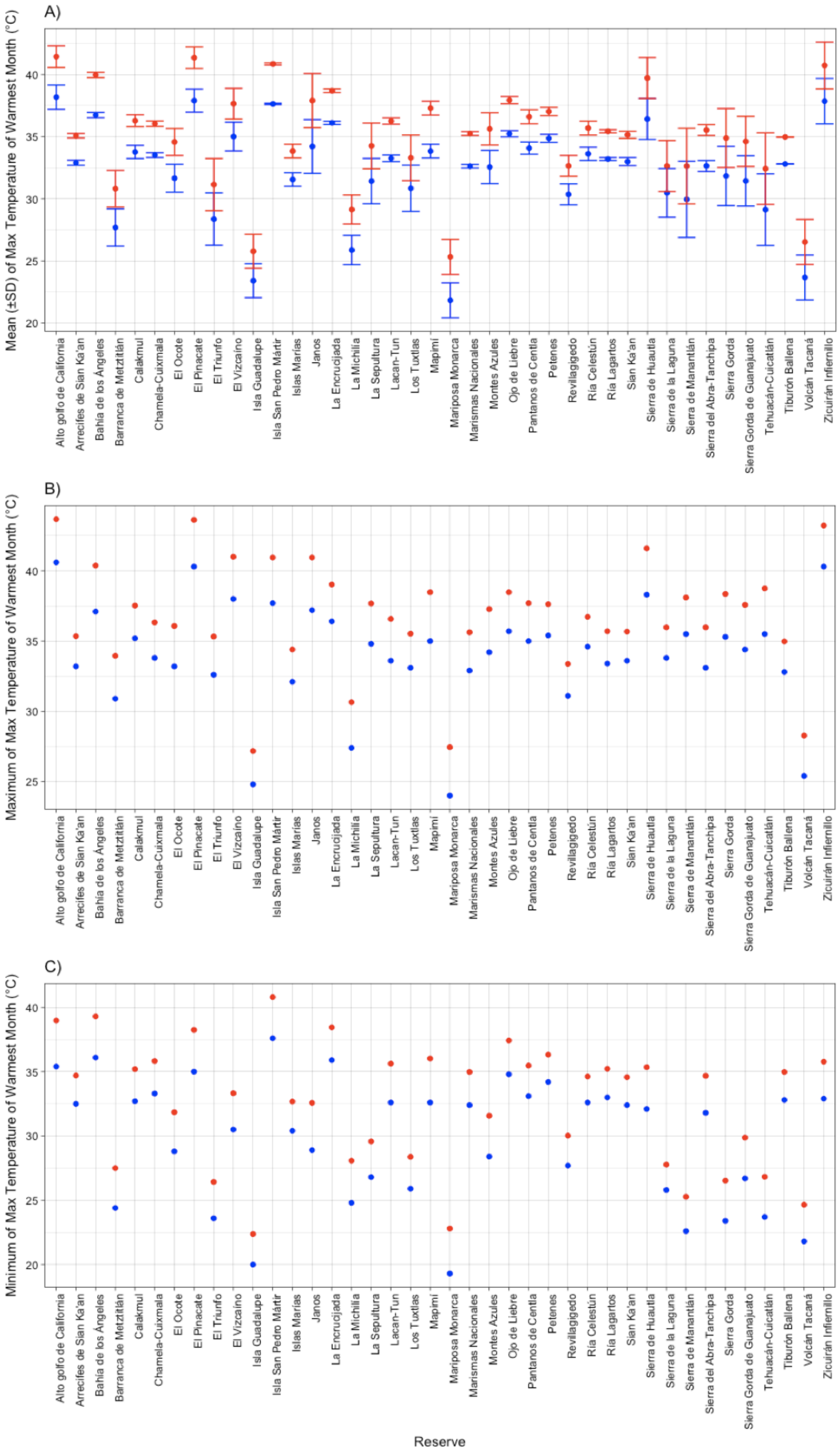


**Figure A2.1**. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Max Temperature of Warmest Month (*MTWM*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

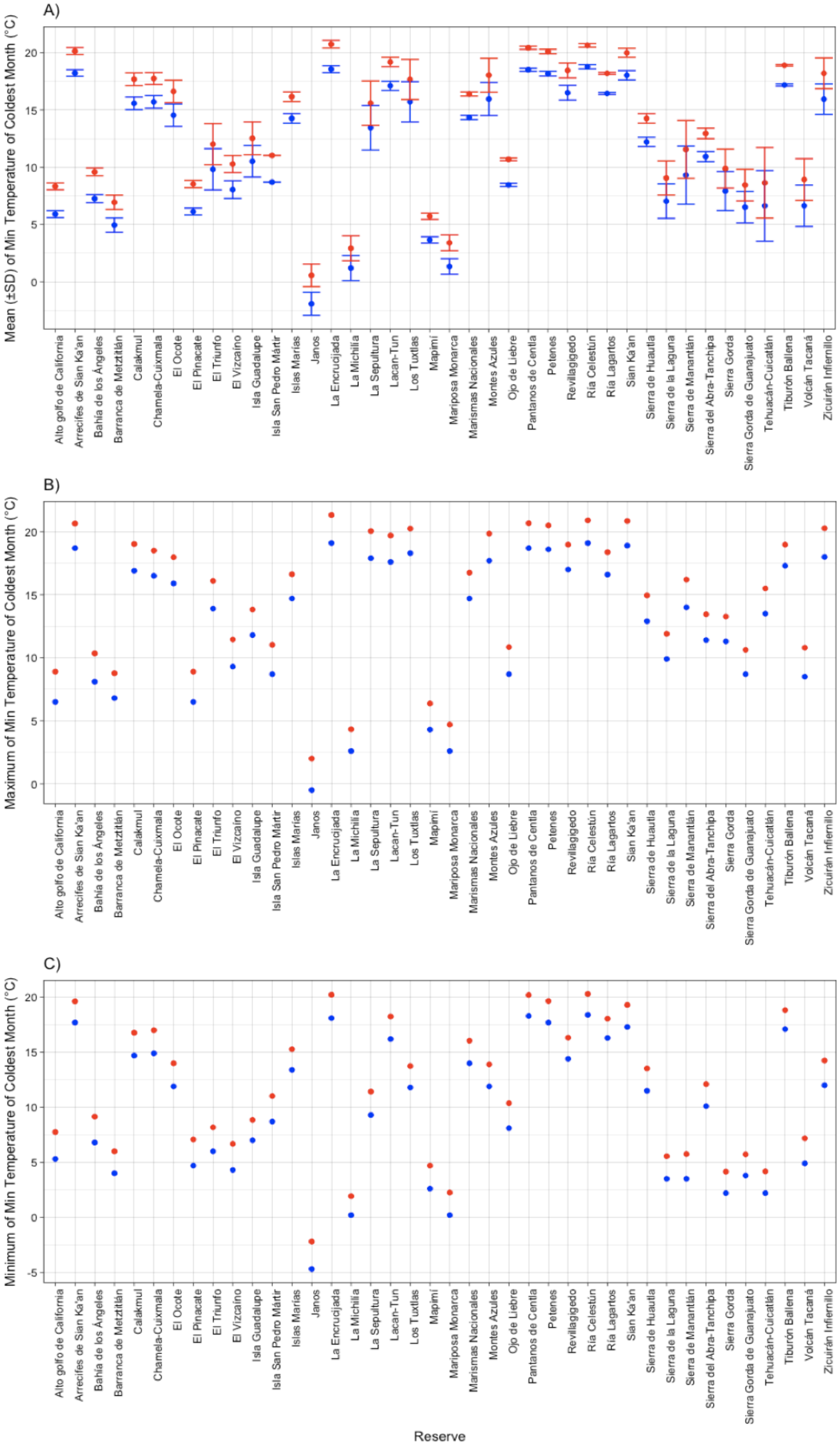


**Figure A2.2**. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Min Temperature of Coldest Month (*MTCM*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

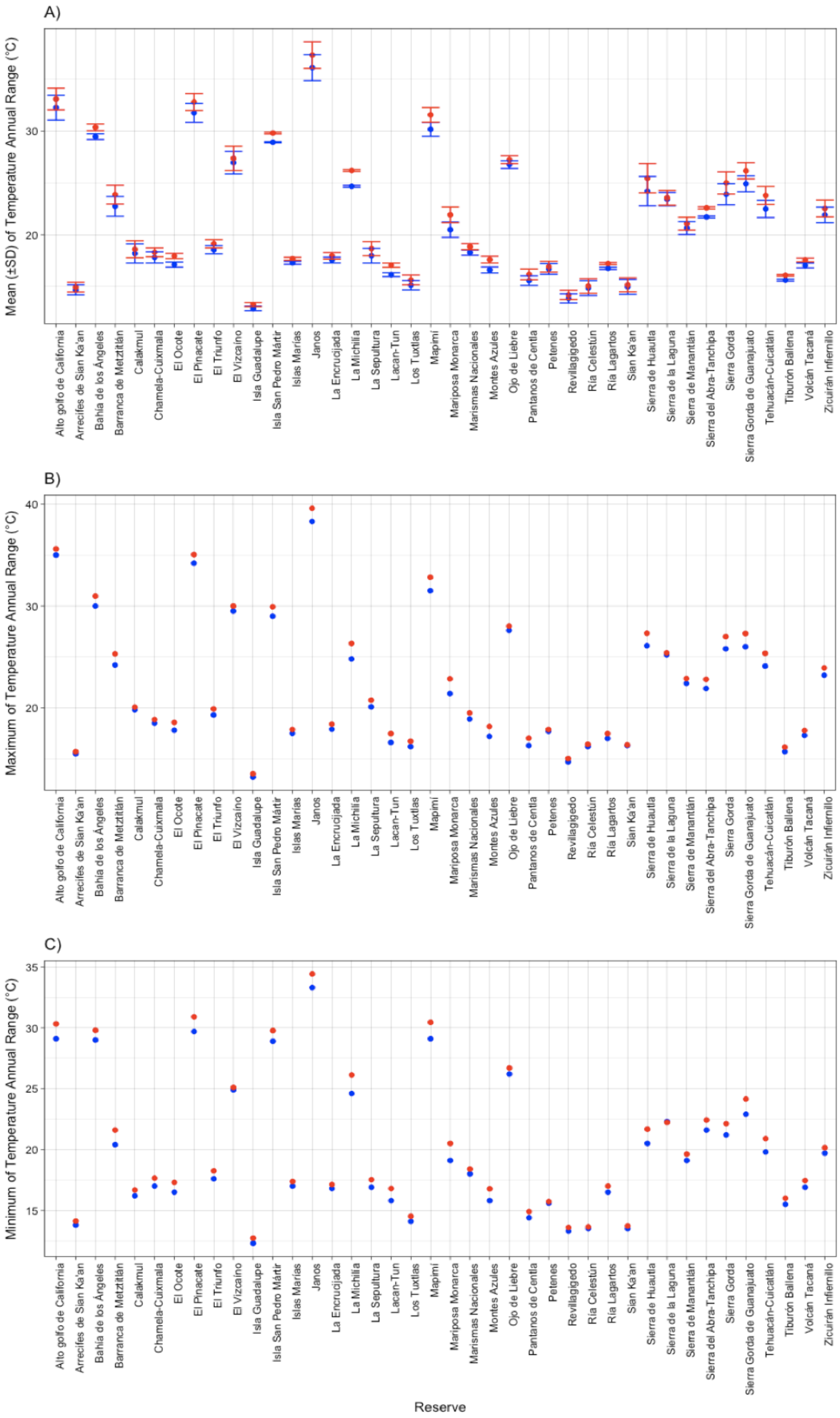


**Figure A2.3**. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Temperature Annual Range (*TAN*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

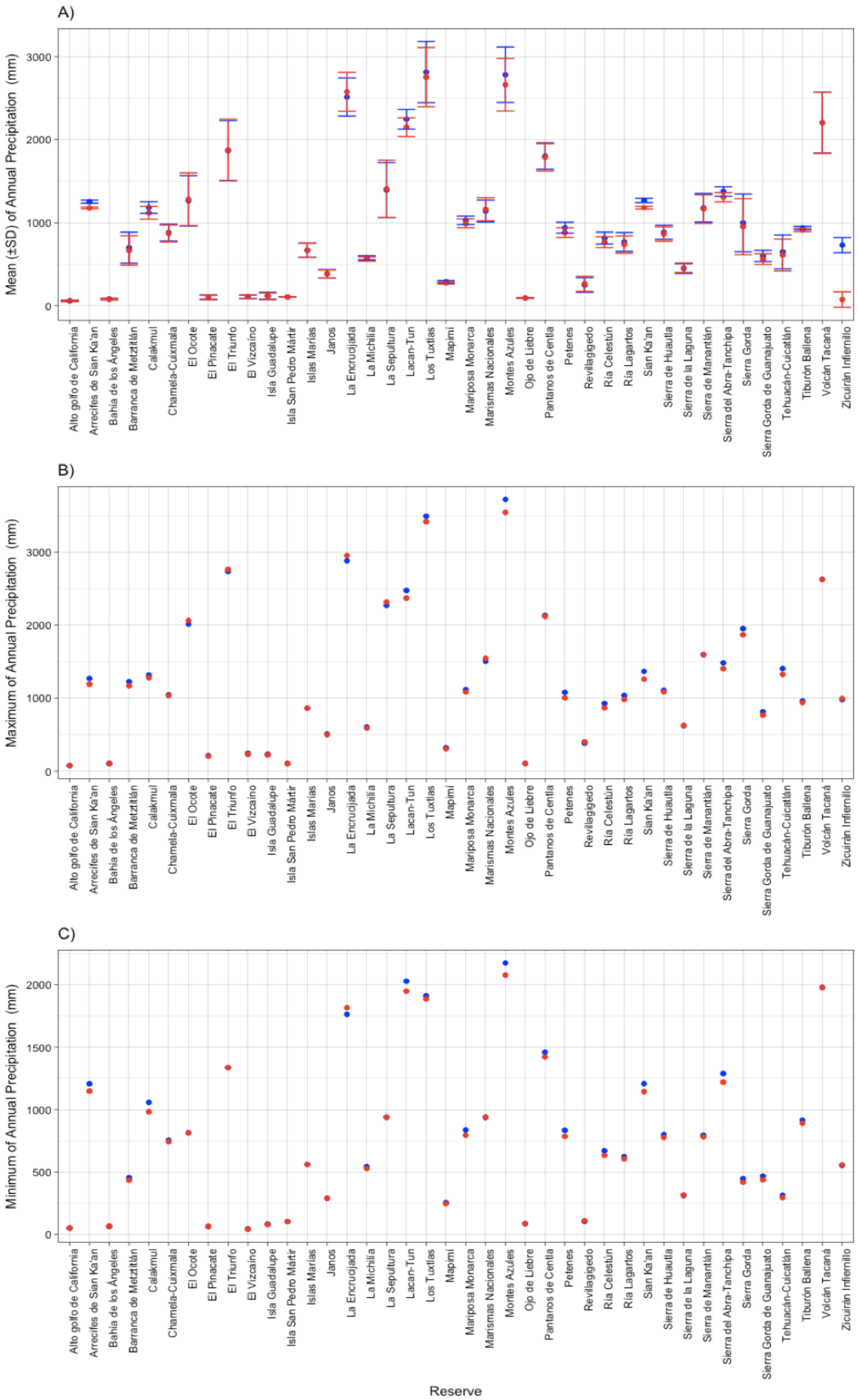


**Figure A2.4**. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Annual Precipitation (*AP*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

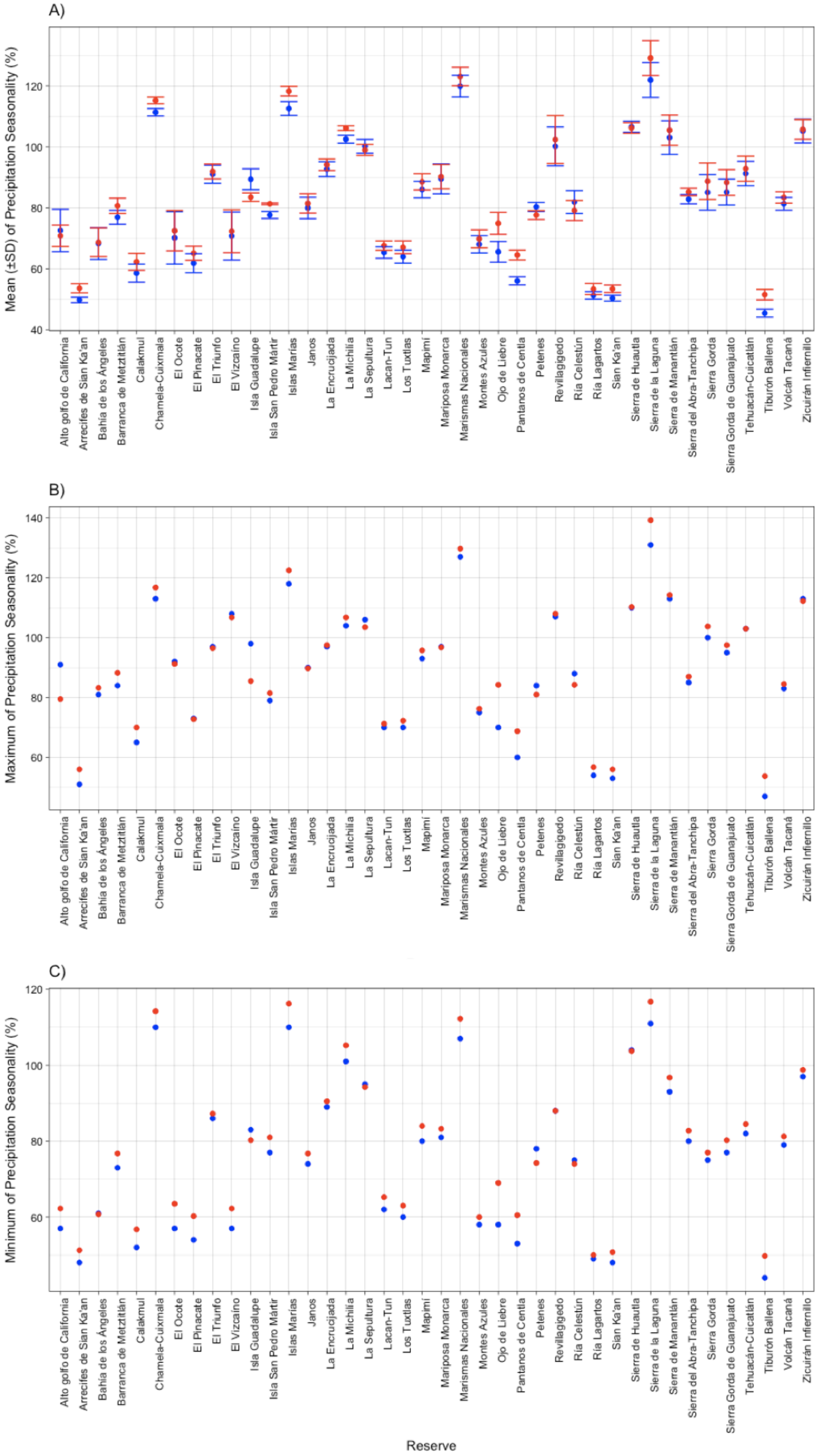


**Figure A2.5**. Changes in mean and standard deviation (A), maximum (B) and minimum (C) values of Precipitation Seasonality (*PS*) comparing two time periods (blue: baseline, 1960-1990; red: future, 2050 [average for 2041-2060]) for 40 protected areas of Mexico.

## Appendix 3

Changes in climate spaces comparing baseline (averages between 1960 and 1990) and future (2050 [average for 2041-2060]; average of four global circulation models) conditions across the 40 NPAs.

**Table A3.1**. For 40 protected areas of Mexico, we estimated baseline (**BCS**) and future (**FCS**) climatic space, the **stable** climatic space (i.e. intersection of baseline and future climatic spaces, as a proportion of the baseline hypervolume), the **loss** of climatic space (i.e. proportion of baseline climatic space that is no longer represented in the future) and the **gain** of novel climatic space (i.e. the proportion of future climatic space that was not represented under current climate). Additionally, we used the **loss** of analogue climate, total **area** and the number of **species** at each protected area to develop a comparative vulnerability index (***V***) that allowed us to **rank** these protected areas according to their vulnerability from high (1) to low (40). The unit of BCS and FCS is the product of the units (SD) of the five environmental variables.

| Protected area | BCS | FCS | Stable (%) | Loss (%) | Gain (%) | Area (km$^2$) | Species | *V* | Rank |
|---|---|---|---|---|---|---|---|---|---|
| Alto G olfo de California y delta del rio Colorado | 23.1 | 11.9 | 0 | 100 | 100 | 9347.6 | 941 | 0.58 | 36 |

| Protected area | BCS | FCS | Stable (%) | Loss (%) | Gain (%) | Area (km$^2$) | Species | *V* | Rank |
|---|---|---|---|---|---|---|---|---|---|
| Archipielago de Revillagigedo | 59.7 | 96.6 | 0 | 100 | 100 | 6366.9 | 587 | 0.61 | 33 |
| Arrecifes de Sian Ka'an | 181.3 | 32.4 | 0 | 100 | 100 | 349.3 | 864 | 0.70 | 21 |
| Bahia de los Angeles, canales de Ballenas y de Salsipuedes | 108.2 | 80.4 | 0 | 100 | 100 | 3879.6 | 1256 | 0.67 | 28 |
| Barranca de Metztitlan | 50.8 | 56.8 | 0 | 100 | 100 | 960.4 | 3223 | 0.80 | 5 |
| Calakmul | 17.7 | 10.1 | 0 | 100 | 100 | 7231.9 | 3099 | 0.71 | 20 |
| Chamela-Cuixmala | 182.3 | 54.1 | 0 | 100 | 100 | 131.4 | 1967 | 0.75 | 11 |
| Complejo Lagunar Ojo de Liebre | 98.4 | 65.6 | 0 | 100 | 100 | 603.4 | 654 | 0.69 | 23 |
| El Pinacate y Gran Desierto de Altar | 41.3 | 26.5 | 0 | 100 | 100 | 7145.6 | 542 | 0.60 | 35 |
| El Triunfo | 57.2 | 148.9 | 37.7 | 62.27 | 57.99 | 1191.8 | 4280 | 0.71 | 17 |

| Protected area | BCS | FCS | Stable (%) | Loss (%) | Gain (%) | Area (km²) | Species | *V* | Rank |
|---|---|---|---|---|---|---|---|---|---|
| El Vizcaino | 22.6 | 19.2 | 0 | 100 | 100 | 24930.9 | 2619 | 0.45 | 38 |
| Isla Guadalupe | 89.6 | 207.4 | 0 | 100 | 100 | 4769.7 | 461 | 0.62 | 32 |
| Isla San Pedro Martir | 271.2 | 287.3 | 56.7 | 43.29 | 42.82 | 301.7 | 98 | 0.48 | 37 |
| Islas Marias | 112.3 | 165.9 | 0 | 100 | 100 | 6412.9 | 559 | 0.61 | 34 |
| Janos | 20.0 | 25.5 | 1.1 | 98.77 | 99.03 | 5264.8 | 1427 | 0.66 | 31 |
| La Encrucijada | 41.1 | 19.9 | 0 | 100 | 100 | 1448.7 | 3196 | 0.79 | 6 |
| La Michilia | 203.0 | 593.7 | 86.1 | 13.87 | 6.70 | 93.3 | 501 | 0.40 | 39 |
| La Sepultura | 44.3 | 60.7 | 15 | 84.97 | 83.71 | 1673.1 | 4056 | 0.77 | 8 |
| Lacan-Tun | 85.3 | 87.3 | 0 | 100 | 100 | 618.7 | 1344 | 0.72 | 15 |
| Los Petenes | 74.8 | 31.6 | 0 | 100 | 100 | 2828.6 | 1098 | 0.68 | 26 |
| Los Tuxtlas | 73.7 | 160.4 | 0 | 100 | 100 | 1551.2 | 5945 | 0.91 | 1 |
| Mapimi | 49.0 | 31.7 | 0 | 100 | 100 | 3423.9 | 963 | 0.66 | 30 |
| Mariposa Monarca | 67.9 | 107.2 | 0 | 100 | 100 | 562.6 | 2194 | 0.76 | 10 |
| Marismas Nacionales | 47.2 | 24.6 | 0 | 100 | 100 | 1338.5 | 825 | 0.69 | 24 |

| Protected area | BCS | FCS | Stable (%) | Loss (%) | Gain (%) | Area (km$^2$) | Species | *V* | Rank |
|---|---|---|---|---|---|---|---|---|---|
| Montes Azules | 44.3 | 94.8 | 0 | 100 | 100 | 3312.0 | 4785 | 0.83 | 3 |
| Pantanos de Centla | 36.6 | 59.9 | 0 | 100 | 100 | 3027.1 | 1424 | 0.69 | 22 |
| Reserva de la biosfera Zicuiran Infiernillo | 36.1 | 46.5 | 0 | 100 | 100 | 2651.2 | 1781 | 0.71 | 18 |
| Ria Celestun | 38.5 | 23.0 | 0 | 100 | 100 | 814.8 | 1166 | 0.71 | 19 |
| Ria Lagartos | 79.4 | 82.7 | 0 | 100 | 100 | 603.5 | 1453 | 0.72 | 14 |
| Selva El Ocote | 63.9 | 131.0 | 0 | 100 | 100 | 1012.9 | 3697 | 0.82 | 4 |
| Sian Ka'an | 22.1 | 6.1 | 0 | 100 | 100 | 5281.5 | 2688 | 0.72 | 16 |
| Sierra de Huautla | 91.9 | 74.8 | 0 | 100 | 100 | 590.3 | 2308 | 0.76 | 9 |
| Sierra de la Laguna | 34.5 | 60.1 | 0 | 100 | 100 | 1124.4 | 1943 | 0.74 | 12 |
| Sierra de Manantlan | 42.8 | 121.8 | 53.4 | 46.58 | 42.95 | 1395.8 | 4441 | 0.67 | 29 |
| Sierra del Abra-Tanchipa | 161.8 | 348.0 | 0 | 100 | 100 | 214.6 | 279 | 0.68 | 27 |
| Sierra Gorda | 29.1 | 50.2 | 0 | 100 | 100 | 3835.7 | 5347 | 0.85 | 2 |

| **Protected area** | **BCS** | **FCS** | **Stable (%)** | **Loss (%)** | **Gain (%)** | **Area ($km^2$)** | **Species** | ***V*** | **Rank** |
|---|---|---|---|---|---|---|---|---|---|
| Sierra Gorda de Guanajuato | 42.0 | 76.3 | 0 | 100 | 100 | 2368.8 | 2277 | 0.74 | 13 |
| Tehuacan-Cuicatlan | 44.6 | 87.0 | 44.2 | 55.78 | 56.64 | 4901.9 | 7524 | 0.79 | 7 |
| Tiburon Ballena | 51.0 | 13.8 | 85.2 | 14.80 | 4.49 | 1459.9 | 334 | 0.38 | 40 |
| Volcan Tacana | 746.4 | 626.2 | 52 | 81.39 | 96.14 | 63.8 | 1734 | 0.68 | 25 |

## Appendix 4

For each taxonomic group in Mexico, the number of records, and the number of species and families represented, are given in **Table A4.1**. The number of species varied across the 40 protected areas. On average, protected areas had 2398 ± 1759 species recorded (mean ± standard deviation). The highest number of species was found in Tehuacán-Cuicatlán (Oaxaca-Puebla; 7524 species) and the lowest in Sierra del Abra-Tanchipa (San Luis Potosí; 279 species) (**Table A4.2, Figure A4**). Some taxonomic groups are not recorded at all within the studied network of protected areas. Amphibians and reptiles were the most under-represented groups with 20 ± 21 species and 56 ± 38 species, respectively. Records of amphibians and fungi were absent in three and eight protected areas, respectively. Also, we found only one amphibian species recorded in Ojo de Liebre (Baja California Sur) and Lacan-Tun (Chiapas), and one fungi species in Lacan-Tun. In contrast, vascular plants had the highest number of species (1267 ± 1168), followed by arthropods (383 ± 403). Tehuacán-Cuicatlán had the highest number of records per individual group, in contrast to Isla Guadalupe (Baja California) and Isla San Pedro Mártir (Sonora), which had fewest records (**Table A4.3**).

**Table A4.1**. Number of families, species, and occurrence records for each taxonomic group.

| **Taxonomic group** | **No. families** | **No. species** | **No. records** |
|---|---|---|---|
| Amphibians | 22 | 743 | 179,886 |
| Arthropods | 1071 | 17,161 | 600,135 |
| Birds | 63 | 2281 | 883,093 |
| Mammals | 50 | 1408 | 64,905 |
| Reptiles | 45 | 2159 | 250,666 |
| Fungi | 352 | 6674 | 90,653 |
| Vascular plants | 566 | 45,767 | 1,516,873 |

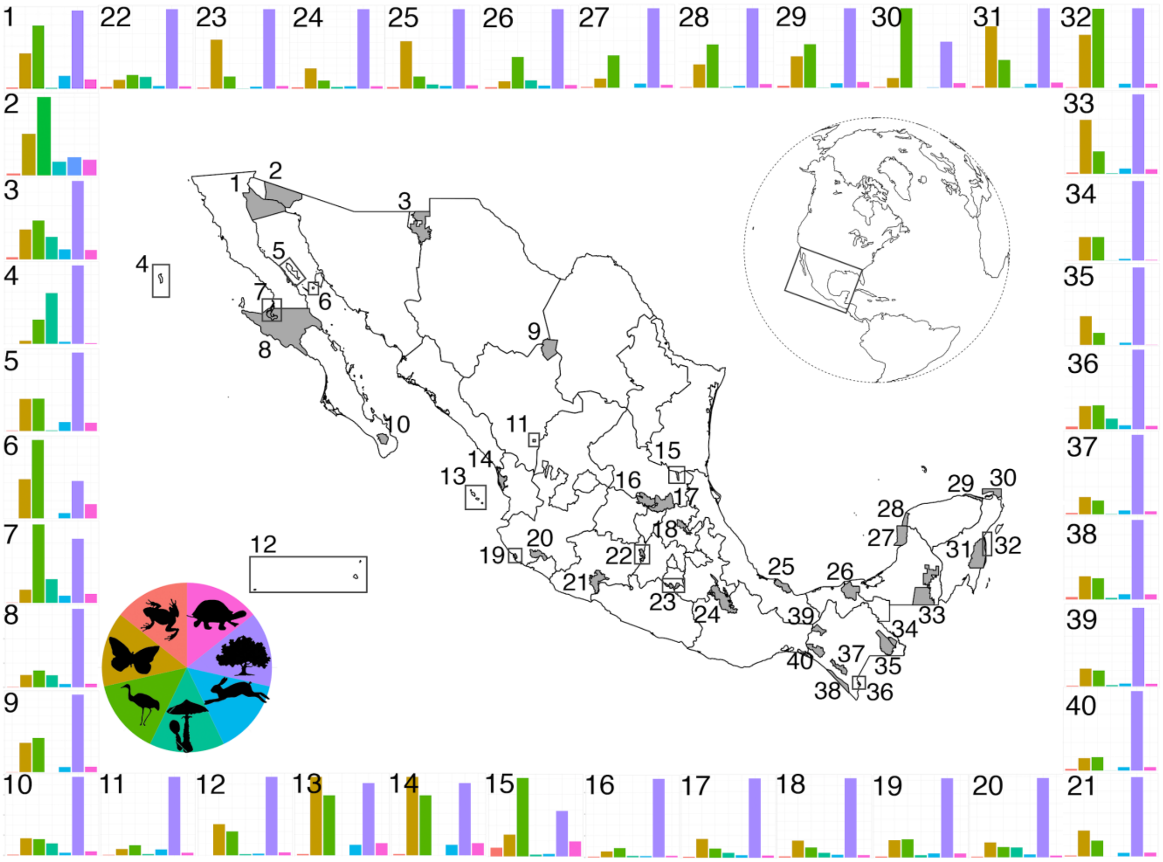


**Figure A4**. Location of the 40 protected areas of Mexico and histograms indicating the number of species recorded of seven major taxonomic groups within three kingdoms: 1) vascular plants (Tracheophytes); 2) fungi; and 3) animals (amphibians, arthropods, birds, mammals, and reptiles) (see details on **Table A4.3**). Protected areas are indicated as follows: 1) Alto Golfo de California y delta del río Colorado; 2) El Pinacate y Gran Desierto de Altar; 3) Janos; 4) Isla Guadalupe; 5) Bahia de los Angeles, canales de Ballenas y de Salsipuedes; 6) Isla San Pedro Mártir; 7) Complejo lagunar Ojo de Liebre; 8) El Vizcaíno; 9) Mapimí; 10) Sierra de la Laguna; 11) La Michilía; 12) Archipielago de Revillagigedo; 13) Islas Marias; 14) Marismas Nacionales; 15) Sierra del Abra-Tanchipa; 16) Sierra Gorda de Guanajuato; 17) Sierra Gorda; 18) Barranca de Metztitlán; 19) Chamela-

Cuixmala; 20) Sierra de Manantlán; 21) Zicuirán Infiernillo; 22) Mariposa Monarca; 23) Sierra de Huautla; 24) Tehuacán-Cuicatlán; 25) Los Tuxtlas; 26) Pantanos de Centla; 27) Los Petenes; 28) Ría Celestún; 29) Ría Lagartos; 30) Tiburón Ballena; 31) Sian Ka'an; 32) Arrecifes de Sian Ka'an; 33) Calakmul; 34) Lacan-Tún; 35) Montes Azules; 36) Volcán Tacaná; 37) El Triunfo; 38) La Encrucijada; 39) Selva el Ocote; and 40) La Sepultura.

**Table A4.2**. Mean and standard deviation (SD), maximum (Max) and minimum (Min) number of species reported for each taxonomic group in 40 protected areas of Mexico. Names in parentheses indicate the reserves where those values were found.

| **Taxonomic group** | **Mean** | **SD** | **Max** | **Min** |
|---|---|---|---|---|
| Amphibia | 20 | 21 | 87<br>(Tehuacán-Cuicatlán) | 0<br>(Archipiélago de Revillagigedo, Isla Guadalupe, Isla San Pedro Mártir) |
| Arthropoda | 383 | 403 | 1867<br>(Los Tuxtlas) | 9<br>(Isla Guadalupe) |
| Aves | 298 | 131 | 530<br>(Tehuacán-Cuicatlán) | 44<br>(Isla San Pedro Mártir) |
| Mammalia | 59 | 44 | 162<br>(Tehuacán-Cuicatlán) | 1<br>(Tiburón Ballena) |
| Reptilia | 56 | 38 | 161<br>(Tehuacán-Cuicatlán) | 2<br>(Isla Guadalupe) |
| Fungi | 64 | 89 | 366<br>(Sierra de Manantlán) | 0<br>(Arrecifes de Sian Ka'an, Isla San Pedro Mártir, Islas Marías, Mapimí, Marismas Nacionales, los Petenes, Tiburón Ballena, Zicuirán Infiernillo) |
| Tracheophyte | 1267 | 1168 | 5161<br>(Tehuacán-Cuicatlán) | 21<br>(Isla San Pedro Mártir) |

**Table A4.3**. Names and locations by state of 40 protected areas of Mexico. The total number of species and records of seven taxonomic groups (amphibians, Amph; arthropods, Arthr; birds; mammals, Mamm; reptiles, Rept; fungi; and plants) were obtained from the Global Biodiversity Information Facility (GBIF, http://www.gbif.org).

| **Reserve** | **State** | **Total no. species** | **No. of species** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Records** | **Amph** | **Arthr** | **Birds** | **Mamm** | **Rept** | **Fungi** | **Plants** |
| Alto Golfo de California y delta del río Colorado | Baja California, Sonora | 937 | 1,009 | 4 | 166 | 297 | 60 | 43 | 3 | 368 |
| Archipiélago de Revillagigedo | Colima | 587 | 7,515 | 0 | 131 | 101 | 7 | 12 | 5 | 331 |
| Arrecifes de Sian Ka'an | Quintana Roo | 864 | 14,642 | 2 | 208 | 310 | 16 | 16 | 0 | 312 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Bahía de los Ángeles, canales de Ballenas y de Salsipuedes | Baja California | 1256 | 50,170 | 4 | 250 | 252 | 70 | 64 | 5 | 611 |
| Complejo Lagunar Ojo de Liebre | Baja California Sur | 654 | 34,827 | 1 | 44 | 262 | 24 | 30 | 79 | 214 |
| El Triunfo | Chiapas | 4280 | 153,007 | 50 | 621 | 494 | 137 | 107 | 12 | 2,859 |
| Isla Guadalupe | Baja California | 461 | 7,980 | 0 | 9 | 70 | 6 | 2 | 147 | 227 |
| Isla San Pedro | Sonora | 98 | 1,457 | 0 | 22 | 44 | 3 | 8 | 0 | 21 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Mártir | | | | | | | | | | |
| Islas Marías | Nayarit | 559 | 6,351 | 3 | 187 | 143 | 25 | 29 | 0 | 172 |
| La Sepultura | Chiapas | 4056 | 45,300 | 60 | 442 | 480 | 121 | 122 | 4 | 2,827 |
| Mapimí | Chihuahua, Coahuila, Durango | 963 | 16,672 | 7 | 185 | 215 | 37 | 39 | 0 | 480 |
| Marismas Nacionales | Nayarit | 825 | 23,085 | 18 | 147 | 358 | 47 | 50 | 0 | 205 |
| Pantanos de Centla | Tabasco | 1424 | 22,498 | 15 | 78 | 334 | 33 | 38 | 88 | 838 |
| Reserva de la Biosfera | Jalisco | 1967 | 36,781 | 16 | 270 | 283 | 64 | 63 | 36 | 1,235 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Chamela-Cuixmala | | | | | | | | | | |
| Reserva de la biosfera de Calakmul | Campeche | 3099 | 115,329 | 24 | 987 | 410 | 96 | 84 | 10 | 1,455 |
| Reserva de la Biósfera de la Barranca de Metztitlán | Hidalgo | 3223 | 25,050 | 33 | 469 | 281 | 77 | 65 | 130 | 2,201 |
| Reserva de la biosfera de | México, Michoacan | 2194 | 33,300 | 31 | 161 | 250 | 50 | 42 | 215 | 1,445 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| la Mariposa Monarca | | | | | | | | | | |
| Reserva de la biosfera de los Petenes | Campeche | 1098 | 9,768 | 7 | 78 | 276 | 36 | 25 | 0 | 676 |
| Reserva de la biosfera el Pinacate y Gran Desierto de Altar | Sonora | 542 | 16,376 | 6 | 133 | 251 | 58 | 50 | 44 | 393 |
| Reserva de la | Baja California Sur | 2619 | 71,360 | 8 | 253 | 347 | 69 | 74 | 248 | 1,227 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| biosfera ElVizcaíno | | | | | | | | | | |
| Reserva de la Biosfera Janos | Chihuahua | 1427 | 15,744 | 16 | 223 | 290 | 75 | 70 | 168 | 585 |
| Reserva de la Biósfera La Encrucijada | Chiapas | 3196 | 55,254 | 56 | 536 | 489 | 121 | 118 | 37 | 1,839 |
| Reserva de la Biosfera La Michilía | Durango | 501 | 1745 | 2 | 30 | 48 | 28 | 12 | 6 | 375 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Reserva de la Biosfera Lacan-Tun | Chiapas | 1344 | 5,897 | 1 | 245 | 245 | 18 | 6 | 1 | 828 |
| Reserva de la Biosfera Los Tuxtlas | Veracruz | 5945 | 151,657 | 63 | 1,867 | 478 | 114 | 134 | 167 | 3,122 |
| Reserva de la Biósfera Montes Azules | Chiapas | 4785 | 123,172 | 42 | 1,108 | 509 | 155 | 81 | 29 | 2,861 |
| Reserva de la biosfera | Chiapas | 3697 | 45,849 | 46 | 547 | 493 | 110 | 102 | 65 | 2,334 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Selva ElOcote | | | | | | | | | | |
| Reserva de la Biosfera Sierra de Manantlán | Colima, Jalisco | 4441 | 51,768 | 25 | 551 | 383 | 108 | 64 | 366 | 2,944 |
| Reserva de la biosfera Sierra Gorda | Querétaro | 5347 | 65,958 | 41 | 854 | 414 | 116 | 101 | 224 | 3,597 |
| Reserva de la biosfera Tehuacán- | Oaxaca, Puebla | 7524 | 143,849 | 87 | 1,316 | 530 | 162 | 161 | 107 | 5,161 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Cuicatlán | | | | | | | | | | |
| Reserva de la Biosfera Tiburón Ballena | Quintana Roo | 334 | 5,115 | 2 | 23 | 188 | 1 | 11 | 0 | 109 |
| Reserva de la biosfera Zicuirán Infiernillo | Michoacán | 1781 | 38,701 | 12 | 357 | 217 | 49 | 52 | 0 | 1,094 |
| Ría Celestún | Campeche, Yucatan | 1166 | 29,111 | 5 | 178 | 330 | 15 | 28 | 5 | 605 |
| Ría Lagartos | Yucatán | 1453 | 83,183 | 18 | 274 | 379 | 39 | 50 | 2 | 691 |

| Reserve | State | Total no. species | No. of species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Records | Amph | Arthr | Birds | Mamm | Rept | Fungi | Plants |
| Sian Ka'an | Quintana Roo | 2688 | 81,973 | 25 | 916 | 416 | 60 | 78 | 7 | 1,186 |
| Sierra de Huautla | Morelos | 2308 | 33,855 | 16 | 772 | 192 | 32 | 42 | 2 | 1,252 |
| Sierra de la Laguna | Baja California Sur | 1943 | 29,892 | 9 | 253 | 240 | 38 | 58 | 178 | 1,167 |
| Sierra del Abra-Tanchipa | San Luis Potosí | 279 | 778 | 14 | 35 | 126 | 4 | 24 | 3 | 73 |
| Sierra Gorda de Guanajuato | Guanajuato | 2277 | 12,827 | 16 | 136 | 212 | 29 | 34 | 33 | 1,817 |
| Volcán Tacaná | Chiapas | 1734 | 16,968 | 31 | 273 | 282 | 46 | 39 | 124 | 939 |